Simulating VLBI Images of Sgr A*

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Very Long Baseline Interferometry (VLBI) at sub-millimeter/millimeter wavelengths shows promise at resolving the silhouette of the supermassive black hole at the Galactic Center, Sagittarius A* (Sgr A*), in the near future. In order to accurately test theoretical models of Sgr A* using these observations, a direct comparison of VLBI data to numerical models must be made. We present calculated images and spectra of Sgr A* using accretion disk simulation data from general relativistic magnetohydrodynamics (GRMHD) evolutions. Synchrotron and bremsstrahlung emission models are considered in the optically thin limit, which allows us to solve the radiative transfer equations using only simulation and geodesic data in a post-processing step. We show predictions of millimeter observations at the expected angular resolution limit and the spectrum's variability.

Keywords: accretion,accretion disks; Galaxy:center; radiative transfer; MHD

Introduction: A particularly interesting object that is now receiving a great deal of attention is the black hole at the center of our galaxy, the radio source known as Sgr A*. The black hole's mass, $M \simeq 4 \times 10^6\,\mathrm{M}_\odot$, and distance from Earth, $R = 8$kpc,[1–3] are such that it is the black hole with the largest angular size on our sky. This makes it the best candidate for directly viewing the silhouette—or "shadow"[4]—of an event horizon. However, it is puzzling since it seems to accrete little matter and the matter it does accrete radiates weakly.[5,6]

Current popular theories of Sgr A* fall into two categories: jet models[7,8] and radiatively inefficient accretion flow (RIAF) models.[9] Each of these models are freely specified by a number of degrees of freedom and, consequently, can predict the spectrum quite well.

These two theories neglect spacetime curvature effects and do not account for dynamical variations of the spectrum self-consistently. More detailed calculations have been performed but they either include general relativity (GR) and omit plasma dynamics,[10,11] or they include the dynamics but neglect GR effects.[12] Here we include both aspects and present the first self-consistent optically thin calculations of Sgr A*'s image and spectrum at about $\lambda = 1$mm, near the peak of its spectral energy distribution (SED) and is approximately where the disk becomes optically thin.[13,14] This band of radiation is particularly interesting since improvements in millimeter and sub-millimeter VLBI will soon permit features at the scale of the horizon to be resolved.[15]

Theory and Results: For Sgr A*, the material is well described by a well ionized plasma moving within the background potential of the black hole. We thus evolve the ideal GRMHD equations on a fixed, stationary metric—i.e. the Kerr spacetime—and omit radiation back-reaction since we only consider optically thin emission.

The GRMHD equations of motion in axisymmetry are integrated using the flux-conservative scheme known as HARM.[16,17] Our initial data consists of an orbiting torus in hydrodynamic equilibrium.[18] A weak poloidal magnetic field is embedded within the torus along density contours. The magnetorotational instability[19] drives the development of turbulence in the disk and material accretes onto the black hole.

The disk's emission is calculated as a post-processing step using simulation data over the time-steady phase of accretion. We consider non-polarized emission from a thermal distribution of electrons, assuming that electron temperature is equal to the baryon temperature. We include both synchrotron and bremsstrahlung radiation, confirming that the former dominates. The radiative transfer equation in GR is integrated along geodesics that penetrate the accretion flow. We use an anisotropic, angle-dependent approximation for the synchrotron emissivity given by,[20] which yields results to an accuracy no worse than any of our other assumptions or approximations.[21]

Figure 1 shows spectra calculated from different snapshots of the simulation. The filled circles with error bars represent observed flux values of Sgr A* during quiescence.[5,22–26] The exes are flux measurements during flare events,[25] and the arrows indicate upper limits at NIR/IR wavelengths.[22] Error bars indicate the measured errors quoted in the references, which sometimes include intrinsic variability as well as measurement uncertainty. We calculate L_ν assuming isotropic emission. The accretion rate used for all SEDs was set by constraining the flux density at $\lambda = 1$mm to 4Jy at $t = 1250GMc^{-3}$. We find that variability near the power maximum is at the same order of magnitude as what is observed. Further, we find that, for the particular model considered here, the emission at higher frequencies is within upper limits but can lie near observed fluxes at NIR frequencies. Departures from observations at low frequencies is the result of the finite extent of our simulation data and the fact that the disk is optically thick there. We also find the spectrum becomes harder as the inclination angle decreases or for simulations with faster spinning black holes.[27]

Shown in Figure 1 are both an "infinite" resolution image and an image simulating what an Earth-based VLBI observation would see at 1mm. The simulated VLBI image was created by convolving the original with a Gaussian beam the size corresponding to a 8000km baseline observation. Since anisotropic scattering from the interstellar medium becomes comparable to the theoretical diffraction limits of VLBI at wavelengths greater than 1mm, it is ignored. We find that the black hole silhouette is noticeable in images calculated at VLBI resolutions for inclinations greater than 30° (45° is shown here).[27]

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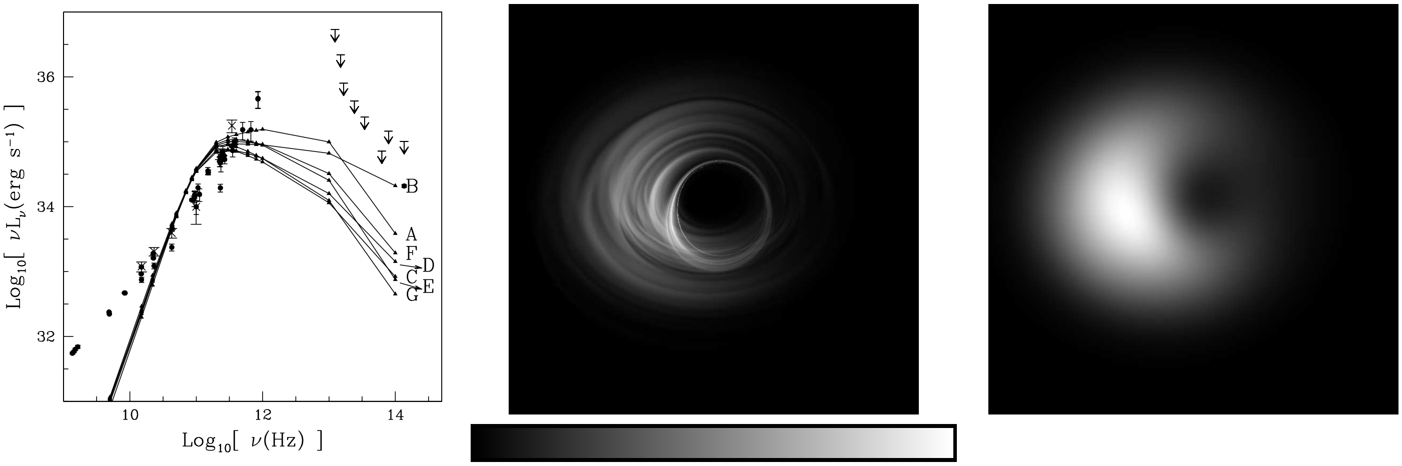

Fig. 1. Left frame: spectra taken at $i_{\rm inc} = 30°$ using snapshots of the $a_* = 0.94$ disk at different points along its evolution. Lines A-G are spectra from times 1150, 1250, 1326, 1434, 1500, 1560, $1666GMc^{-3}$, respectively. Middle frame: image of the accretion disk viewed at a wavelength of 1mm seen at an inclination angle of 45°. The frame is $60M$ wide in the plane of the singularity. Right frame: Gaussian convolution of the middle image simulating a diffraction limited, 8000km baseline VLBI observation. Bottom: relative greyscale map used in each image.

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