Testing Accretion Physics and Strong-Field Gravity by Imaging Accreting Black Holes

PROJECT SUMMARY

The two largest black holes on the sky are SgrA* and M87. Recent observations (Doeleman et al. 2008) have demonstrated that the apparent size of their horizons (tens of micro-arcseconds) can be resolved by Very Large Baseline Interferometry (VLBI) at sub-millimeter wavelengths. Imaging the silhouette of these black holes with existing technology will open a new window for probing general relativity, accretion flow physics, and the launching site of relativistic outflows.

This imaging technique is made feasible at a wavelength $\lambda \lesssim 1$mm owing to three fortunate coincidences: *(i)* the accreting gas is transparent to synchrotron self-absorption at $\lambda \lesssim 1$mm; *(ii)* the scattering by interstellar electrons along the line-of-sight does not blur the image beyond the horizon scale at $\lambda \lesssim 1$mm; and *(iii)* the resolution of an aperture that has the diameter of the Earth is of order the horizon angular scale for SgrA* and M87 at $\lambda \sim 1$mm.

We propose to study in detail the black hole silhouettes on the background illumination by their surrounding gas. Our primary goals would be to: *(i)* examine the sensitivity of features in the black hole image to details of the accretion flow and jet physics of the surrounding gas; and *(ii)* separate features which provide generic tests of general relativity. Our simulated images will employ a general-relativistic code which incorporates ray-tracing, gas dynamics, and the relevant plasma physics.

Our library of black hole images will characterize the dependence of the image features on the black hole spin, the existence of a jet, and the parameters of the accretion flow. In the second phase of our study, we will examine the ability of future observations to resolve the predicted images for different choices of the VLBI stations around the globe. Our analysis will incorporate interstellar bluring as well as instrumental noise. We will seek to optimize the observing strategy in order to obtain the most scientific output from a given observing time.

The proposed work has a broader impact in a variety of contexts. Testing General Relativity in the strong field limit is of great importance for fundamental physics. Advances in radio imaging technology will likely have spin-offs with possible practical applications to both the civil and the defence industry. Also, black holes are known to attract much interest from the general public. We intend to distribute our images of black hole silhouettes to the general public through popular-level articles and movies that would be provided freely to museums and the popular media.

PROJECT DESCRIPTION

1 Aims & Background

Testing general relativity (GR) in a regime where spacetime curvature is large remains one of the primary goals of observational astronomy. Black holes provide a natural target in which to focus these efforts.

A variety of techniques have been brought to bear upon studying black hole accretion flows in the vicinity of the black hole horizon, the most fruitful of which has been observations and detailed analysis of broad line-like features in the X-ray spectra of AGN. These are usually interpreted as the Fe Kα flourescence line, the shape of which is diagnostic of the strong gravity region, and in particular the frame dragging from rapidly rotating black holes (see, e.g., Reynolds and Nowak, 2003; Pariev et al., 2001). While theoretical uncertainties remain, in at least a few sources (e.g., MCG-6-30-15) it appears this interpretation is unambiguous, providing evidence for the presence of large spins in supermassive black holes.

General relativistic effects can also play a substantial role in the polarization properties of Thomson thick disks (see, e.g. Connors et al., 1980; Laor et al., 1990; Bao et al., 1997). Therefore, detailed spectropolarimetric observations may shed light on both the physics of the accretion flow and the curvature of space-time. However, these necessarily require an accretion model and consequently suffer from considerable uncertainties associated with the accretion physics. Nevertheless, careful study and modeling of the X-ray spectra of a number of black hole binaries have yielded the first reliable estimates of stellar-mass black hole spin, ranging from $a = 0.65$ to $a \simeq 1$ (Shafee et al., 2006; McClintock et al., 2006; Liu et al., 2008).

Direct imaging of the silhouette around the horizon of a black hole (Broderick and Loeb, 2006a; Falcke et al., 2000) would provide the first direct measurement (via the induced strong lensing of emission from surrounding gas) of the space-time curvature near the black hole. The two largest black holes on the sky are SgrA* and M87. Recent observations (Doeleman et al., 2008) have demonstrated that the apparent size of their horizons (tens of micro-arcseconds) can be resolved by Very Large Baseline Interferometry (VLBI) at sub-millimeter wavelengths (Broderick et al., 2008; Fish et al., 2008). Imaging the silhouette of these black holes with existing technology will open a new window for probing general relativity, accretion flow physics, and the launching site of relativistic outflows.

