Mem. S.A.It. Vol. 76, 65
© SAIt 2005

Memorie della

The Centre of the Milky Way: Stellar Dynamics, Potential Star Formation, and Variable NIR Emission from Sgr A*

R. Schödel, and A. Eckart

I.Physikalisches Institut, Universität zu Köln, Zülpicher Str.77, 50937 Köln, Germany

Abstract. The Galactic Centre (GC) is a typical quiescent galactic nucleus. Located at a distance of a mere 8.0 kpc, it is the only case where we can test the black hole paradigm directly and study the interaction of the central black hole with its environment in detail. Here we report on some recent results of high-resolution near-infrared observations of the central parsec of the GC: The analysis of stellar dynamics, especially the orbits of several individual stars near Sagittarius A* (Sgr A*), can exclude almost all alternative scenarios to the black hole hypothesis. Particularly, the dark cluster and neutrino ball models are not compatible with the data. There are several groups of massive, young stars near Sgr A* that show striking deviations from dynamical isotropy. The observed dynamical anisotropies show that the young stars are not dynamically relaxed and may provide insights as to their formation. Just north of the so-called IRS 13 complex, there is a group of embedded, highly reddened stars. These sources are either unresolved bow-shocks created by the interaction of windy stars with the surrounding ISM or – an exciting possibility – recently formed stars. The third focus of this talk is variable NIR emission from Sgr A* itself that has only been discovered very recently and is vital for constraining theoretical models of accretion/emission near Sgr A*. The short timescales involved in the variability of the NIR emission indicates that the radiation must be produced within about 10 Schwarzschild radii of the black hole. Finally, we report on the simultaneous observations of Sgr A* in the NIR and X-ray regimes. The variability at both wavelength regimes is highly correlated, but the ratio of the NIR to X-ray emission appears to take on rather different values in the individual flares.

Key words. Galactic Centre – Sagittarius A* – stellar dynamics – star formation

1. Introduction

With a distance of only 8.0 kpc (Reid 1993; Eisenhauer et al. 2003) the centre of the Milky Way offers the singular chance to study a galactic nucleus in detail. After the discovery of quasars and AGN, it appeared a logical step to suspect the presence of a supermassive black hole in the centre of our own galaxy (e.g., Lynden-Bell & Rees 1971). An obvious candidate was found with the non-thermal radio point source Sagittarius A* (Sgr A*) by Balick & Brown (1974).

Send offprint requests to: R. Schödel
Correspondence to: I.Physikalisches Institut, Universität zu Köln, Zülpicher Str.77, 50937 Köln, Germany

Due to the strong interstellar extinction toward the GC, it can only be observed at radio/mm, NIR, and X-ray wavelengths. The strength of NIR observations is that at this wavelength the properties of the stellar cluster in the GC can be studied, particularly stellar dynamics. NIR speckle interferometric observations in the 1990s achieved the sensitivity and resolution to show that the gravitational potential in the GC is dominated by a point mass in the innermost parsec down to distances of a few light days from Sgr A* (e.g., Eckart & Genzel 1996; Ghez et al. 1998; Genzel et al. 2000). The acceleration measured on a few individual stars constrained the gravitational potential even further (Ghez et al. 2000; Eckart et al. 2002).

The advent of adaptive optics on 8-10 m class telescopes near the beginning of this decade boosted the sensitivity and resolution of NIR observations significantly and lead to a range of new breakthroughs. Here, we focus on a few important recent discoveries, concerning stellar dynamics and the nature of Sgr A*, potential star formation in the GC, and the NIR emission from Sgr A*.

