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The Jet Model for Sgr A*

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Abstract. In this paper the jet model for the supermassive black hole candidate Sgr A* in the Center of the Galaxy is reviewed. The most recent model, with a reduced set of parameters, is able to account for all major radio properties of the source: size, structure, flux density, and spectrum. The model requires a minimum jet power of $\sim 10^{39}$ erg/sec and in a symbiotic jet/disk system implies a minimum accretion rate of a few times $10^{-8} M_{\odot}$/yr for a radio loud jet or $\sim 10^{-5} M_{\odot}$/yr for a radio quiet jet. Low near-infrared limits on the Sgr A* flux then imply that the accretion flow onto the central black hole must be radiatively deficient, but most likely has a high viscosity. Within the jet model the high-frequency part of the Sgr A* spectrum is self-consistently explained as the nozzle of the outflow. In a symbiotic model this innermost region of the jet could possibly be identified with the innermost region of an advection dominated accretion disk, a Bondi-Hoyle accretion flow, or any other type of under-luminous accretion process. The compact nozzle region is of particular importance since it can be used as a background photon source against which the central black hole could be directly imaged with future mm-VLBI experiments.

1. Introduction

Sgr A* has been at the center of an extensive discussion at this workshop. An overwhelming number of observations now demonstrate that this compact radio source in the center of the Galaxy is associated with a dark mass of $2.6 \cdot 10^6 M_{\odot}$ (Haller et al. 1996; Ghez et al. 1998 & 1999; Eckart & Genzel 1999; Zhao et al. 1999). In the past Sgr A* was only detected in the radio and many properties were associated with it only because of it being the most unusual radio object in the entire region (see Falcke 1996a for a review). Now we have much more direct information about its various properties. For example Ghez et al. (1999) show that the central dark mass concentration does indeed peak at the position of Sgr A* without any a priori assumptions about its nature. Stolovy et al. (1999) find that the only short-term variable source in their NICMOS near-infrared images of the very center also coincides with Sgr A*. Eckart & Genzel (1999) also claim the detection of a variable NIR source as a counterpart to Sgr A*. Cotera et al. (1999) report a detection of an unusual and narrow mid-infrared ridge at the position of Sgr A* but it is unclear how and if that is related to the central dark mass concentration.

While the amount of dark mass itself and its association with Sgr A* now seems well established, the nature of Sgr A* is not. Any model needs to explain the compact size, the possibly elongated structure (Lo et al. 1998), the inverted radio spectrum, the cut-off of the spectrum towards the infrared, and the faintness of emission at other wavelengths. At present it is still completely unclear which of the proposed emission models, if any, would be a fair description of the actual processes in the Galactic Center. Models proposed so far include advection dominated two-temperature accretion flows (ADAFs, Narayan et al. 1995), Bondi-Hoyle accretion (Melia 1994), emission from mono-energetic electrons (Duschl & Lesch 1994), or a jet (Falcke, Mannheim, & Biermann 1993). Even though they involve different physical assumptions, all models usually assume the presence of a supermassive black hole in Sgr A*; a comparison of the various approaches is given in Falcke (1996a) and Melia (1999). This paper will now mainly focus on the jet model and its recent improvements.

2. The Jet Model

The jet model originally proposed by Falcke et al. (1993) assumes that the radio emission from Sgr A* can be explained as emission from a radio jet, similar to, but with much lower power than, those seen in other nearby active galaxies or even quasars. Since the original publication the model has been refined further in Falcke (1996b) and Falcke & Biermann (1999). 'Refined' in this context means that the model was further simplified to have fewer free parameters: equipartition factors were set to unity, the electron distribution was assumed to be mono-energetic[1], and the velocity field of the jet was calculated self-consistently.

The basic idea is to start with a certain power $Q_{\rm jet}$ which is used to accelerate plasma through a nozzle of characteristic scale height $Z_{\rm nozz}$. The plasma is treated as an almost relativistic proton/electron gas with a sound speed of $\simeq 0.4c$ and an adiabatic index $\Gamma = 4/3$. The magnetic field is assumed to be tangled and in equipartition with relativistic particles. Moreover, the combined energy of relativistic particles and magnetic field is assumed to be in equipartition with the kinetic energy of the outflow. With these equipartition assumptions the particle density and magnetic field energy densities then follow directly from the input parameter $Q_{\rm jet}$ at the sonic point inside the nozzle.