This imaging technique is made feasible at a wavelength $\lambda \lesssim 1$mm owing to three fortunate coincidences: *(i)* the accreting gas is transparent to synchrotron self-absorption at $\lambda \lesssim 1$mm; *(ii)* the scattering by interstellar electrons along the line-of-sight does not blur the image beyond the horizon scale at $\lambda \lesssim 1$mm; and *(iii)* the resolution of an aperture that has the diameter of the Earth is of order the horizon angular scale for SgrA* and M87 at $\lambda \sim 1$mm.

Black hole imaging would have sweeping implications for both the astrophysics of compact objects and the fundamental physics of gravity the strongly-nonlinear regime (where General Relativities predictions are most divergent from Newtonian gravity). The lensed horizon of the nuclear black hole in the Galactic center ($M \approx 4.5 \times 10^6 M_\odot$) spans $\sim 55\,\mu$as across, about twice as much as the black hole horizon in M87 ($M \approx 3 \times 10^9 M_\odot$). As mentioned above, observations with sufficient resolution and sensitivity have *already* been performed with an array of millimeter ($\lambda = 1.3$mm) telescopes: the *JCMT* in Hawaii, the *SMTO* in Arizona and *CARMA* in southern California. These observations have demonstrated that the required resolution can be achieved through mm and sub-mm VLBI. Interestingly, the existing data are already constraining models for SgrA*'s accretion flow (Broderick et al., 2008; Fish et al., 2008; Doeleman et al., 2008). When combined with recent near and mid-infrared observations, these have significantly constrained the existence of black hole horizons, requiring radiative (including outflows) efficiencies above 99.7% to avoid such a horizon (Broderick et al., 2009). Within the next decade, it is expected that larger arrays operating at sub-millimeter wavelengths will provide imaging capabilities with resolutions below $20\,\mu$as (Doeleman et al., 2005; Doeleman and Bower, 2004; Miyoshi et al., 2004). In the near-infrared (NIR) the *GRAVITY* instrument, currently under construction at the Very Large Telescope Array (*VLTA*), is expected to obtain sub-milli-arcsecond astrometry (Gillessen et al., 2006; Eisenhauer et al., 2005), promising minute-timescale monitoring of the variability in the centroid position at $10\,\mu$as scales.

More importantly for the purposes of gravitational physics, however, are observations of NIR and X-ray flares in Sgr A*, which imply that near the horizon the accretion flow is strongly dynamic and non-uniform (Baganoff et al., 2001; Genzel et al., 2003; Goldwurm et al., 2003; Eckart et al., 2004; Ghez et al., 2004). The time scale of the variability, ~ 10 min, is comparable to the period of the innermost stable circular orbit (ISCO), and thus when considered in the context of existing models for Sgr A* suggestive of an orbiting hot spot. Such a hot spot can be used as a test particle, and together with measurements of its multiple images presents a method by which to probe the strong gravity region quantitatively. In Broderick and Loeb (2005) it was shown that the images and lightcurves associated with a hot spot could be used to measure the mass and spin of the black hole. Recent observations of the polarization lightcurve of a NIR flare have been consistent with these predictions (Eckart et al., 2006). Hence, continued refinement of the theoretical predictions for the images and lightcurves (including polarization), and evaluating observational strategies to probe the source of Sgr A*'s variability is warranted.