2. Stellar Dynamics and the Nature of Sgr A*

The observation of the peri-centre passage of the star S2 on its orbit around Sgr A* in spring 2002 represents a milestone in the quest to prove the black hole nature of the central object in our Milky Way. With two-thirds of its 15-year orbit observed, a unique Kepler solution for the motion of S2 could be determined (Schödel et al. 2002; Ghez et al. 2003). Combining the information of the central mass measured from Kepler's third law with the observed peri-centre distance of $\sim$17 light hours, the density of the central dark mass could be constrained to values exceeding $10^{17}\,M_\odot\,pc^{-3}$ (Schödel et al. 2002). Thus, a cluster of dark astrophysical bodies and the neutrino ball model (e.g., Munyaneza & Viollier 2002) could be excluded, providing extraordinary support for the supermassive black hole model. In Fig. 1 we illustrate the constraints on the lifetime of hypothetical dark clusters of astrophysical bodies with given masses and densities. In the case of the GC such a dark cluster would have a lifetime of less than 10^5 yrs. Hence, the evidence appears overwhelming that Sgr A* is indeed a supermassive black hole. It has a mass of $3.6 \pm 0.6 \times 10^6\,M_\odot$ (Eisenhauer et al. 2003).

Spectroscopic measurements of the line-of-sight velocity of S2 (first measurements by Ghez et al. 2003) break the degeneracy between the central mass and its distance and thus offered the possibility, for the first time, of a direct geometric determination of the distance to Sgr A* (Eisenhauer et al. 2003). Schödel et al. (2003) and Ghez et al. (2004) constrained the orbits of several other stars close to Sgr A*. Including the proper motion of Sgr A* as a free parameter in a simultaneous fit of multiple orbits, Ghez et al. (2004) could also show that the centre of mass has a negligible proper motion.

Since the above mentioned analyses of stellar orbits near Sgr A* all make the implicit assumption of the validity of a Keplerian approach, a point of special interest is whether any extended dark mass may be present near the supermassive black hole. Mouawad et al. (2003) have presented the first analysis of this type based on the data of Schödel et al. (2003). They come to the conclusion that a hypothetical symmetric extended dark mass component around Sgr A* that follows the radial density profile of a Plummer model cannot comprise more than about 10% of the mass of Sgr A* itself.

3. Dynamics of the young stellar population

There exist two peculiar groups of young, massive stars near Sgr A*: The so-called He-stars (due to the strong Helium emission line in their NIR spectra) and the brighter stars in the cluster immediately surrounding Sgr A*, such as S2 (e.g., Krabbe et al. 1995; Gezari et al. 2002; Genzel et al. 1997, 2000; Ghez et al. 2003; Genzel et al. 2003b). Both groups show peculiar signs of dynamical anisotropy. Presumably, they have not had the time to relax into dynamical equilibrium with the background cluster, which would be expected to

