VIEWING THE SHADOW OF THE BLACK HOLE AT THE GALACTIC CENTER

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Received 1999 September 14; accepted 1999 October 26; published 1999 December 7

ABSTRACT

In recent years, evidence for the existence of an ultracompact concentration of dark mass associated with the radio source Sagittarius A* in the Galactic center has become very strong. However, unambiguous proof that this object is indeed a black hole is still lacking. A defining characteristic of a black hole is the event horizon. To a distant observer, the event horizon casts a relatively large “shadow” with an apparent diameter of ~10 gravitational radii that is due to the bending of light by the black hole, and this shadow is nearly independent of the black hole spin or orientation. The predicted size (~30 μas) of this shadow for Sgr A* approaches the resolution of current radio interferometers. If the black hole is maximally spinning and viewed edge-on, then the shadow will be offset by ~8 μas from the center of mass and will be slightly flattened on one side. Taking into account the scatter broadening of the image in the interstellar medium and the finite achievable telescope resolution, we show that the shadow of Sgr A* may be observable with very long baseline interferometry at submillimeter wavelengths, assuming that the accretion flow is optically thin in this region of the spectrum. Hence, there exists a realistic expectation of imaging the event horizon of a black hole within the next few years.

Subject headings: black hole physics — galaxies: active — Galaxy: center — relativity — submillimeter techniques: interferometric

1. INTRODUCTION

High-resolution spectroscopy (especially with the Hubble Space Telescope) of galactic nuclei has produced an abundance of evidence for compact dark mass concentrations of up to $10^6 M_\odot$ pc$^{-3}$, whose nature is strongly suspected to be indicative of supermassive black holes (Kormendy & Richstone 1995). Even better evidence exists for the galaxy NGC 4258 and the Milky Way, for which spectroscopic and proper-motion studies have provided an unprecedented three-dimensional view of the kinematics of gas and stars around a central point mass, pointing to dark mass concentrations of greater than $10^{12} M_\odot$ pc$^{-3}$ with very high significance (Miyoshi et al. 1995; Eckart & Genzel 1996; Lo et al. 1998).

Complementary observations of galactic nuclei with very long baseline interferometry (VLBI) reveal the presence of compact radio cores (Zensus 1997) that appear to be coincident with the central black hole candidates. An intriguing case is that of the Galactic center where the bright, compact radio source Sagittarius A* lies at the dynamical origin (Menten et al. 1997; Ghez et al. 1998). The nature of Sgr A* is still unclear since its structure is completely washed out by strong interstellar scattering at centimeter wavelengths (Lo et al. 1998). It is only at millimeter wavelengths that we may begin to see some internal structure (Bower & Backer 1998; Krichbaum et al. 1998; Lo et al. 1998). Although the dark mass concentration could in principle be distributed in the form of exotic objects on a scale slightly larger than the size of Sgr A*—but with difficulties accounting for its radiation characteristics (Melia & Coker 1999)—it is expected to be associated with Sgr A* itself since the latter, unlike the surrounding stars, has a tightly restricted proper motion indicating that it is very heavy (Reid et al. 1999; Genzel et al. 1997).

The key spectral features of Sgr A* are a slightly inverted centimeter-wavelength spectrum, an apparent excess (or bump) at millimeter wavelengths, and a steep cutoff toward the infrared (Falcke et al. 1998; Serabyn et al. 1997). The radio emission is circularly polarized but undetected in linear polarization (Bower et al. 1999a, 1999b). Proposed models for the radio emission range from quasi-spherical inflows (Melia 1992, 1994; Narayan, Yi, & Mahadevan 1995) to a jetlike outflow (Falcke, Mannheim, & Biermann 1993; Falcke & Biermann 1999).

The submillimeter bump is particularly interesting since this should be the signature of a very compact synchrotron-emitting region with a size of a few Schwarzschild radii (Falcke 1996; Falcke et al. 1998). The presence of compact radio emission in Sgr A* at a wavelength as short as 1.4 mm has been confirmed recently by the first VLBI detection at this wavelength (Krichbaum et al. 1998). This detection is exciting for several reasons. First, it lies in a region of the spectrum where the intrinsic source size should become apparent over scatter broadening by the intervening screen (Melia, Jokipii, & Narayan 1992). Second, this component is sufficiently bright to be detected with VLBI techniques at even shorter wavelengths, and third, Sgr A* is sufficiently close that the size scale where general relativistic effects are significant could be resolved with VLBI at submillimeter wavelengths. In addition, at submillimeter wavelengths, the various models predict that the synchrotron emission is not self-absorbed, allowing a view into the region near the horizon. The horizon has a size of $[1 + (1 - a^2)^{1/2}] R_s$, where $R_s = GM/c^2$, $M$ is the mass of the black hole, $G$ is Newton’s constant, $c$ is the speed of light, $a_s = Jc/(GM^2)$ is the dimensionless spin of the black hole in the range of 0–1, and $J$ is the angular momentum of the black hole.