For the purpose of calculating the radio emission one can treat the acceleration region as a black box which pushes the plasma through the sonic point. In a one-dimensional treatment the flow can then be described as a pressure-driven wind with the jet proper velocity $\gamma_{\rm j}\beta_{\rm j}$ given by the Euler equation to be

$$\left(\frac{\left(\frac{\Gamma+\xi}{\Gamma-1}\right)(\gamma_{\rm j}\beta_{\rm j})^2-\Gamma}{\gamma_{\rm j}\beta_{\rm j}}\right)\frac{\partial\gamma_{\rm j}\beta_{\rm j}}{\partial z}=\frac{2}{z} \tag{1}$$

[1] In contrast to Duschl (1999) the mono-energetic distribution here is not an essential ingredient of the model since the final spectrum will result from a superposition of many self-absorbed components.

and with $\xi = (\gamma_{\rm j}\beta_{\rm j}/(\Gamma(\Gamma-1)/(\Gamma+1)))^{1-\Gamma}$ (Falcke 1996b).

Assuming a vacuum, the jet will expand transversally with roughly sound speed after leaving the nozzle. The resulting pressure gradient along the jet (Fig. 1, left) will accelerate the flow to bulk Lorentz factors of a few (Fig. 1, right). This is of course an extremely simplified treatment and if there are additional acceleration processes (centrifugal, magnetic) the velocity would be higher still. The resulting shape of the outflow is roughly conical and depicted in Figure 2 (left). The axial ratio is of the order 3 to 4:1.

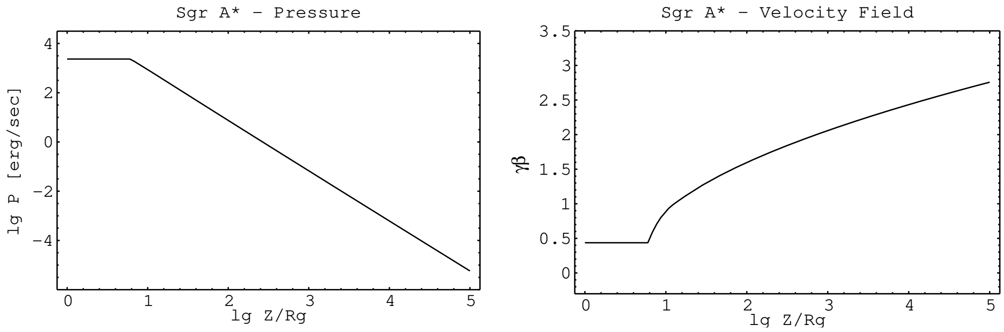

Figure 1. Run of pressure (left) and proper velocity (right) in the Sgr A* jet as a function of radius (in gravitational radii $GM_\bullet c^{-2}$) calculated for a simple pressure driven outflow of relativistic plasma.

Based on this velocity field, density distribution, and geometry it is then possible to calculate the expected radio spectrum of Sgr A*. Here, another free parameter is the energy distribution of the radiating particles (electrons or pairs). The simplest approach is to use a quasi mono-energetic electron distribution with a characteristic energy $\gamma_{\rm e}$ (Duschl & Lesch 1994). However, any other distribution with a similar characteristic energy (e.g., power-law with low-energy break or even thermal distributions) would lead to similar results.

As shown in Falcke & Biermann (1999) all these simplifications yield the following expressions for the observed flux density and angular size of Sgr A* observed at a frequency ν as a function of jet power. For a source at a distance D, with black hole mass $M_\bullet$, size of nozzle region $Z_{\rm nozz}$ (in $R_{\rm g} = GM_\bullet/c^2$), jet power $Q_{\rm jet}$, inclination angle i, and characteristic electron Lorentz factor $\gamma_{\rm e}$, the observed flux density spectrum is given as

$$\begin{aligned} S_\nu \quad &= 10^{3.03\cdot\xi_0}\ {\rm m}Jy\ \left(\frac{Q_{\rm jet}}{10^{39}{\rm erg/sec}}\right)^{1.27\cdot\xi_1} \\ &\cdot\left(\frac{D}{10{\rm kpc}}\right)^{-2}\left(\frac{\nu}{8.5{\rm GHz}}\right)^{0.20\cdot\xi_2}\left(\frac{M_\bullet}{2.5\cdot10^6M_\odot}\frac{Z_{\rm nozz}}{10R_{\rm g}}\right)^{0.20\cdot\xi_2} \\ &\cdot\left(3.9\cdot\xi_3\left(\frac{\gamma_{\rm e,0}}{200}\right)^{-1.4\cdot\xi_4} - 2.9\cdot\xi_5\left(\frac{\gamma_{\rm e,0}}{200}\right)^{-1.89\cdot\xi_6}\right), \end{aligned} \tag{2}$$

with the correction factors ξ_{0-6} depending on the inclination angle i (in radians):