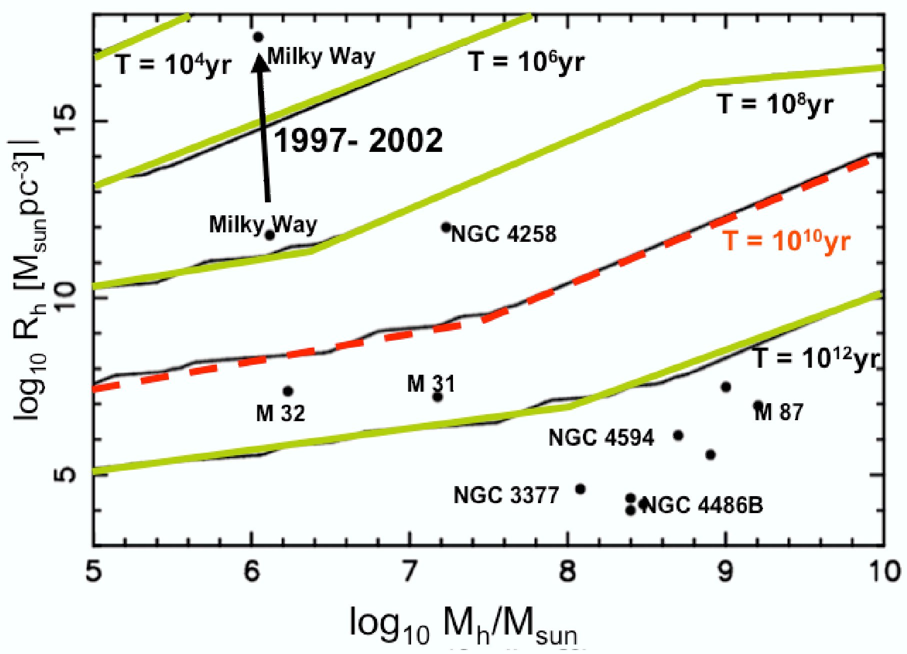

Fig. 1. Figure illustrating the lifetime of clusters of astrophysical bodies. Following Maoz (1998), we have plotted the half density vs. the half mass of a cluster and calculated the stability of a given cluster with respect to evaporation and collisions. The lifetime of a hypothetical dark cluster with the mass density as measured from stellar orbits in the centre of the Milky Way would be less than 10^5 yrs. The arrow between the two data points for the Milky Way refers to the increase in constraints from Genzel et al. (1997) (stellar velocity dispersions) to Schödel et al. (2002) (orbit of S2). Values for extragalactic objects are taken from Kormendy (2004).

result in an isotropic, random velocity field. On the one hand, the He-stars at $p \sim 3''$ projected distance from Sgr A* appear to be arranged in one (possibly two) rotating thin disk(s) (Levin & Beloborodov 2003; Genzel et al. 2003b). The young stars in the cluster immediately surrounding Sgr A* (at $p < 1''$), on the other hand, show indications of radial anisotropy (Genzel et al. 2000; Schödel et al. 2003). The dynamics of these associations may provide clues as to their formation. The He-stars may have formed in a previously existent dense accretion disk around Sgr A* (Levin & Beloborodov 2003), or perhaps via the collision of two counter-rotating molecular clouds (Genzel et al. 2003b). The Sgr A*-cluster stars, on the other hand, may be stars with low angular momentum from the same star formation episode that were scattered into orbits near the black hole.

4. Possible Star Formation in the Central Cluster

As described in the previous section, there is clear evidence for the presence of massive young stars in the central parsec and even very close to the central supermassive black hole. These stars cannot be older than a few million