Bardeen (1973) described the idealized appearance of a black hole in front of a planar-emitting source, showing that it literally would appear as a “black hole.” At that time, such a calculation was of mere theoretical interest and limited to calculating just the envelope of the apparent black hole. To test whether there is a realistic chance of seeing this black hole in Sgr A* (Falcke...
et al. 1998), we here report the first calculations obtained with our general relativistic (GR) ray-tracing code that allows us to simulate observed images of Sgr A* for various combinations of the black hole spin, inclination angle, and morphology of the emission region directly surrounding the black hole and not just for a background source. A more detailed description of our calculations is in preparation (E. Agol, H. Falcke, & M. Melia 1999, in preparation).

2. THE APPEARANCE OF A BLACK HOLE

We determine the appearance of the emitting region around a black hole under the condition that it is optically thin. For Sgr A*, this might be the case for the submillimeter bump (Falcke et al. 1998) indicated by the turnover in the spectrum and can always be achieved by going to a suitably high frequency. Here we simply assume that the overall specific intensity $I_\nu$ observed at infinity is an integration of the emissivity $j_\nu$, times the differential path length along geodesics (Jaroszynski & Kurfeweisski 1997). In line with the qualitative discussion of this Letter, we assume that $j_\nu$ is independent of frequency and that it is either spatially uniform or scales as $r^{-\alpha}$. These two cases cover a large range of conditions expected under several reasonable scenarios, be it a quasi-spherical infall, a rotating thick disk, or the base of an outflow.

The calculation of the photon trajectories and the intensity integrated along the line of sight is based on the standard formalism (Thorne 1981; Viergutz 1993; Rauch & Blandford 1994). Our calculations take into account all the well-known relativistic effects, e.g., frame dragging, gravitational redshift, light bending, and Doppler boosting. The code is valid for all possible spins of the black hole and for any arbitrary velocity field of the emission region.

For a planar-emitting source behind a black hole, a closed curve on the sky plane divides a region where geodesics intersect the horizon from a region where geodesics miss the horizon (Bardeen 1973). This curve, which we refer to as the “apparent boundary” of the black hole, is a circle of radius $(27)^{1/2}R_g$ in the Schwarzschild case ($a_*=0$), but it has a more flattened shape of similar size to a Kerr black hole, slightly dependent on inclination. The size of the apparent boundary is much larger than the event horizon because of the strong bending of light by the black hole. When the emission occurs in an optically thin region surrounding the black hole, the case of interest here, the apparent boundary has the same exact shape since the properties of the geodesics are independent of where the sources are located. However, photons on geodesics located within the apparent boundary that can still escape to the observer experience strong gravitational redshift and a shorter total path length, leading to a smaller integrated emissivity, while photons just outside the apparent boundary can orbit the black hole near the circular photon radius several times, adding to the observed intensity (Jaroszynski & Kurfeweisski 1997). This produces a marked deficit of the observed intensity inside the apparent boundary, which we refer to as the “shadow” of the black hole.

Here we consider a compact, optically thin emitting region surrounding a black hole with spin parameter $a_*=0$ (i.e., a Schwarzschild black hole) and a maximally spinning Kerr hole with $a_*=0.998$. In the set of simulations shown here, we take the viewing angle $i$ to be $45^\circ$ with respect to the spin axis (when it is present), and we consider two distributions of gas velocity $v$. The first has the plasma in free fall, i.e., $v^\prime=\frac{-2r(a^2+r^2)}{\Delta}$ and $\Omega=2ar\Omega$, where $v^\prime$ is the Boyer-Lindquist radial velocity, $\Omega$ is the orbital frequency, $\Delta=r^2-2r+a^2$, and $A=(r^2+a^2)^2-a^2\Delta\sin^2\theta$. (We have set $G=M=c=1$ in this paragraph.) The second has the plasma orbiting in rigidly rotating shells with the equatorial Keplerian frequency $\Omega=1/(r^{1/2}+a)$ for $r>r_{\text{ms}}$ with $v^\prime=0$ and infalling with constant angular momentum inside $r<r_{\text{ms}}$ (Cunningham 1975) with $v^\prime=0$ for all $r$.

In order to display concrete examples of how realistic our proposed measurements of these effects with VLBI will be, we have simulated the expected images for the massive black hole candidate Sgr A* at the Galactic center. For its measured mass (Eckart & Genzel 1996; Ghez et al. 1998) $M=2.6 \times 10^6 M_\odot$, the scale size for this object is the gravitational radius $R_g=3.9 \times 10^{11}$ cm, which is half of the Schwarzschild radius $R_s=2GM/c^2$.