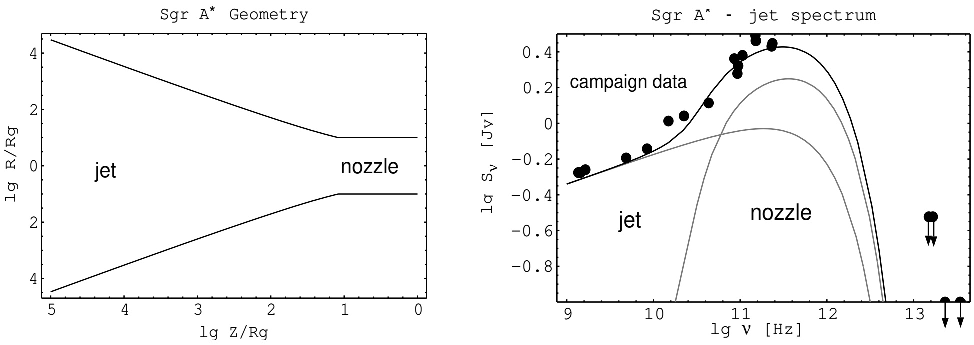

Figure 2. Left: geometry of the jet model for Sgr A*. Note the logarithmic scale on the vertical axis ending at and not going through zero. Right: radio spectrum of Sgr A*. The radio data are from Falcke et al. (1998) and references therein. The solid line is the prediction of the jet model, where the gray lines indicate which parts are contributed by the jet and the nozzle respectively.

$$\xi_0 = 2.38 - 1.90\,i + 0.520\,i^2 \tag{3}$$
$$\xi_1 = 1.12 - 0.19\,i + 0.067\,i^2 \tag{4}$$
$$\xi_2 = -0.155 + 1.79\,i - 0.634\,i^2 \tag{5}$$
$$\xi_3 = 0.33 + 0.60\,i + 0.045\,i^2 \tag{6}$$
$$\xi_4 = 0.68 + 0.50\,i - 0.177\,i^2 \tag{7}$$
$$\xi_5 = 0.09 + 0.80\,i + 0.103\,i^2 \tag{8}$$
$$\xi_6 = 1.19 - 0.29\,i + 0.101\,i^2. \tag{9}$$

Likewise, the characteristic angular size scale of the emission region is given by

$$\begin{aligned}\Phi_{\rm jet} &= 4.7\cdot\chi_0\,{\rm mas}\,\sin i\\ &\cdot \left(\frac{\gamma_{\rm e,0}}{200}\right)^{1.77\cdot\chi_1}\left(\frac{D}{10{\rm kpc}}\right)^{-1}\left(\frac{\nu}{8.5{\rm GHz}}\right)^{-0.89\cdot\chi_1}\\ &\cdot \left(\frac{Q_{\rm jet}}{10^{39}{\rm erg/sec}}\right)^{0.60\cdot\chi_1}\left(\frac{M_\bullet}{2.5\cdot10^6 M_\odot}\frac{Z_{\rm nozz}}{10R_{\rm g}}\right)^{0.11\cdot\chi_2},\end{aligned} \tag{10}$$

with the angle dependent correction factors

$$\chi_0 = 4.01 - 5.65\,i + 3.40\,i^2 - 0.76\,i^3 \tag{11}$$
$$\chi_1 = 1.16 - 0.34\,i + 0.24\,i^2 - 0.059\,i^3 \tag{12}$$
$$\chi_2 = -0.238 + 2.63\,i - 1.85\,i^2 + 0.459\,i^3, \tag{13}$$

where again the inclination angle i is in radians. All correction factors are normalized to yield unity at $i = 1$ rad ($\sim 57^\circ$).