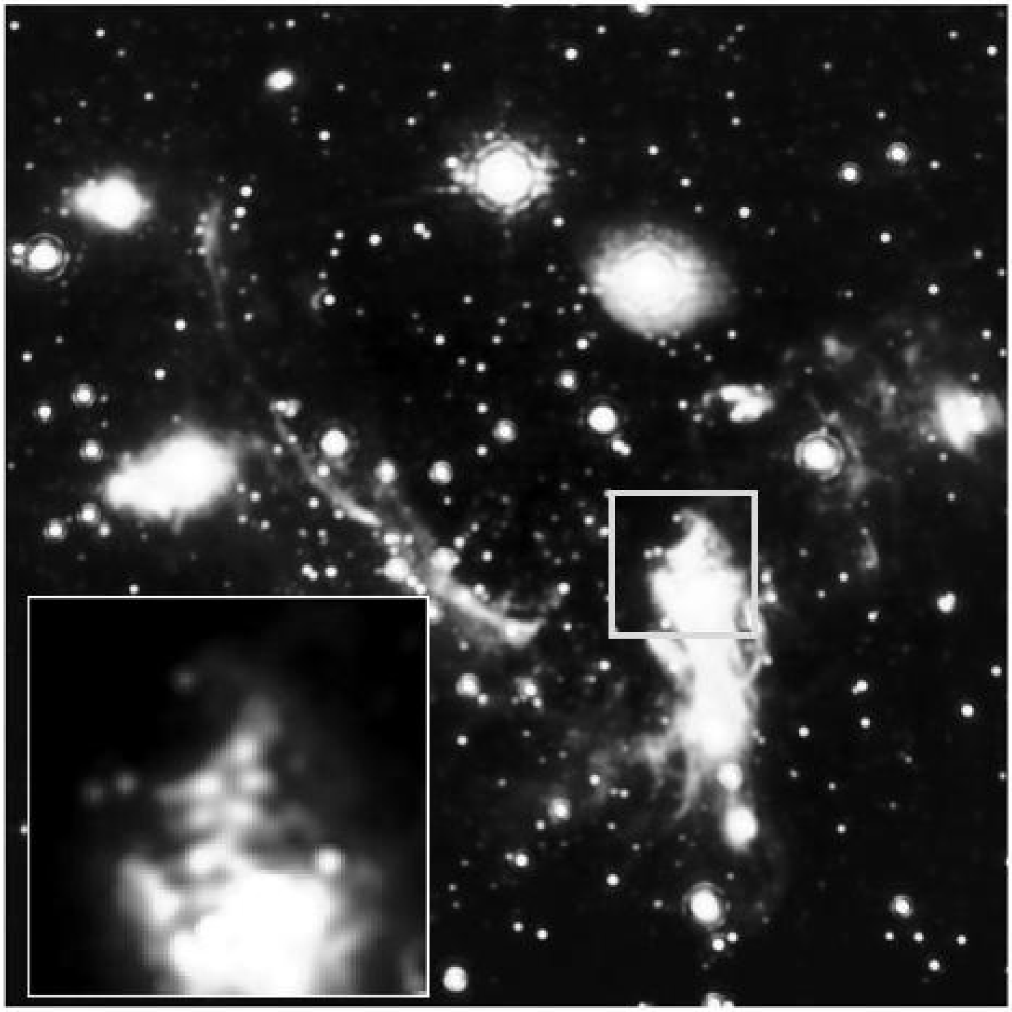

Fig. 2. NACO/VLT adaptive optics L-band (3.8 μm) image of the central parsec of the Milky Way. The image covers about $16.5'' \times 16.5''$. The inset image shows a zoom onto the IRS 13 complex (marked by a box on the large image). The IRS 13N sources are the string of stars extending north from the IRS 13 cluster (the bright clump at the bottom of the inset image). The IRS 13N sources are highly reddened and may be embedded young stars (Eckart et al. 2004).

years. This raises the question whether star formation processes may still be active in this region. Originally, a group of highly reddened, embedded stars, such as the well known source IRS 21, were considered potential protostars (e.g., Krabbe et al. 1995). However, Tanner et al. (2002) and Tanner et al. (2003) showed that these embedded stars along the northern arm of the mini-spiral are most probably mass-losing sources, such as Wolf-Rayet stars, that interact with the surrounding ISM, thereby creating bow-shocks.

Using new adaptive optics imaging data, Eckart et al. (2004) could identify a peculiar cluster of highly reddened stars north of the enigmatic IRS 13 complex (termed IRS 13N, see Fig. 2). Eckart et al. (2004) offer two