While direct imaging will only be possible for two supermassive black holes (Sgr A* and M87), they are in many respects complementary to other methods of probing supermassive black holes. Unlike the AGN studied via Fe-line observations, Sgr A* is vastly underluminous in comparison to its Eddington luminosity, and representative of the vast majority of supermassive black holes in the universe. Furthermore, the comparison of Sgr A* and M87 provides a means to compare and contrast two very different accretion black hole systems, the most important distinction being the absence of jet in Sgr A* and the presence of a powerful jet in M87. These observations would provide a mechanism to probe the role of black hole spin in jet formation, presently believed to be critical (Blandford and Znajek, 1977; McKinney, 2006; Hawley and Krolik, 2006). We propose to study

- The imprint of black hole accretion flows on sub-millimeter VLBI images of Sgr A* and M87
- The imprint of relativistic outflows, such as jets, on these images
- The generic signatures of black hole mass and spin, including possible deviations due to alternate theories of strong gravity
- The optimization of VLBI array configuration and observing strategy for sub-millimeter imaging of SgrA* and M87

These goals will be explored using state-of-the-art accretion flow models, which satisfy all known observational constraints as well as existing fully relativistic, three-dimensional magnetohydrodynamic simulations, in which hot spots (or flares) naturally arise due to compact magnetic reconnection events or strong shocks.

The computational methods we have presently developed for this purpose are outlined briefly §2. Preliminary results (with references) are summarized in §3, and the proposed extensions of this work are presented in §4. Finally, in §5, we summarize the significance of this project to other active fields within physics. The technological advances that will enable astronomers to image black holes over the next decade offer a new opportunity (complementary to the detection of gravitational waves by projects such as *LIGO* or *LISA*) for testing GR and probing the vicinity of astrophysical black holes. The main goal of this proposal is to examine the implications and limitations of this newly accessible technique.

In what follows geometrized units are used (i.e., $G = c = 1$), and the metric signature is taken to be $-+++$.

2 Computational Methods

2.1 Ray Tracing & Radiative Transfer

Rays are constructed by explicitly integrating the geodesic equation in a Hamiltonian formulation, described in detail in Broderick and Blandford (2003). This is both efficient, accurate and easily implemented for arbitrary metrics. Thus we are able to trace rays through arbitrary solutions to any metric theory of gravity.

Polarized radiative transfer in curved spacetime is most easily performed by integrating the Boltzmann equation (Lindquist, 1966; Broderick, 2006). In this case, it is the photon distribution function $N_\nu \propto I_\nu/\nu^3$ that is evolved. In the case of polarized radiative transfer, it is possible to define and evolve covariant analogues of the Stokes parameters, $\mathrm{N}_\nu = (N_\nu, N_\nu^Q, N_\nu^U, N_\nu^V)$ (Broderick and Blandford, 2004). Again, this is implemented for arbitrary metrics.

The two synchrotron emission components previously considered involve populations of electrons with a thermal (Yuan et al. 2003, supplemented with a polarization model from Petrosian and McTiernan 1983) and power-law (Jones and O'Dell, 1977) distributions, appropriate for Sgr A*.

2.2 Simple Accretion Disk Models

We employ a simple, qualitatively correct Radiatively Ineffecient Accretion Flow (RIAF) model for Sgr A*, motivated by Yuan et al. (2003), and described in detail in Broderick et al. (2008). This model is characterized by a two-temperature, geometrically thick accretion flow, with the thermal electron temperature and density having a power-law radial dependence and a Gaussian vertical profile. This is supplemented with a population of non-thermal electrons, critical for fitting the radio spectra of Sgr A* & M87, which is taken to have a similar distribution. Finally, the magnetic field is assumed to be in rough equipartition with the accreting ions. The radial power-laws were taken directly from the numerical results of Yuan et al. (2003). However, we determined the normalizations of the electron densities and temperature via spectral fitting.

2.3 Simple Jet Models

For M87 we produced a simple jet model that fits existing jet-formation simulations well (Broderick and Loeb, 2008). This ensures that we both capture the relevant physical character of the jet while ensuring that we maintain sufficient freedom to investigate the ability of high-resolution imaging to constrain jet formation parameters. The jet itself is characterized by an axisymmetric, self-collimating solution to the force-free equations. In this the current distribution was assumed to be self-similar, resulting in a family of solutions corresponding to different rates of collimation, and thus different acceleration models. The jet plasma's velocity was taken set to the drift velocity of the jet as seen in the lab-frame, determined by both the magnetic field structure as well as the rotation frequency of the magnetic field lines (which was set by the Keplerian velocity outside of the ISCO, and fixed to the ISCO Keplerian velocity inside, as seen in GR Magneto-hydrodynamic [GRMHD] simulations). Finally, the jet plasma's density profile was determined by fixing it to be a Gaussian at the jet base and then determined everywhere else via the continuity equation. Therefore, the free parameters which define our jet model are: black hole spin, jet inclination, collimation rate, and footprint size.