For Sgr A* we are left with four basic unknown quantities in this equation: the inclination angle i, the jet power $Q_{\rm jet}$, the characteristic electron Lorentz factor $\gamma_{\rm e}$, and the relative nozzle size $Z_{\rm nozz}$. The expectation from fitting of other radio cores is that $Z_{\rm nozz}$ will be close to the jet origin of order 10 $R_{\rm g}$ and $\gamma_{\rm e}$ is of order 10^2. Moreover, given our position in the Galaxy it seems unlikely that Sgr A* would be pointing right at us and the inclination angle should probably be larger than say 30°.

If one assumes that the mm-bump in the spectrum is in fact intrinsic to Sgr A* and is produced by the innermost region of the jet/accretion disk (i.e., the nozzle) one can use this feature to effectively constrain $\gamma_{\rm e}$ and $Z_{\rm nozz}$ for a given $Q_{\rm jet}$. In addition, for a given flux density and size of the core at frequencies below the bump, one can also solve for the jet power and the inclination angle.

Unfortunately, the exact size of Sgr A* is still uncertain. Lo et al. (1998) claim that the intrinsic size of Sgr A* is ~ 0.45 mas at 43 GHz for a flux density of 1.1 Jy. Even though these numbers should be considered to be very tentative at present (see Bower et al. 1999a for a discussion of the uncertainties involved), we will use these number to fit the jet model. Figure 2 shows the predictions of the jet model for the Sgr A* radio spectrum in comparison to the data. The overall spectrum including the submm-bump is well reproduced for a nozzle size of $Z_{\rm nozz} = 12R_{\rm g} = 35\mu$as (needs to be multiplied by two if we see both sides), a characteristic electron Lorentz factor of 125, an inclination angle of $\sim 45°$, and a jet power of $Q_{\rm jet} \gtrsim 10^{38.7}$ erg/sec. The predicted spectral index of the low-frequency part of the spectrum is $\alpha \simeq 0.17$ ($S_\nu \propto \nu^\alpha$) which agrees well with the observed one. The predicted size as a function of frequency roughly scales as $\nu^{-0.9}$ and is shown in Fig. 3 together with results from recent mm-VLBI experiments. As far as the observations are concerned, one has to point out that the measurements at λ3 and λ1.3 mm do not probe the NS direction, and hence for a jet geometry along the axis seen by Lo et al. (1998) could underestimate the true size of Sgr A* (see Doleman et al. 1999 for a discussion of this important detail).

3. Discussion

3.1. Results of the Jet Model

In general it can be said that the jet model explains all known observational details of Sgr A* reasonably well. This shows that the claim by Lo et al. (1998) that none of the existing model could reproduce their data is unfounded. In fact, all the observational results Lo et al. claim (i.e., elongation, intrinsic size, intrinsic size scaling with frequency) had already been well predicted earlier by the jet model within reasonable margins. Nevertheless, one needs to point out that the core size within the current version of the jet model cannot be very accurately predicted since it depends quite sensitively on the electron Lorentz factor, leaving an inherent uncertainty of a few.

Another important benefit of the jet model is that it not only fits a single source, Sgr A*, but the same relatively simple equations presented here can be used to explain in detail well-constrained radio cores in other galaxies like

