Black Holes from Stars to Galaxies – Across the Range of Masses
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The Galactic Center

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Abstract. In the past decade high resolution measurements in the infrared employing adaptive optics imaging on 10m telescopes have allowed determining the three dimensional orbits stars within ten light hours of the compact radio source at the center of the Milky Way. These observations show the presence of a three million solar mass black hole in Sagittarius A* beyond any reasonable doubt. The Galactic Center thus constitutes the best astrophysical evidence for the existence of black holes which have long been postulated, and is also an ideal 'lab' for studying the physics in the vicinity of such an object. Remarkably, young massive stars are present there and probably have formed in the innermost stellar cusp. Variable infrared and X-ray emission from Sagittarius A* are a new probe of the physical processes and space-time curvature just outside the event horizon.

Keywords. Galaxy: center – black hole physics

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1. Introduction – Sagittarius A*

The central light years of our Galaxy contain a dense and luminous star cluster, as well as several components of neutral, ionized and extremely hot gas (Genzel, Hollenbach & Townes 1994). The Galactic Center also contains a very compact radio source, Sagittarius A* (Sgr A*; Balick & Brown 1974) which is located at the center of the nuclear star cluster and ionized gas environment. Short-wavelength centimeter and millimeter VLBI observations have established that its intrinsic radio size is a mere 10 light minutes (Bower *et al.* 2004; Shen *et al.* 2005). Sgr A* is also an X-ray emission source, albeit of only modest luminosity (Baganoff *et al.* 2001). Most recently, Aharonian *et al.* (2004) have discovered a source of TeV γ-ray emission within 10 arcsec of Sgr A*. It is not yet clear whether these most energetic γ-rays come from Sgr A* itself or whether they are associated with the nearby supernova remnant, Sgr A East.

Sgr A* thus may be a supermassive black hole analogous to QSOs, albeit of much lower mass and luminosity. Because of its proximity – the distance to the Galactic Center is about 10^5 times closer than the nearest quasars – high resolution observations of the Milky Way nucleus offer the unique opportunity of stringently testing the black hole paradigm and of studying stars and gas in the immediate vicinity of a black hole, at a level of detail that will not be accessible in any other galactic nucleus in the foreseeable future.

Since the center of the Milky Way is highly obscured by interstellar dust particles in the plane of the Galactic disk, observations in the visible light are not possible. Investigations require measurements at longer wavelengths – the infrared and microwave bands, or at shorter wavelengths – hard X-rays and γ-rays, where the veil of dust is transparent. The dramatic progress in our knowledge of the Galactic Center over the past two decades is a direct consequence of the development of novel facilities, instruments and techniques across the whole range of the electromagnetic spectrum.