2.4 Hot Spot Model

We model the hot spot by an over-density of non-thermal electrons, moving within the background accretion/outflow model (Broderick and Loeb, 2006b). For simplicity this is modeled by a spherical Gaussian (as seen in the comoving frame). In M87 such ejections have been observed for nearly a decade now. For Sgr A*, these compact hot spots are a natural explanation of the observed flaring. If angular momentum is transported by the MRI, as presently believed, magnetic reconnection events associated with the ion-driven magnetic turbulence are unavoidable. While it is not presently clear how precisely such events accelerate electrons to high Lorentz factors, such acceleration is observed in solar ejections, and is the prime explanation for the x-ray disk-corona of efficiently accreting systems. Unlike the Sun however, in the case of Sgr A*, the energy dumped into these electrons is dynamically inconsequential (this is a direct consequence of the low radiative efficiency, which implies that Sgr A*'s luminosity must increase by many orders of magnitude before these electrons have sufficient pressure to compete with the ions). A direct consequence is that these electrons will be trapped within the local magnetic turbulence, maintaining a compact morphology. The hot spots are eventually destroyed by orbital shear, magnetic turbulence itself, or synchrotron cooling. Which of these dominate depends upon the hot spot location and the observational wavelength of interest, though at mm and sub-mm wavelengths we expect such spots to survive many orbits, corresponding to hours.

In addition to its location, our model of the hot spot is characterized by the spot central density and its size. These are determined by the properties of the variability we are attempting to explain. For example, in the case of the Galactic Center, we set the size to be sufficiently small to reproduce the observed variability ($\sim 1-2GM/c^3$) and sufficiently dense to generate the measured flare luminosities ($\sim 11\,$mJy, e.g., Eckart et al. (2006)). For the Galactic center, the orbital time scale near the ISCO is between 5 min and 30 min for orbits around maximally and non-rotating black holes, respectively.

2.5 Implementation

The algorithms and models briefly described in the preceding section have been implemented in C++ due to its portability and extensibility. In addition it is massively parallelized (trivially) using the Message Passing Interface (MPI) so that existing large-scale computing resources can be leveraged to produce the large number of images (which can be many hundreds of thousands for dynamical environments) required to properly sample the appropriate parameter space for the purpose of data fitting. The required large-scale super-computing resources essential to pursue the proposed work are available *in situ* at both of the PI's locations, and thus the computing component of our funding request is solely for analysis and visualization hardware.

3 Preliminary Results

3.1 Quiescent Disk Emission

Horizon scale images of the quiescent disk emission have the potential to probe the physics of the accretion flow at the inner boundary. A number of such images for different black hole spins and orientations are shown in Fig 1. Even when interstellar scattering is included (right panels) the signatures of the horizon, spin and inclination are easily observed.

In Broderick and Loeb (2006a) it has been shown that the opacity of a quiescent accretion flow combined with relativistic effects lead to a specific asymptotic behavior in the polarization fraction spectra and a specified shift in the location of the image centroid as a function of frequency. The reason for this is clear from Figure 1 which shows images of the disk model described in the previous section at radio and NIR frequencies. At high frequencies the accretion disk is optically thin, and thus the emission is dominated by the inner edge of the accretion disk, highlighting the relativistic aspects of the orbit at this location (including the effects of spin). At low frequencies the accretion disk is optically thick, with a photosphere extending far from the black hole where relativistic effects are less significant.

This results in a polarization fraction which is dominated in the high frequency limit by a small patch of the accretion flow and thus asymptotes to a fixed value (shown in Fig. 2, left). Current sub-millimeter observations tend to favor higher spins for the disk models we have considered, but this is not yet conclusive.

