The Shadow of the Black Hole at the Galactic Center[1]

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Abstract. We show that perhaps already with the next generation of long-baseline interferometers at submm-wavelengths we will able to image the shadow of the black hole in the Galactic Center. To a distant observer, the event horizon casts a relatively large "shadow" with an apparent diameter of ~ 10 gravitational radii due to bending of light by the black hole, nearly independent of the black hole spin or orientation. The predicted angular size for the Galactic Center black hole is $\sim 30\,\mu$arcseconds, a mere factor two smaller than the highest currently achieved resolution with VLBI techniques. Taking into account scatter-broadening of the image in the interstellar medium and the finite achievable telescope resolution, we show that the shadow of Sgr A* can be observed at suitably high frequencies. The main problems are possible optical depth effects for an ADAF model and Doppler boosting for a jet model. This has an influence on which dynamic range and which observing frequency is ultimately required to prove or disprove the existence of an event horizon.

INTRODUCTION

Many energetic events in the universe are considered to be connected with black holes, be it powerful radio jets, UV, X-ray, and γ-ray emission from quasars, stellar mass black hole candidates, or even Gamma-ray bursts (e.g., Pugliese et al. 1999; see also this volume). The best evidence for the existence of a supermassive black hole is found in our Galaxy (Eckart & Genzel 1996) where the compact radio source Sgr A* lies at the dynamical center of the central stellar cluster (Ghez, et al. 1998; Reid, et al. 1999; Backer & Sramek 1999). Sgr A* is surrounded by thermally radiating gas streamers (Sgr A West) spiraling into the nucleus (Zhao & Goss 1998) and a non-thermal radio shell, possibly a hypernova resulting from the tidal disruption of a star by the central black hole (Khokhlov & Melia 1996). The nature of the radio emission in Sgr A* is not clear; the latter may be due either to

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an outflow/jet (Falcke et al. 1993; Falcke & Biermann 1999) from the black hole or an inflow/accretion onto the black hole (Melia 1992,1994; Narayan et al. 1995).

Very Long Baseline Interferometry (VLBI) observations have confirmed that the radio emission of Sgr A* is very compact up to the highest frequencies (215 GHz; Krichbaum et al. 1998) and its radio spectrum at mm- and submm-wavelengths indicates the presence of an even more compact radio-emitting plasma component (Falcke et al. 1998; Serabyn et al. 1997). This is intriguing since the size of Sgr A* could be less than 17 Schwarzschild radii (0.11 mas at 215 GHz) for a black hole mass of $2.6\times10^{6}M_{\odot}$ at a distance of 8 kpc. Of all the known black hole candidates, Sgr A* is the source where the angular size on the sky of its Schwarzschild radius is the largest. In fact, the angular resolution of ground-based VLBI experiments now comes interestingly close to the scale where significant general relativistic effects are important. We here report on calculations we have made with a general relativistic ray-tracing program which aim at clarifying what general relativistic effects might be realistically measurable in future VLBI experiments.

CALCULATIONS AND RESULTS

We consider an optically thin emission region with frequency-independent emissivity around a black hole with arbitrary spin. The intensity and structure of the emission region can be arbitrary as well, but we choose a number of generic scenarios where we have either a spherical distribution of the intensity scaling as a power-law with radius r or a jet-like distribution (hollow cylinder). We also can allow for various velocity fields, e.g., with rotation, inflow, or outflow. The appearance of the emission region for an observer at infinity, taking all general relatvistic effects into account, is then calculated using standard formalism (e.g., Thorne 1981; Viergutz 1993; Jaroszynski & Kurpiewski 1997).

To test whether general relatvistic effects would be visible we convolved the resulting images from the ray-tracing calculations with two Gaussian beams: one representing the scatter-broadening of the image due to the interstellar material along our line-of-sight towards the Galactic Center and one representing the finite resolution of VLBI with 8000 kilometer baselines. The width of the former has a ν^{-2} (e.g., Lo et al. 1998) and the latter a ν^{-1} dependence.

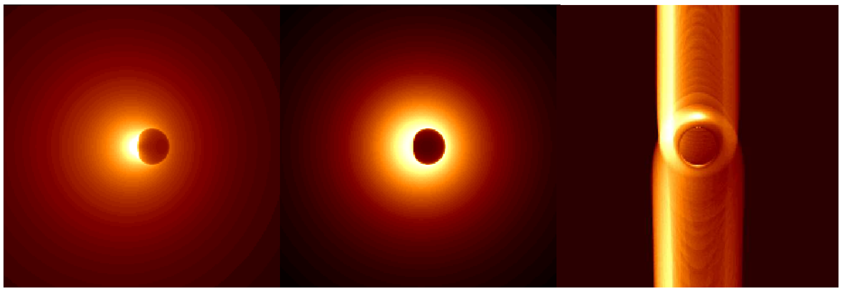

FIGURE 1. Images of the shadow of a black hole for rotating and non-rotating black holes and for spherical and jet-like emission models.

Regardless of the exact emission model we use, we find a characteristic structure in all models: a bright ring of emission with a pronounced deficit of emission inside of that (Fig. 1). We call the deficit in the inner region the "shadow" of the black hole since it is caused by the deficit of photons emitted near the black hole that have disappeared into the event horizon or are bent away from our line of sight. The circumference of the shadow is determined by the 'photon-orbit'—a theoretical orbit where photons can circle the black hole an infinite number of times, but when perturbed may escape to infinity (Bardeen 1973). Interestingly, the size of this shadow is much larger than the event horizon—due to gravitational lensing—and is always of the order 10 $R_{\rm g}$ ($R_{\rm g} = GM_\bullet/c^2$) for rotating and non-rotating black holes.