To simulate an observed image, we have to take two additional effects into account: interstellar scattering and the finite telescope resolution achievable from the ground. Scatter broadening at the Galactic center is incorporated by smoothing the image with an elliptical Gaussian with a FWHM of $24.2 \mu\text{as} \times (\lambda/1.3 \text{ mm})^2$ along the major axis and $12.8 \mu\text{as} \times (\lambda/1.3 \text{ mm})^2$ along the minor axis (Lo et al. 1998). The position angle of this ellipse is arbitrary since we do not know yet the spin axis of the black hole on the sky, and we have assumed a position angle of $90^\circ$ for the major axis. The telescope resolution—in an idealized form—is then added by convolving the smoothed image with a spherical Gaussian point-spread function of FWHM $=33.5 \mu\text{as} \times (\lambda/1.3 \text{ mm})^{-1}(l/8000 \text{ km})^{-1}$, which is the possible resolution of a global interferometer with 8000 km baselines (Krichbaum 1996). In reality, the exact point-spread function will of course depend on the number and placement of the participating telescopes.

In Figure 1, we show the resulting image of Sgr A* for a maximally rotating black hole viewed at an angle of $i=45^\circ$, for a compact region in free fall, with an emissivity of $j_\nu=\nu^{\alpha}r^{-\beta}$. We first show the original, unsmoothed image of the emission region as calculated with the GR code in Figure 1a and then present the simulated “observed” images at 0.6 and 1.3 mm wavelengths in Figures 1b and 1c, respectively. The two distinct features that are evident in Figure 1a are (1) the clear depression in $I_\nu$—the shadow—produced near the black hole, which in this particular example represents a modulation of up to 90% in intensity from peak to trough, and (2) the size of the shadow, which here is $9.2R_g$ in diameter. This represents a projected size of 27 $\mu$as, which is already within a factor of 2 of the current VLBI resolution (Krichbaum et al. 1995). The shadow is a generic feature of various other models that we have looked at, including those with outflows, cylindrical emissivity, and various inclinations or spins.

To illustrate the expected image for another extreme case, we show in Figure 1d the analogous to Figure 1a for the case with $a_*=0$ (i.e., no rotation), an emitting plasma orbiting in Keplerian shells (as described above), and a uniform $j_\nu$ for $r<25R_g$. Even though these conditions are distinctly different compared with those of Figure 1a, the black hole shadow is still clearly evident; here it represents a modulation in $I_\nu$ in the range of 50%–75% from peak to trough (Fig. 1d) with a diameter of roughly 10.4$R_g$. In this case, the emission is asymmetric due to the strong Doppler shifts associated with the emission by a rapidly moving plasma along the line of sight (with velocity $v_\circ$).

The important conclusion is that the diameter of the shadow—in marked contrast to the event horizon—is fairly independent of the black hole spin and is always of order 10$R_g$. 

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Fig. 1.—Image of an optically thin emission region surrounding a black hole with the characteristics of Sgr A* at the Galactic center. The black hole is here either (a–c) maximally rotating (a = 0.998) or (d–f) nonrotating (a = 0). The emitting gas is assumed to be in free fall with an emissivity proportional to $r^{-2}$ (top panels) or on Keplerian shells (bottom panels) with a uniform emissivity (viewing angle $i = 45^\circ$). (a, d) GR ray-tracing calculations; (b, e) images seen by an idealized VLBI array at 0.6 mm wavelength, taking interstellar scattering into account; and (c, f) images seen for a wavelength of 1.3 mm. The intensity variations along the x-axis (solid green curve) and the y-axis (dashed purple curve) are overlayed. The vertical axes show the intensity of the curves in arbitrary units, and the horizontal axes show the distance from the black hole in units of $R_g$, which, for Sgr A*, is $3.9 \times 10^{16}$ cm $\sim 3 \mu$as.

Indeed, this is consistent with the observed 0.8 mm–size limit being greater than $4R_g$ for Sgr A* owing to a lack of scintillation (Gwinn et al. 1991). The presence of a rotating hole viewed edge-on will lead to a shifting of the apparent boundary (by as much as $2.5R_g$ or 8 $\mu$as) with respect to the center of mass or the centroid of the outer emission region.

Interestingly, the scattering size of Sgr A* and the resolution of global VLBI arrays become comparable to the size of the shadow at a wavelength of about 1.3 mm. As one can see from Figures 1c and 1f, the shadow is still almost completely washed out for VLBI observations at 1.3 mm, while it is very apparent at a factor of 2 shorter wavelength (Figs. 1b and 1e). In fact, already at 0.8 mm (not shown here), the shadow can be easily seen. Under certain conditions, i.e., a very homogeneous emission region, the shadow would be visible even at 1.3 mm (Fig. 1f).