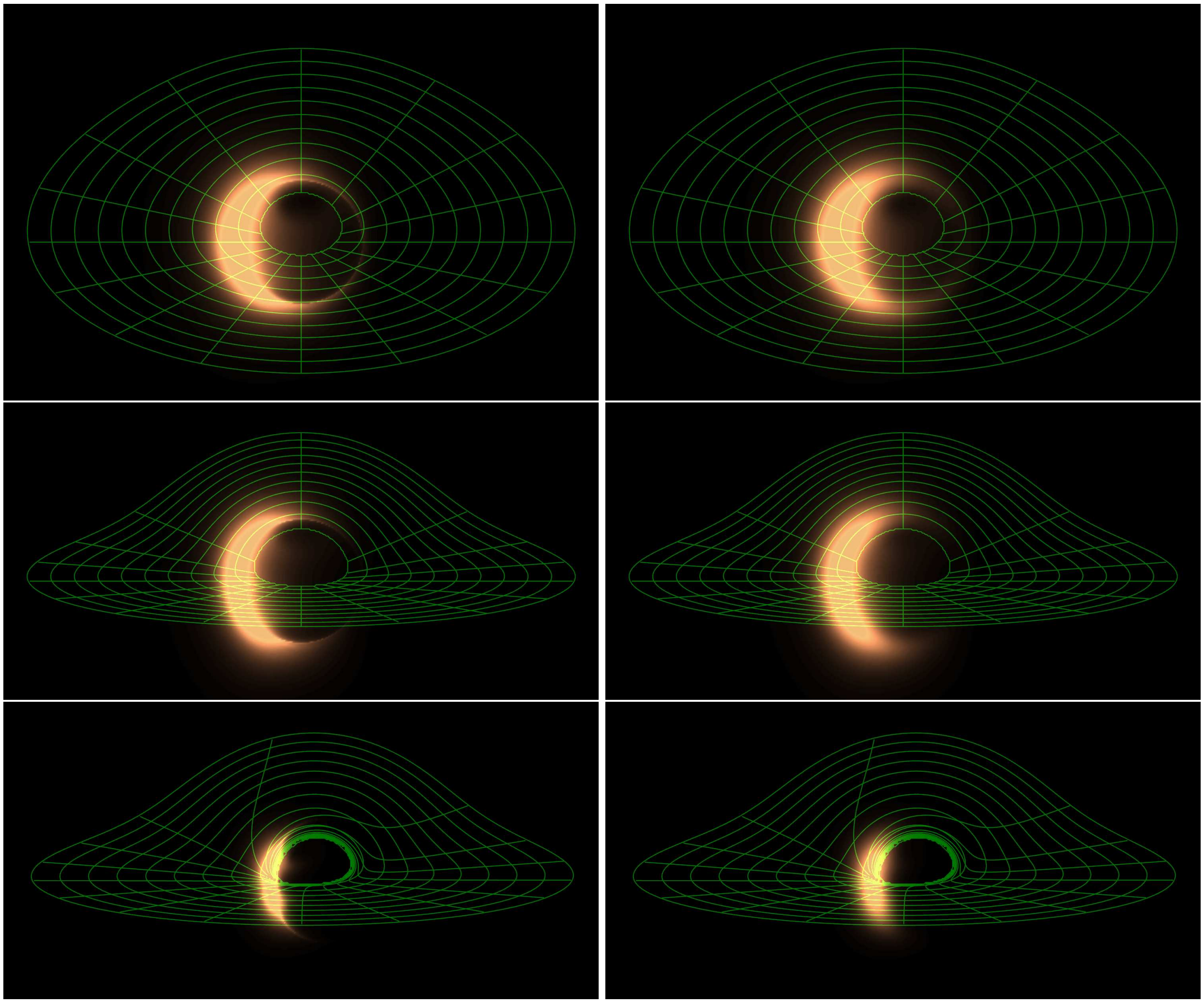

Figure 1: Theoretical images of the accretion flow around Sgr A* at 1.3 mm. The lensed equatorial plane is shown by the green grid. *Top:* Non-rotating black hole viewed from 30° above the equatorial plane (the most common inclination). *Middle:* Non-rotating black hole viewed from 10° above the equatorial plane. *Bottom:* Rapidly rotating black hole viewed from 10° above the equatorial plane. Images on the left are at ideal resolution while those on the right have been broadened by interstellar electron scattering. In all cases the image is strikingly asymmetric due to the relativistic motion of the emitting plasma. Nevertheless, the silhouette of the black hole is clearly visible.