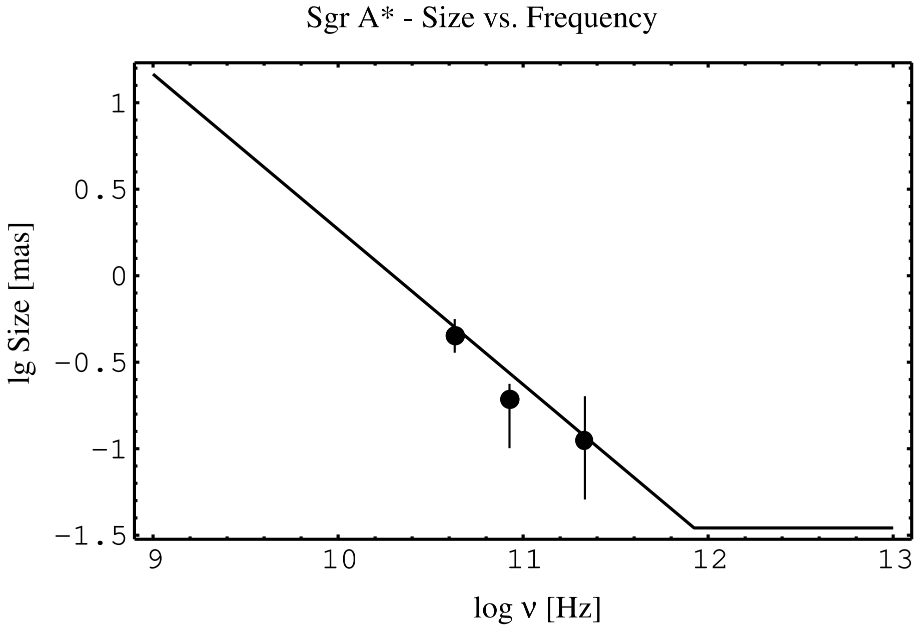

Figure 3. Intrinsic size of Sgr A* (major axis, probably north-south) versus frequency as predicted in the jet model (solid line). The parameters (i, γ_e, $Q_{\rm jet}$) have been chosen to match the intrinsic NS size of 0.44 mas at λ7mm given by Lo et al.(1998). The data points at λ3 and λ1.3 mm were taken from Krichbaum et al. (1999) and Doleman et al. (1999). The error bars indicate the reported range of values. Note that the sizes at λ3 and λ1.3 mm are not for the NS direction.

M81 or NGC4258 and even the galactic superluminal jet source GRS1915+105 (Falcke & Biermann 1996, 1999).

3.2. The Accretion Flow in Sgr A*

Moreover, the jet model allows one to make interesting inferences for the nature of the accretion process in Sgr A*. Our current understanding is that jets are formed in the innermost region of an accretion disk near a compact object. This seems to be true for young stars as well as for neutron stars and black holes. Jet and disk therefore cannot be considered in isolation but form a symbiotic system (Falcke & Biermann 1995). In many cases one finds that the jet power is a significant fraction of the total accretion power and is comparable to the accretion luminosity.

Sgr A* adds another twist to this story. Since the jet model used here basically assumed the most efficient type of radio jet, we can place a firm lower limit on the jet power. Any modifications to the model, other than assuming unreasonably small inclination angles, will only lead to an increased energy demand and a larger $Q_{\rm jet}$. If we assume that half of the energy released in an accretion process onto a rotating black hole is used to drive the jet, we need a *minimum* accretion rate of $5{\cdot}10^{-8}M_{\odot}$. Interestingly, any standard accretion disk model with such an accretion rate would violate the current upper limits on the NIR emission of Sgr A* as presented for example in this volume. Hence, we must conclude that the accretion disk in Sgr A* must be radiatively deficient, e.g., is optically thin and advection dominated (Narayan et al. 1995). As discussed in Falcke & Heinrich (1994) the disk in Sgr A* would turn optically thin when the viscosity parameter is $\alpha \gtrsim 10^{-3}$. The jet model therefore also indirectly suggests that a relatively efficient viscosity mechanism is at work in Sgr A*.

Unfortunately, it is not easy to give a similarly robust estimate for an upper limit of the accretion rate. From studies of other AGN (see discussion in Falcke et al. 1995; Falcke & Biermann 1995) we know that there is a dichotomy of the radio-luminosity of jets, the nature of which is completely unknown. At least in quasars the radio cores of radio-quiet jets seem to be roughly a factor hundred less luminous for a given accretion rate than radio-loud jets. Assuming that Sgr A* would physically resemble such a radio-quiet quasar core, would imply that in fact the accretion rate needed to power Sgr A* is of the order $10^{-5}M_{\odot}$/yr. This is close to the value needed in the ADAF model, though not quite yet the value predicted by 3D hydrodynamic simulations of the GC region (Melia 1999; Coker & Melia 1999). In either case a radio-quiet jet model would still require a very high 'inefficiency factor' for the production of thermal radiation to explain the low NIR limits for Sgr A*.

The idea of the jet/disk-symbiosis could be pushed even further for Sgr A*: an interesting part of the jet model is the nozzle, which is supposed to be the innermost part of the jet and in more luminous AGN is usually invisible due to energy-loss arguments. In a symbiotic system this region would be the interface between the accretion flow (inflow) and the jet (outflow) and it cannot really be claimed to belong to either one—the nozzle could be as much part of the disk as it is part of the jet. This would allow one to easily combine existing models for the accretion flow (e.g., Melia 1999, Coker & Melia 1999; Narayan et al. 1995) with the jet model, by dropping the assumption that these models explain the cm-spectrum and assuming that their mm-emission components are in fact the black box labeled 'nozzle' in the jet picture. An ADAF or Bondi-Hoyle accretion flow with outflow in its innermost region might do just that and explain what the nozzle really is.