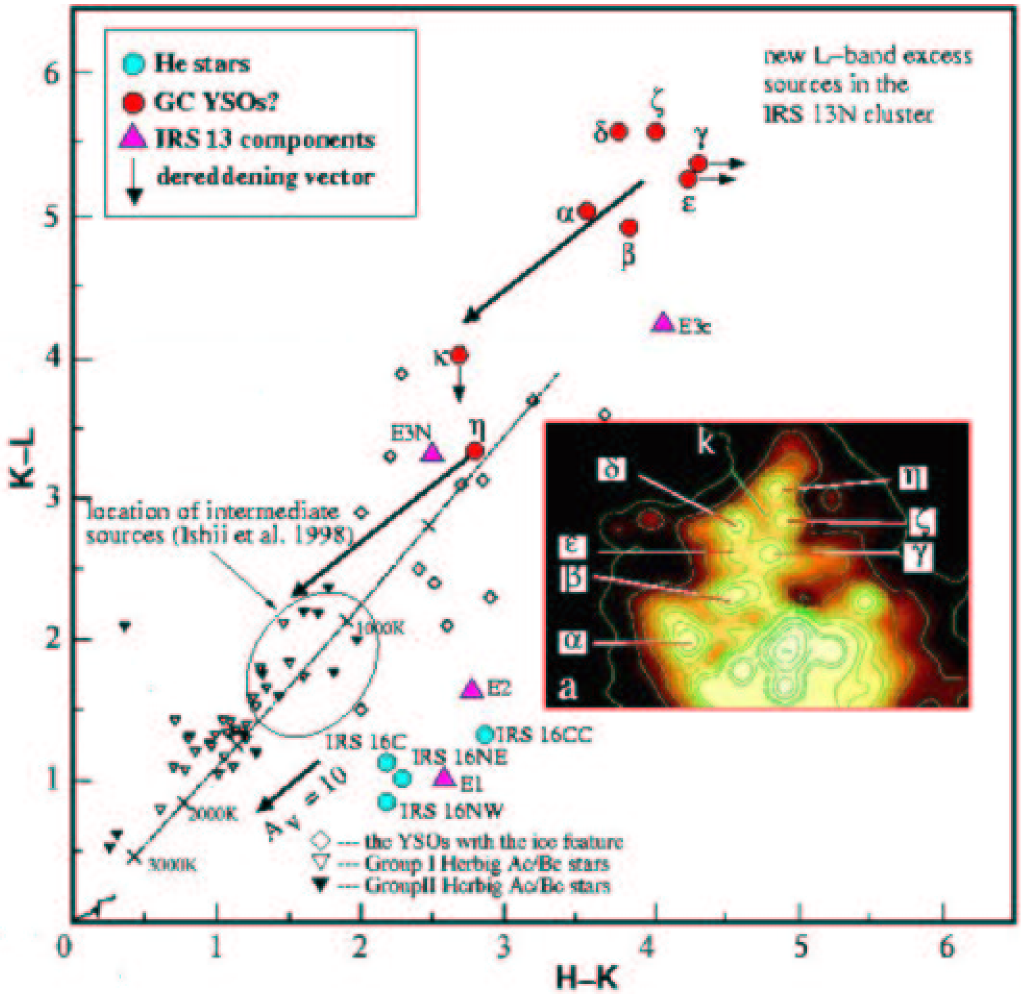

Fig. 3. NIR K-L vs. H-K colour-colour diagram showing the location of the sources in the IRS 13 North complex (labelled α to ζ – see small inset image). When de-reddening the sources with a vector corresponding to the extinction towards the GC cluster, they end up in a region of the diagram where one can usually find young stars. For details, see Eckart et al. (2004).

most probable scenarios: On the one hand, the IRS 13N-sources may be bow-shock sources similar to the northern arm sources, but of much lower luminosity. On the other hand, they find that the IRS 13N sources are located in a NIR colour-colour diagram in a region between Young Stellar Objects and Herbig Ae/Be stars (after taking into account the interstellar extinction toward the GC, see Fig. 3) and may therefore be young stars. In the latter case we would be witnessing ongoing star formation in an environment previously thought hostile to such processes. This exiting possibility awaits further investigation to clearly distinguish between the two scenarios.

5. Variable NIR Emission from Sgr A*

The non-thermal radio source Sgr A* is considered the manifestation of plasma accreted