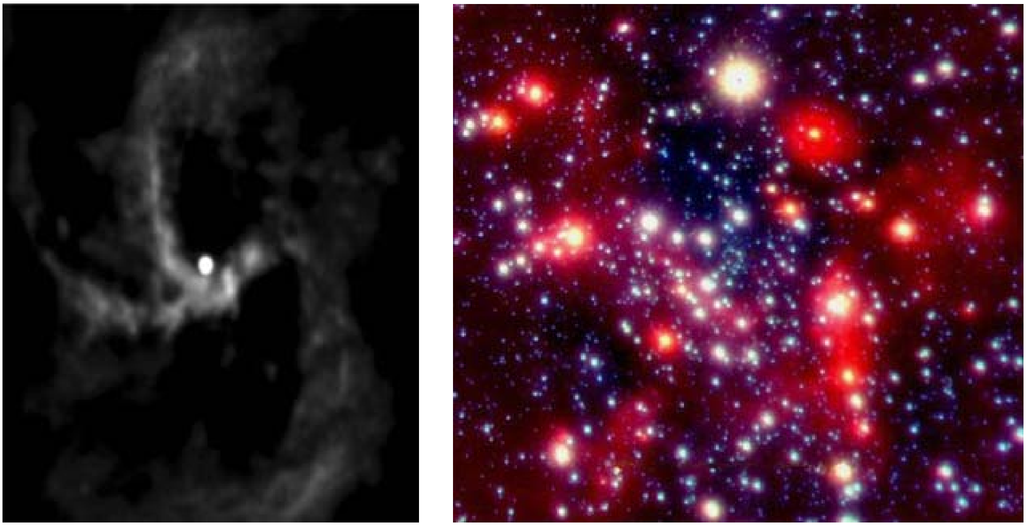

Figure 1. Left: VLA radio continuum map of the central parsec (Roberts & Goss 1993). The radio emission delineates ionized gaseous streams orbiting the compact radio source Sgr A*. Spectroscopic measurements in the radio band (Wollman *et al.* 1977) provided the first dynamical evidence from large gas velocities that there might be a hidden mass of 3–4 million solar masses located near Sgr A*. Right: A diffraction limited image of Sgr A* ($\sim$ 0.05 arcsec resolution) from the 8m ESO VLT, taken with the NACO AO-camera and an infrared wavefront sensor at 1.6/2.2/3.7 μm (Genzel *et al.* 2003b). The central black hole is located in the centre of the box. NACO is a collaboration between ONERA (Paris), Observatoire de Paris, Observatoire Grenoble, MPE (Garching), and MPIA (Heidelberg) (Lenzen *et al.* 1998; Rousset *et al.* 1998).

2. High angular resolution astronomy

The key to the nature of Sgr A* obviously lies in very high angular resolution measurements. The Schwarzschild radius of a 3.6 million solar mass black hole at the Galactic Center subtends a mere 10^{-5} arcsec. For the high-resolution imaging from the ground it is necessary to correct for the distortions of an incoming electromagnetic wave by the refractive and dynamic Earth atmosphere. VLBI overcomes this hurdle by phase-referencing to nearby QSOs; sub-milliarcsecond resolution can now be routinely achieved.

In the optical/near-infrared wavebands the atmosphere smears out long-exposure images to a diameter at least ten times greater than the diffraction limited resolution of large ground-based telescopes (Fig. 1). From the early 1990s onward initially speckle imaging (recording short exposure images, which are subsequently processed and co-added to retrieve the diffraction limited resolution) and then later adaptive optics (AO, correcting the wave distortions on-line) became available. With these techniques it is possible to achieve diffraction limited resolution on large ground-based telescopes. The diffraction limited images are much sharper and also much deeper than the seeing limited images. In the case of AO (Beckers 1993) the incoming wavefront of a bright star near the source of interest is analyzed, the necessary corrections for undoing the aberrations of the atmosphere are computed (on time scales shorter than the atmospheric coherence time of a few milli-seconds) and these corrections are then applied to a deformable optical element (e.g. a mirror) in the light path.

The requirements on the brightness of the AO star and on the maximum allowable separation between star and source are quite stringent, resulting in a very small sky coverage of natural star AO. Fortunately, in the Galactic Center there is a bright infrared star only 6 arcsec away from Sgr A*, such that good AO correction can be achieved with an infrared wavefront sensor system. Artificial laser beacons can overcome the sky coverage problem to a considerable extent. For this purpose, a laser beam is projected from the telescope into the upper atmosphere and the backscattered laser light can then be used for AO correction. The Keck telescope team has already begun successfully exploiting the new laser guide star technique for Galactic Center research (Ghez *et al.* 2005a). After AO correction, the images are an order of magnitude sharper and also much deeper than in conventional seeing limited measurements. The combination of AO techniques with advanced imaging and spectroscopic instruments (e.g. integral field imaging spectroscopy) have resulted in a major breakthrough in high resolution studies of the Galactic Center.