For the same reason, the centroid position evolves as a function of frequency, again asymptoting to a fixed value in the high frequency limit. This is clearly seen in the inset to Figure 2b, which shows the location of the image centroid projected onto the axis orthogonal to the line-of-sight and the disk and black hole orbital momentum. In each of these, high black hole spins lead to distinct behaviors.

3.2 RIAF Parameter Estimation

If we take the RIAF model seriously, we can begin to constrain its parameters using the pioneering results of Doeleman et al. (2008). Because the 3-station VLBI experiment has insufficient *u*–*v* coverage to produce an image, we fit the visibilities directly (see, e.g., Fig. 3). This is done in the normal way, adjusting for the fact that on the Hawaii-California baseline only an upper limit was obtained. Assuming a uniform prior on the

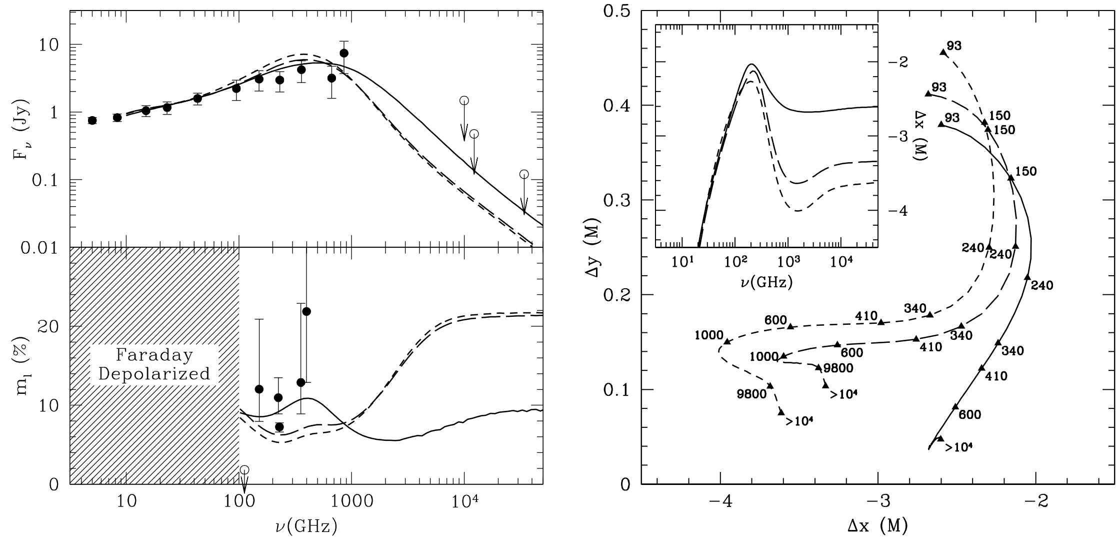

Figure 2: *Left:* The spectral flux (upper panel) and linear polarization fraction (lower panel) are shown for the non-rotating ($a = 0$, short-dash), moderately rotating ($a = 0.5$, long-dash) and maximally rotating ($a = 0.998$, solid) black hole at the center of the Milky Way galaxy. The accretion disk models are described in §2.2 and the disk is viewed at an angle of 45°. In all cases the spectra give an acceptable fit to the existing data with the maximally rotating black hole model giving the best fit. The polarization fraction appears to be a sensitive diagnostic of the spin of the black hole near 350 GHz and above 10^4 GHz (30 μm). Below 100 GHz it is believed that Sgr A* is Faraday depolarized, and thus our calculation (in which Faraday rotation was ignored) is inapplicable. The data are taken from Aitken et al. (2000); Bower et al. (2002, 2003). The polarization at high frequencies is a direct result of the localization of the emission evident in Figure 1. *Right:* The position of the centroid of the disk image is shown as a function of observing frequency (labeled in GHz) for the same three models shown on the left. The position shifts are measured relative to the black hole (where the y-axis is aligned with the black hole spin). The projection of the trajectories on the Δx axis are shown as functions of frequency in the inset. For Sgr A*, the angular scale of the axes is $M \simeq 5\mu$as times the black hole mass in units of $4\times10^6 M_\odot$. (From Broderick and Loeb (2006a).)

magnitude of the black hole spin and an isotropic prior on its direction, our best estimate of the probability density as a function of spin and inclination for the existing best estimates of the mass and distance to Sgr A* is shown in Fig. 4 (Broderick et al., 2008).