The exact intensity distribution of the bright ring depends significantly on the nature of the emission region, however. A rotating inflow would produce a slightly asymmetric ring due to Doppler-boosting of one side of the shells in Keplerian rotation. A jet would look even more asymmetric since boosting due to rotation plus fast outflow would enhance one quadrant of the ring (Fig. 1).

The relatively large size of the shadow is of particular interest for Sgr A*, since at a wavelength of around 1.3 mm the black hole shadow, the scattering disk, and the possible resolution of mm-VLBI become comparable. This is illustrated in Figure 2. It is clear that at wavelengths shortward of λ1.3 mm the shadow could actually be imaged with ground-based telescopes.

DISCUSSION

The possibility of seeing the effect of an event horizon is tantalizing. The shadow of the black hole in the Galactic Center is expected to have a diameter of $\sim 30\,\mu$as. The highest resolution so far achieved with VLBI is $\sim 50\,\mu$as. To achieve the additional improvement of a factor of two to three in resolution would require extending mm-VLBI to submm wavelengths. While this is difficult because of atmospheric effects, it is not technically impossible. Quite a number of submm-telescopes and arrays are currently under construction or consideration that could be used for such an experiment.

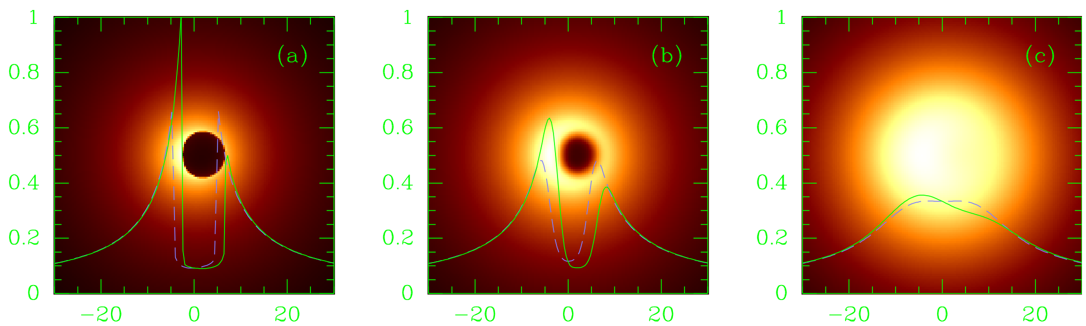

FIGURE 2. The expected shadow of Sgr A*. a) the ray-tracing simmulation; b) simmulated VLBI image at λ0.6mm; c) simmulated VLBI image at λ1.3mm (see Falcke et al. 2000 for details).

Another concern is whether the source itself could become an obstacle. Clumpiness of the emission may not be a major source of confusion because of the short rotation timescale of about 100 seconds. Optical depth effects could be a major problem. However, currently available submm spectra of Sgr A* (e.g., Serabyn et al. 1997) indicate a rather flat spectrum with a turnover towards the infrared. Hence at some wavelength between mm-radio and IR the source is bound to be optically thin. A second pitfall is anisotropic beaming. For example, in the jet model a quadrant is amplified due to relativistic beaming, making it more difficult to pick out the entire faint ring with low resolution or low dynamic range observations.

Without a better understanding of spectrum, structure, and nature of the emission it will be difficult to predict exactly at what wavelength the shadow will be unambiguously detectable and how much technical development still has to be done. In any case there is no reason to think that imaging the shadow is in principal impossible and any upcoming VLBI experiment at 1.3 mm and shorter wavelengths involving Sgr A* from now on could already show the first signs of the event horizon.

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REFERENCES

1. Backer, D. C. & Sramek, R. A. 1999, ApJ, 524, 805
2. Bardeen, J. M. 1973, in Black Holes, ed. C. DeWitt & B. S. DeWitt, (New York: Gordon & Breach), 215
3. Eckart, A. & Genzel, R. 1996, Nature, 383, 415
4. Falcke, H. & Biermann, P. L. 1999, A&A, 342, 49
5. Falcke, H., Mannheim, K., & Biermann, P. L. 1993, A&A, 278, L1
6. Falcke, H., Goss, W. M., Matsuo, H., et al. 1998, ApJ, 499, 731
7. Falcke, H., Melia, F., Agol, E. 2000, ApJ, 528, L13
8. Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678
9. Jaroszynski, M. & Kurpiewski, A. 1997, A&A, 326, 419
10. Lo, K. Y., Shen, Z. Q., Zhao, J. H., & Ho, P. T. P. 1998, ApJ, 508, L61
11. Khokhlov, A. & Melia, F. 1996, ApJ, 457, L61
12. Krichbaum, T. P. et al. 1998, A&A, 335, L106
13. Melia, F. 1992, ApJ, 387, 25
14. Melia, F. 1994, ApJ, 426, 577
15. Narayan, R., Yi, I., & Mahadevan, R. 1995, Nature, 374, 623
16. Pugliese, G., Falcke, H. & Biermann, P. L. 1999, A&A, 344, L37
17. Reid, M. J., Readhead, A. C. S., Vermeulen, R. C. et al. 1999, ApJ, 524, 816
18. Serabyn, E., Carlstrom, J., Lay, O., et al. 1997, ApJ, 490, L77
19. Thorne, K. S. 1981, MNRAS, 194, 439
20. Viergutz, S. U. 1993, A&A, 272, 355
21. Zhao, J. -H. & Goss, W. M. 1999, in: "The Central Parsecs of the Galaxy", ASPC 186, eds. H. Falcke, A. Cotera, W.J. Duschl, F. Melia, M.J. Rieke, 224