3. Nuclear star cluster and the paradox of youth

One of the big surprises is a fairly large number of bright stars in Sgr A*, a number of which were already apparent on the discovery infrared images of Becklin & Neugebauer (1975, 1978). High-resolution infrared spectroscopy reveals that many of these bright stars are actually somewhat older, late-type supergiants and AGB stars. Starting with the discovery of the AF-star (Allen *et al.* 1990; Forrest *et al.* 1987), however, an ever increasing number of the bright stars have been identified as being young, massive and early type. The most recent counts from the deep SINFONI integral-field spectroscopy yields about one hundred OB stars, including various luminous blue supergiants and Wolf-Rayet stars, but also normal main-sequence OB stars (Paumard *et al.* 2006a). The nuclear star cluster is one of the richest concentrations of young massive stars in the Milky Way.

The deep adaptive optics images also trace the surface density distribution of the fainter stars, to about K 17–18 mag, corresponding to late B or early A stars (masses of 3–6 solar masses), which are a better probe of the density distribution of the overall mass density of the star cluster. While the surface brightness distribution of the star cluster is not centered on Sgr A*, the surface density distribution is. There is clearly a cusp of stars centered on the compact radio source (Genzel *et al.* 2003b; Schödel *et al.* 2006). The inferred volume density of the cusp is a power-law $\propto R^{-1.4\pm0.1}$, consistent with the expectation for a stellar cusp around a massive black hole (Alexander 2005).

If there is indeed a central black hole associated with Sgr A* the presence of so many young stars in its immediate vicinity constitutes a significant puzzle (Allen & Sanders 1986; Morris 1993; Alexander 2005). For gravitational collapse to occur in the presence of the tidal shear from the central mass, gas clouds have to be denser than $\sim 10^9(R/(10''))^{-3}$ hydrogen atoms per cm^{-3}. This 'Roche' limit exceeds the density of any gas currently observed in the central region. Recent near-diffraction limited AO spectroscopy with both the Keck and VLT shows that almost all of the cusp stars brighter than K $\sim$ 16 mag appear to be normal, main sequence B stars (Ghez *et al.* 2003; Eisenhauer *et al.* 2005a). If these stars formed in situ, the required cloud densities approach the conditions in outer stellar atmospheres.

Several scenarios have been proposed to account for this paradox of youth. In spite of this effort the origin of central stars (S-stars) is not well understood: models have difficulties in reconciling different aspects of the Galaxy Centre – on one side it is a low level of present activity, indicating a very small accretion rate, and on the other side it is the spectral classification that suggests these stars have been formed relatively recently; see Alexander (2005) for a detailed discussion and references. The most prominent ideas to resolve the apparent problem are in situ formation in a dense gas accretion disk that can overcome the tidal limits, re-juvenation of older stars by collisions or stripping, and