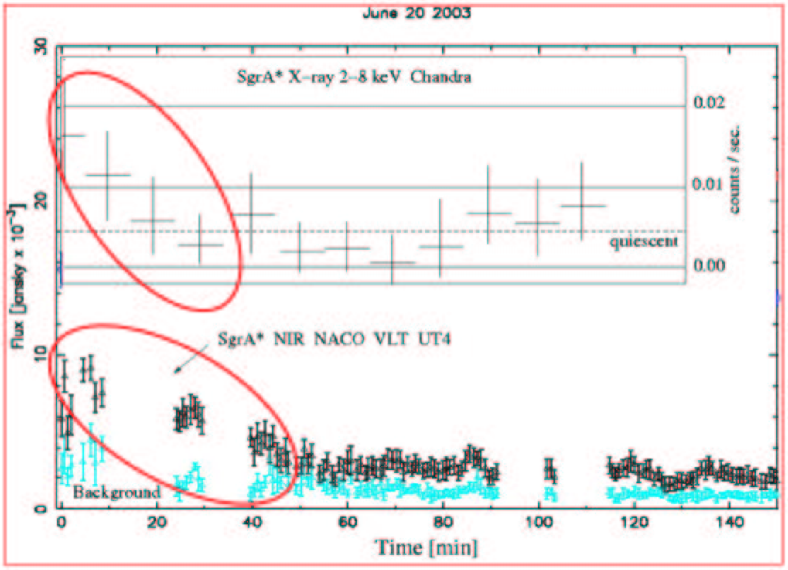

Fig. 4. Simultaneous X-ray and NIR light curves of Sgr A* observed in June 2003 with Chandra and VLT (Eckart et al. 2004a). The light curves are plotted with a common time axis. The lower (light grey) NIR light curve is a measure of the background fluctuations in a field free of sources. A decaying flare was detected at the beginning of the NIR observations, which started 0.38 min before the peak of an X-ray flare detected by Chandra.

onto the supermassive black hole (e.g., see the review by Melia & Falcke 2001). Only recently, Sgr A* has been detected as a point source in the X-ray (e.g., Baganoff et al. 2001) and NIR (Genzel et al. 2003; Ghez et al. 2004) regimes. In both wavelength ranges, it is a faint source, but the general quasi-quiescent state is interrupted by flares during which the emission increases within a few minutes by factors of a few (NIR) up to ~100 (X-ray). The extremely short timescales involved in the flares implies that the emission must originate from a region of the scale 10 Schwarzschild radii (Baganoff et al. 2001; Genzel et al. 2003). Intriguingly, in some of the best measured NIR flare light curves, a quasi-periodicity of ~15 min was found. This raises the exciting possibility of being able to measure the angular momentum of Sgr A* (Genzel et al. 2003).

Due to the continuous and strong variability of Sgr A* at NIR/X-ray wavelengths, it is crucial to observe its flux simultaneously in these wavelength bands in order to understand emission and accretion processes. The first coordinated campaign using both high-resolution NIR and X-ray imaging that successfully detected Sgr A* is reported by Eckart et al. (2004a). Due to the ~20-fold higher resolution of the NIR images, their observations confirm that the variable X-ray source observed by Chandra is indeed identical with Sgr A*. Also, they derive an upper limit of 15 min for any possible time lag between the X-ray and NIR emission. This implies a close spatial relation between the sources of the NIR and X-ray radiation. They find that the emission during the flare can be successfully described by a SSC model in which the NIR and X-ray flux density excess is produced by up-scattering submm-wavelength photons into the NIR and X-ray domains.

We performed new coordinated NIR/X-ray observations with VLT/Chandra in July 2004. Variable seeing made the NIR observations somewhat difficult, but on July 7, almost 300 min of simultaneous NIR/X-ray imaging data were recorded. The decaying part of one flare and one additional entire flare could be detected in both wavelength regimes. Analysis of the data is in progress, but preliminary inspection of the light curves shows that NIR and X-ray activity are strongly correlated, but that the ratio of NIR to X-ray flux appears highly variable.

6. Summary

We have presented some results of recent high-resolution NIR observations of the central parsec of the Milky Way. The amount and density of the dark mass measured via stellar dynamics (velocity dispersion and individual stellar orbits) now provide overwhelming evidence for the black hole nature of Sgr A*. The supermassive black hole has a mass of $3.6 \pm 0.6 \times 10^6\,M_\odot$. A non-Keplerian analysis of the orbital data of S2 gives an upper limit of 10% of the mass of Sgr A* for any hypothetical extended dark mass component that may be present around the black hole. The massive young stars found near Sgr A* exhibit peculiar dynamical features and are not dynamically relaxed. Immediately north of the IRS 13 complex, a group of potentially recently formed stars has been identified by Eckart et al. (2004). This finding awaits further investigation, but may provide the spectacular result that star formation is an on-going process in the GC. The first successful simultaneous high-resolution observations of Sgr A* at NIR and X-ray wavelengths have been reported by Eckart et al. (2004a). Similar observations in this year's (2004) observing season and campaigns in planning for the upcoming year have gathered/will gather additional crucial data to understand accretion and emission processes near the supermassive black hole. First results show that the emission at NIR and X-ray wavelengths is highly correlated, but allows for a wide range of NIR to X-ray flux ratios.