We have also used our simple RIAF model to predict which additional baselines would be most useful for improving these constraints (Fish et al., 2008). We expect these results to be quite generic among more sophisticated RIAF models since our estimates depend primarily upon the geometry and velocity structure of the accretion flow, which is a common feature of all such models.

3.3 Hot Spot Emission

The images of hot spots are shaped by a variety of factors, including strong gravitational lensing, the relativistic motion of the spot and the opacity of the underlying accretion flow. Figure 5 shows the a sequence of images throughout the orbital period of a single spot, with (top) and without (bottom) the interstellar electron scattering. Of primary interest is the relationship between the primary and secondary images, in which is encoded the null-geodesic structure of the intervening spacetime. That is, because the secondary image is produced by photons that passed closer and stayed longer near the black hole horizon, they are more affected by the black hole properties. Thus, using the primary image as a calibrator, careful study of the secondary image yields information about the spin and mass of the *spacetime* directly.

At the millimeter and sub-millimeter wavelengths currently proposed for the VLBI imaging of the Galac-

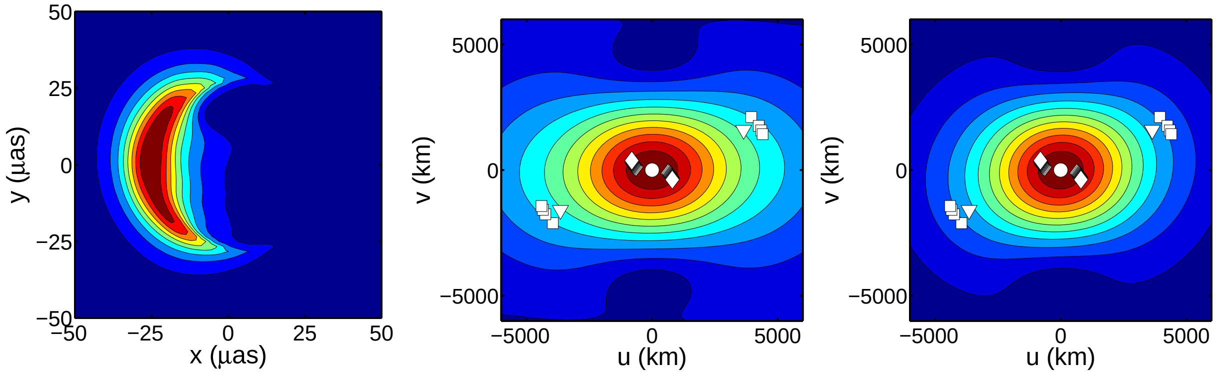

Figure 3: *Left:* An example image of the radiatively inefficient accretion flow around Sgr A* at 230 GHz, viewed at 60° from the black hole spin axis for a moderately rotating ($a = 0.5$) black hole. The image appears as a crescent due primarily to the Doppler beaming and shifting associated with the relativistic orbital velocities. The color-scheme is normalized such that red is bright, blue corresponds to vanishing intensity and the total flux from the image is 2.4 Jy. *Middle:* Visibility magnitudes associated with the image shown on top. For reference, the positions of the observations in the u–v plane are also show by the white points (the circle, diamonds, & squares correspond to the single-dish, SMTO-CARMA, & CARMA-JCMT detections, and the triangle corresponds to the JCMT-SMTO upper limit.) *Right:* Scatter broadened visibility magnitudes. Again the u–v positions of the VLBI observations are shown. (From Broderick et al., 2008).