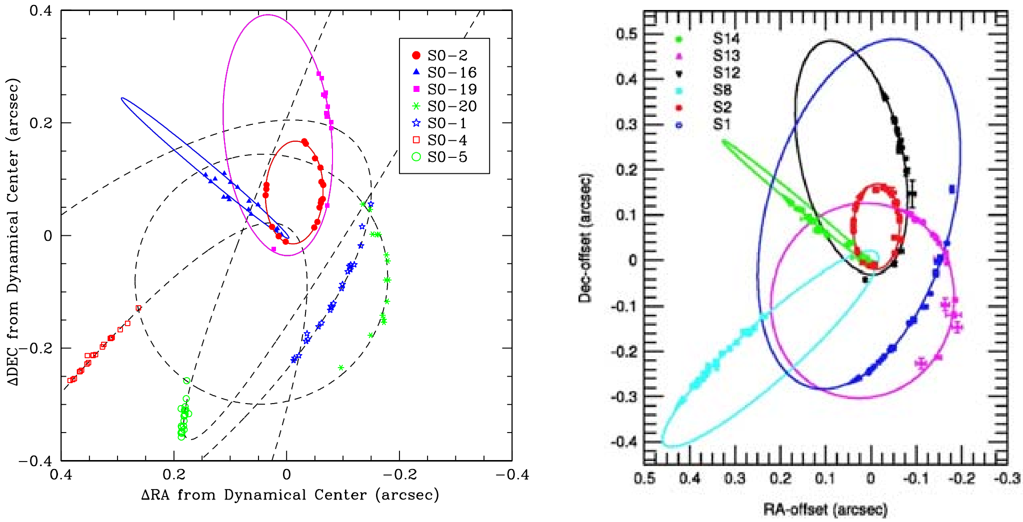

Figure 2. Positions on the sky as a function of time for the central stars orbiting the compact radio source Sgr A*. Left: the data from the UCLA group working with the Keck telescope (Ghez *et al.* 2005b). Right: the data from the MPE–Cologne group at the ESO-VLT (Schödel *et al.* 2003; Eisenhauer *et al.* 2005a; Gillessen *et al.*, in preparation).

rapid in-spiral of a compact, massive star cluster that formed outside the central region and various scattering a three body interaction mechanisms, including resonant relaxation (Alexander 2005). Several other mechanisms have been proposed that could set stars on highly eccentric orbits and bring them to the neighbourhood of the central black hole (e.g., Hansen & Milosavljević 2003; McMillan & Portegies Zwart 2003; Alexander & Livio 2004; Šubr & Karas 2005), but the problem of the S-stars remains open.

4. Compelling evidence for a central massive black hole

With diffraction limited imagery starting in 1991 on the 3.5m ESO New Technology Telescope and continuing since 2002 on the VLT, a group at MPE was able to determine proper motions of stars as close as ~ 0.1 arcsec from Sgr A* (Eckart & Genzel 1996, 1997). In 1995 a group at the University of California, Los Angeles started a similar program with the 10m diameter Keck telescope (Ghez *et al.* 1998). Both groups independently found that the stellar velocities follow Kepler laws and exceed 10^3 km/s within the central light month.

Only a few years later both groups achieved the next and crucial step: they were able to determine individual stellar orbits for several stars very close to the compact radio source (Fig. 2; Schödel *et al.* 2002, 2003; Ghez *et al.* 2003, 2005b; Eisenhauer *et al.* 2005a). In addition to the astrometric imaging they obtained near-diffraction limited Doppler spectroscopy of the same stars (Ghez *et al.* 2003; Eisenhauer *et al.* 2003a,b), yielding precision measurements of the three dimensional structure of several orbits, as well as the distance to the Galactic Center. At the time of writing, the orbits have been determined for about a dozen stars in the central light month. The central mass and stellar orbital parameters derived by the two teams agree mostly very well. The orbits show that the gravitational potential indeed is that of a point mass centered on Sgr A* within the relative astrometric uncertainties of ~ 10 milliarcsec. Most of the mass must be concentrated well within the peri-approaches of the innermost stars, ~ 10–20 light hours, or 70 times the Earth orbit radius and about 1000 times the event horizon of a 3.6 million solar mass black hole. There is presently no indication for an extended mass greater than about 5% of the point mass.

Simulations indicate that current measurement accuracies are sufficient to reveal the first and second order effects of Special and General Relativity in a few years time (Zucker *et al.* 2006). Observations with future 30m+ diameter telescopes will be able to measure the mass and distance to the Galactic Center to $\sim 0.1\%$ precision. They should detect radial precession of stellar orbits due to General Relativity and constrain the extended mass to $< 10^{-3}$ of the massive black hole (Weinberg, Milosavljevic & Ghez 2005). At that level a positive detection of a halo of stellar remnants (stellar black holes and neutron stars) and perhaps dark matter would appear to be likely. Future interferometric techniques will push capabilities yet further.