3. HOW REALISTIC IS SUCH AN EXPERIMENT?

The arguments for the feasibility of such an experiment are rather compelling. First of all, the mass of Sgr A* is very well known within 20%, the main uncertainty being the exact distance to the Galactic center. Since, as we have shown, the unknown spin of the suspected black hole contributes only another 10% uncertainty, we can conservatively predict the angular diameter of the shadow in Sgr A* from the GR calculations alone to be $\sim 30 \pm 7 \mu$as, independent of wavelength.

As seen in Figure 1, the finite telescope resolution and the scatter broadening will make the detectability of the shadow a function of wavelength and emissivity; however, the size of the shadow will remain of similar order, and under no circumstances can it become smaller.

The technical methods to achieve such a resolution at wavelengths shortward of 1.3 mm are currently being developed, and a first detection of Sgr A* at 1.4 mm with VLBI has already been reported. The challenge will be to push this technology even further toward 0.8 or even 0.6 mm VLBI. Over the next decade, many more telescopes are expected to operate at these wavelengths. Depending on how short a wavelength is required, the projected timescale for developing the necessary VLBI techniques may be about 10 yr. A fundamental problem preventing such an experiment is not now apparent, but in light of our results, planning of the new submillimeter telescopes should include sufficient provisions for VLBI experiments.

A potential problem with our model may occur if $j_\text{int}$ has an inner cutoff that is larger than that of the horizon, making the shadow larger than predicted due to a decrease in emissivity rather than to GR effects. However, first of all, the truncation of accretion disk emission at the marginal stable orbit $r_{\text{mss}}$ is somewhat arbitrary (Cunningham 1975), and secondly, if it exists, such a cutoff would likely be frequency dependent, while there will be a frequency-independent minimum radius due to the GR effects we have described. Another problem could be the unknown morphology of the emission region. Anisotropy, strong velocity fields, and density inhomogeneities would make an identification of the shadow in an observed image more difficult. However, inhomogeneities are unlikely to be a major...
issue since the timescale for rotation around the black hole in the Galactic center is only a few hundred seconds and hence much less than the typical duration of a VLBI observation. The strong shear near the black hole would tend to smooth out any inhomogeneities very quickly. Indeed, submillimeter variability studies on such short timescales (Gwinn et al. 1991) have yielded negative results. The same argument applies to emission models that are offset from the black hole (e.g., one-sided). Since the shadow of the black hole has a very well-defined shape, it would under any conditions appear as a distinct feature, given that the dynamic range of the map is large enough (i.e., \( \approx 100 : 1 \)), considering a range of emission models; E. Agol et al. (1999, in preparation).

Finally, synchrotron self-absorption could pose a problem. So far, the available submillimeter spectra show a flattening of the spectrum around 1.3–0.6 mm, indicating a turnover toward an optically thin spectrum. Given the current observational uncertainties, one could in principle construct simple models where the flow does not become optically thin until 0.2 mm. Improved simultaneous measurements at submillimeter wavelengths are therefore highly desirable in order to measure exactly the spectral turnover since the experiment we propose here will only work for an optically thin flow. At hundreds of microns, the atmosphere becomes optically thick, making much more expensive space-based observations necessary. At X-ray wavelengths, the accretion flow will be optically thin to electron scattering, so there may be a better chance of detecting the shadow with future space-based X-ray interferometry as proposed in the MAXIM experiment.

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4. SUMMARY

The importance of the proposed imaging of Sgr A* at submillimeter wavelengths with VLBI cannot be overemphasized. The bump in the spectrum of Sgr A* strongly suggests the presence of a compact component whose proximity to the event horizon is predicted to result in a shadow of measurable dimensions in the intensity map. To our knowledge, such a feature is unique, and Sgr A* seems to have all the right parameters to make it observable. The observation of this shadow would confirm the widely held belief that most of the dark mass concentration in the nuclei of galaxies such as ours is contained within a black hole, and it would be the first direct evidence of the existence of an event horizon. A nondetection with sufficiently developed techniques, on the other hand, might pose a major problem for the standard black hole paradigm. Because of this fundamental importance, the experiment that we propose here should be a major motivation for intensifying the current development of submillimeter astronomy in general and millimeter and submillimeter VLBI in particular.

We thank P. L. Biermann, T. Krichbaum, A. Zensus, O. Blaes, R. Antonucci, and M. Reid for useful discussions. This work was supported in part by a Sir Thomas Lyle Fellowship (F. M.), NASA grant NAG5-8239 (F. M.), DFG grants Fa 358/1-1 and 2 (H. F.), and NSF grant AST 96-16922 (E. A.). E. A. would like to thank the ITP at the University of California at Santa Barbara for their hospitality.