3.3. Predictions

A number of predictions from the jet model can be made that can be tested in the near future. Sgr A* should become resolved at 3 and 1 mm in the NS direction once a suitable mm-VLBI array is available. From analogy to other radio cores one would expect a polarization at the percent level at mm-wavelengths where interstellar propagation effects become negligible (Bower et al. 1999a&b). The most likely direction of the magnetic field is probably along the jet axis (NS?). Because the outflow travels from small to large scales and from small to large wavelengths one would expect that radio outbursts appear first at high frequencies and then propagate to longer wavelengths. The time scale for this delay could be relatively short. The model also predicts a certain level of x-ray emission, since the relativistic electrons in the nozzle will inverse-Compton scatter their own synchrotron radiation into the soft x-ray regime. The luminosity, however, will be relatively low, of the order $\lesssim 10^{34}$ erg/sec with a relatively unusual, curved spectrum. A more detailed calculation was presented already in Beckert & Duschl (1997).

4. Outlook

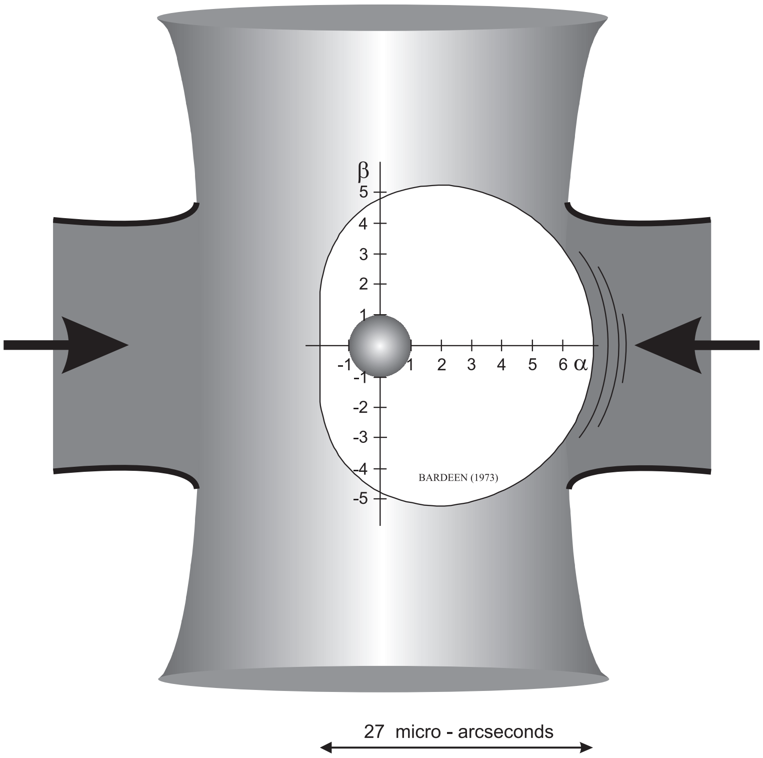

Figure 4. Sketch of the inner region of Sgr A* with accretion flow and nozzle surrounding the black hole. Overlaid is an appropriately scaled reproduction of a Figure from Bardeen (1973), showing the 'hole' of photons absorbed by the black hole if observed against a background source. A similar process could apply to Sgr A* and its compact, high-frequency emission component.

The most intriguing consequence of the radio spectrum and its modeling is the suggestion that the mm-part of the spectrum corresponds to an ultra-compact region in Sgr A*. This follows from a few simple arguments (e.g., Falcke et al. 1998) as well as from basically all models proposed. Within the jet model, the size of the component used here to fit the spectrum corresponds to 35μas. This is interestingly close to the suspected black hole — six Schwarzschild radii. Bardeen (1973) made an interesting calculation, where he showed that photons from a background source behind a rotating black hole would be absorbed within an asymmetric disk of 4.5 Schwarzschild radii diameter. Even though the mm-emission region in Sgr A* is not at infinity behind the black hole one would expect a similar effect here. Figure 4 shows the Bardeen absorption disk overlayed on a sketch of Sgr A* with accretion disk, jet and black hole. Future 220 GHz VLBI experiments—first results of which have already been reported (Krichbaum et al. 1999)—will have enough resolution to start imaging such effects directly. At this frequency scattering will also not be major problem any more. This experiment could provide the final proof, not only for the validity of a specific model, but also for the existence of black holes in general.

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