Acknowledgements. Part of this work was supported by the German *Deutsche Forschungsgemeinschaft* (DFG) SFB 495, Teilbereich A4.

References

Aschenbach, B., Grosso, N., Porquet, D., & Predehl, P. 2004, A&A, 417, 71

Baganoff, F. K., Bautz, M. W., Brandt, W. N., et al. 2001, Nature, 413, 45

Balick, B. & Brown, R. L. 1974, ApJ, 194, 265

Eckart, A. & Genzel, R. 1996a, Nature, 383, 415

Eckart, A., Genzel, R., Ott, T., & Schödel, R. 2002, MNRAS, 331, 917

Eckart, A., Moultaka, J., Viehmann, T., Straubmeier, C., Mouawad, N. 2004, ApJ, 602, 760

Eckart, A., Baganoff, F., Morris, M., et al. 2004a, A&A, in press

Eisenhauer, F., Schödel, R., Genzel, R., et al. 2003, ApJ, 597, L121

Genzel, R., Eckart, A., Ott, T., & Eisenhauer, F. 1997, MNRAS, 291, 219

Genzel, R., Pichon, C., Eckart, A., Gerhard, O. E., & Ott, T. 2000, MNRAS, 317, 348

Genzel, R., Schödel, R., Ott, T., et al. 2003a, Nature, 425, 934

Genzel, R., Schödel, R., Ott, T., Eisenhauer, F., Hofmann, R., Lehnert, M., Eckart, A., Alexander, T., Sternberg, A., Lenzen, R., Clénet, Y., Lacombe, F., Rouan, D., Renzini, A., Tacconi-Garman, L. E. 2003b, ApJ, 594, 812

Gezari, S., Ghez, A. M., Becklin, E. E., et al. 2002, ApJ, 576, 790

Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678

Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A., & Kremenek, T. 2000, Nature, 407, 349

Ghez, A. M., Duchêne, G., Matthews, K., et al. 2003, ApJ, 586, L127

Ghez, A. M., Wright, S. A., Matthews, K., et al. 2004, ApJ, 601, L159

Kormendy, J. 2004, in Coevolution of Black Holes and Galaxies

Krabbe, A., Genzel, R., Eckart, A., et al. 1995, ApJ, 447, L95

Levin, Y. & Beloborodov, A. M. 2003, ApJ, 590, L33

Lynden-Bell, D. & Rees, M. J. 1971, MNRAS, 152, 461

Maoz, E. 1998, ApJ, 494, L181

Marscher, A. P. 1983, ApJ, 264, 296

Melia, F. & Falcke, H. 2001, ARA&A, 39, 309

Mouawad, N., Eckart, A., Pfalzner, S., et al. 2003, Astronomische Nachrichten Supplement, 324, 315

Munyaneza, F., & Viollier, R. 2002, ApJ, 564, 274

Quataert, E. 2003b, Astronomische Nachrichten Supplement, 324, 435

Reid, M. J. 1993, ARA&A, 31, 345

Schödel, R., Ott, T., Genzel, R., et al. 2003, ApJ, 596, 1015

Schödel, R., Ott, T., Genzel, R., Hofmann, R., Lehnert, M., Eckart, A., Mouawad, N., Alexander, T., Reid, M. J., Lenzen, R., Hartung, M., Lacombe, F., Rouan, D., Gendron, E., Rousset, G., Lagrange, A.-M., Brandner, W., Ageorges, N., Lidman, C., Moorwood, A. F. M., Spyromilio, J., Hubin, N., Menten, K. M. 2002, Nature, 419, 694

Tanner, A., Ghez, A. M., Morris, M., et al. 2002, ApJ, 575, 860

Tanner, A., Ghez, A., Morris, M., & Becklin, E. 2003, in Galactic Center Workshop 2002: The Central 300 Parsecs of the Milky Way, 597–603

Viollier, R. D., Leimgruber, F. R., & Trautmann, D. 1992, Physics Letters B, 297, 132

Yuan, F., Quataert, E., & Narayan, R. 2003, ApJ, 598, 301