Long-term VLBA observations have set 2σ upper limits of about 20 km/s and 2 km/s (or 50 micro-arcsec per year) to the motion of Sgr A* itself, along and perpendicular to the plane of the Milky Way, respectively (Reid & Brunthaler 2004; see also Backer & Sramek 1999). This precision measurement demonstrates very clearly that the radio source itself must indeed be massive, with simulations indicating a lower limit to the mass of Sgr A* of $\sim 10^5$ solar masses. The intrinsic size of the radio source at millimeter wavelengths is less than 5 to 20 times the event horizon diameter (Bower *et al.* 2004; Shen *et al.* 2005). Combining the radio size and proper motion limit of Sgr A* with the dynamical measurements of the nearby orbiting stars leads to the conclusion that Sgr A* can only be a massive black hole, beyond any reasonable doubt. An astrophysical dark cluster fulfilling the observational constraints would have a life-time less than a few 10^4 years and thus can be safely rejected, as can be a possible fermion ball of hypothetical heavy neutrinos. In fact all non-black hole configurations can be excluded by the available measurements (Schödel *et al.* 2003; Ghez *et al.* 2005b) – except for a hypothetical boson star and the gravastar hypothesis, but it appears that the two mentioned alternatives have difficulties of their own, and they are less likely and certainly much less understood than black holes (e.g. Maoz 1998; Miller *et al.* 1998). We thus conclude that, under the assumption of the validity of General Relativity, the Galactic Center provides the best quantitative evidence for the actual existence of (massive) black holes that contemporary astrophysics can offer.

5. Zooming in on the accretion zone and event horizon

Recent millimeter, infrared and X-ray observations have detected irregular, and sometimes intense outbursts of emission from Sgr A* lasting anywhere between 30 minutes and a number of hours and occurring at least once per day (Baganoff *et al.* 2001; Genzel *et al.* 2003a; Marrone *et al.* 2006). These flares originate from within a few milli-arcseconds of the radio position of Sgr A*. They probably occur when relativistic electrons in the innermost accretion zone of the black hole are significantly accelerated, so that they are able to produce infrared synchrotron emission and X-ray synchrotron or inverse Compton radiation (Markoff *et al.* 2001; Yuan *et al.* 2003; Liu *et al.* 2005). This interpretation is also supported by the detection of significant polarization of the infrared flares (Eckart *et al.* 2006b), by the simultaneous occurrence of X- and IR-flaring activity (Eckart *et al.* 2006a; Yusef-Zadeh *et al.* 2006) and by variability in the infrared spectral properties (Ghez *et al.* 2005b; Gillessen *et al.* 2006a; Krabbe *et al.* 2006). There are indications for quasi-periodicities in the light curves of some of these flares, perhaps due to orbital motion of hot gas spots near the last circular orbit around the event horizon (Genzel *et al.* 2003a; Aschenbach *et al.* 2004; Bélanger *et al.* 2006).

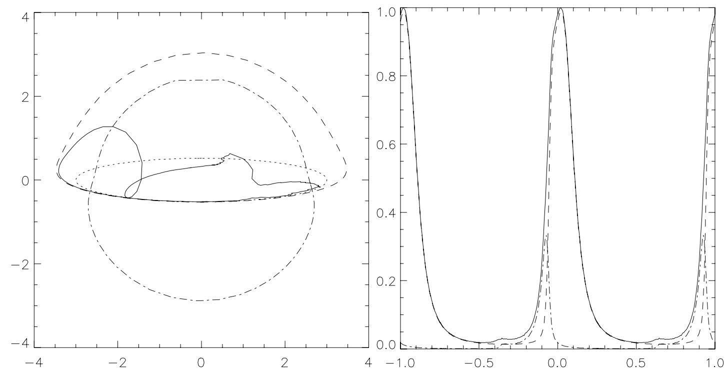

Figure 3. Photo-center wobbling (left) and light curve (right) of a hot spot on the innermost stable orbit around Schwarzschild black hole (inclination of 80 deg), as derived from ray-tracing computations. Dotted curve: 'true' path of the hot spot; dashed curves: apparent path and a predicted light curve of the primary image; dash-dotted curves: the same for secondary image; solid curves: path of centroid and integrated light curve. Axes on the left panel are in Schwarzschild radii of a 3 million solar-mass black hole, roughly equal to the astrometric accuracy of 10 arcsec; the abscissa axis of the right panel is in cycles. The loop in the centroids track is due to the secondary image, which is strongly sensitive to the space-time curvature. The overall motion can be detected at good significance at the anticipated accuracy of GRAVITY. Details can be obtained by analyzing several flares simultaneously (Gillessen *et al.* 2006b; Paumard *et al.* 2005).

The infrared flares as well as the steady microwave emission from Sgr A* may be important probes of the gas dynamics and space-time metric around the black hole (Broderick & Loeb 2006; Meyer *et al.* 2006a,b; Paumard *et al.* 2006b). Future long-baseline interferometry at short millimeter or sub-millimeter wavelengths may be able to map out the strong light-bending effects around the photon orbit of the black hole. It is interesting to realize that the angular size of the "shadow" of black hole (Bardeen 1973) is not very far from the anticipated resolution of interferometric techniques and it may thus be accessible to observations in near future (Falcke, Melia & Agol 2000).

Polarization measurements will help us to set further constraints on the emission processes responsible for the flares. Especially the time-resolved lightcurves of the polarized signal carry specific information about the interplay between the gravitational and magnetic fields near Sgr A* horizon, because the propagation of the polarization vector is sensitive to the presence and properties of these fields along the light trajectories (Bromley, Melia & Liu 2001; Horák & Karas 2006; Paumard *et al.* 2006b). Polarization is also very sensitive also to intrinsic properties of the source – its geometry and details of radiation mechanisms responsible for the emission.

Synthesis of different techniques will be a promising way for the future: the astrometry of central stars gives very robust results because the stellar motion is almost unaffected by poorly known processes of non-gravitational origin, while the flaring gas occurs much closer to the black hole horizon and hence it directly probes the innermost regions of Sgr A*. Eventually the two components – gas and stars of the Galaxy Center – are interconnected and form the unique environment in which the flaring gas is influenced by intense stellar winds whereas the long-term motion and the 'non-standard' evolution of the central stars bears imprints of the gaseous medium though which the stars pass.

Eisenhauer *et al.* (2005b) are developing GRAVITY (an instrument for 'General Relativity Analysis via VLT Interferometry'), which will provide dual-beam, 10 microarcsecond precision infrared astrometric imaging of faint sources. GRAVITY may be able to map out the motion on the sky of hot spots during flares with a high enough

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resolution and precision to determine the size of the emission region and possibly detect the imprint of multiple gravitational images (see Fig. 3). In addition to studies of the flares, it will also be able to image the orbits of stars very close to the black hole, which should then exhibit the orbital radial oscillations and Lense-Thirring precession due to General Relativity. Both the microwave shadows as well as the infrared hot spots are sensitive to the space-time metric in the strong gravity regime. As such, these ambitious future experiments can potentially test the validity of the black hole model near the event horizon and perhaps even the validity of General Relativity in the strong field limit.

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Zdeněk Stuchlík: Do you observe any signs of interaction between a gaseous disc and stars near the massive central black hole in Sagittarius A*?

Reinhard Genzel: We have no observational evidence for such gaseous disc. It might be there to some level – Jorge Cuadra might discuss this matter in more detail – but we have been looking for it and it does not appear to be present.

Alexander Zakharov: Is there a cusp in the center, e.g. within the distance of S2-star orbit?

Reinhard Genzel: We are of course running out of counting statistics, but a core is possible. Physical collisions should be likely in that region.

Thaisa Storchi-Bergmann: Comment: In my presentation on Friday, I will show that, as in the Galactic center, nearby galaxies, when in inactive phase, exhibit nuclear stellar discs, while AGN matched to the inactive galaxies in host galaxy properties exhibit instead nuclear gas plus dust spirals.

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