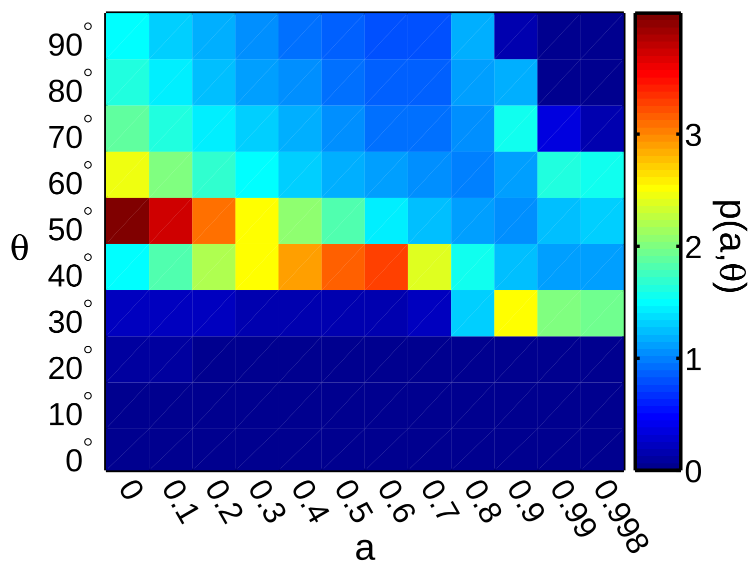

Figure 4: Probability density implied by recent millimeter VLBI detections of Sgr A* as a function of inclination and black hole spin. $p(a, \theta)$ is normalized such that the average is unity, providing a clear sense of the significance of the variations in probability. Generally, it appears that these observations strongly favor moderate inclinations and relatively low black hole spins. However, such statements are predicated upon the correctness of the RIAF model employed. (From Broderick et al., 2008)

tic center, the opacity of the underlying steady accretion flow has a significant effect upon the images and centroid motions. Nonetheless, it remains possible to extract the black hole mass and spin from these. Furthermore, combined with the NIR data (at which the accretion flow opacity is negligible) this provides a method by which the accretion flow may be isolated (Broderick and Loeb, 2006b).

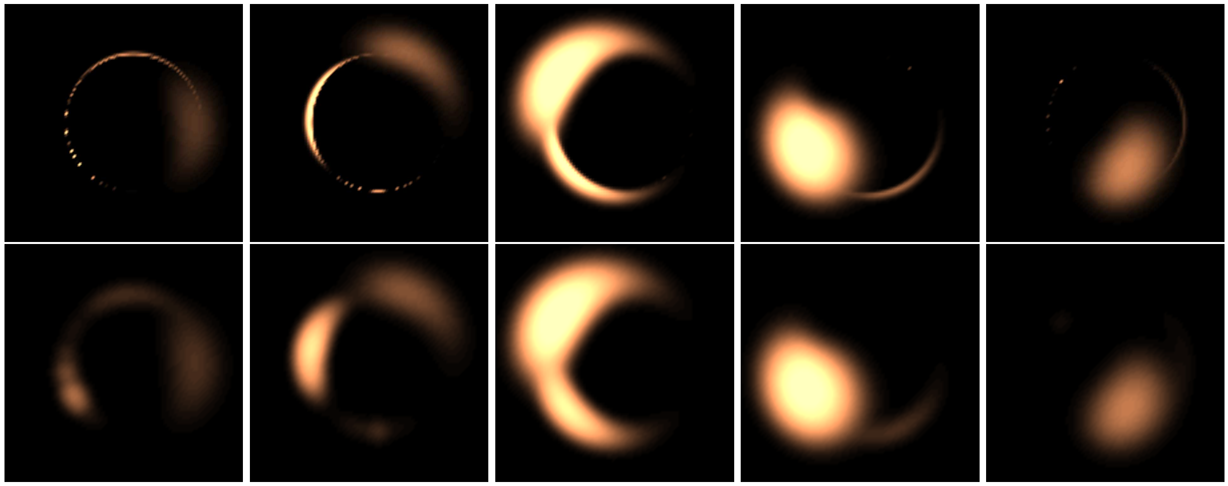

Figure 5: *Top:* Instantaneous theoretical images of a bright spot orbiting a moderately rotating black hole, viewed from 45° above the orbital plane. *Bottom:* The same images including the blurring effect of interstellar electrons. Note in particular the appearance of multiple images and the large variations in image brightness.

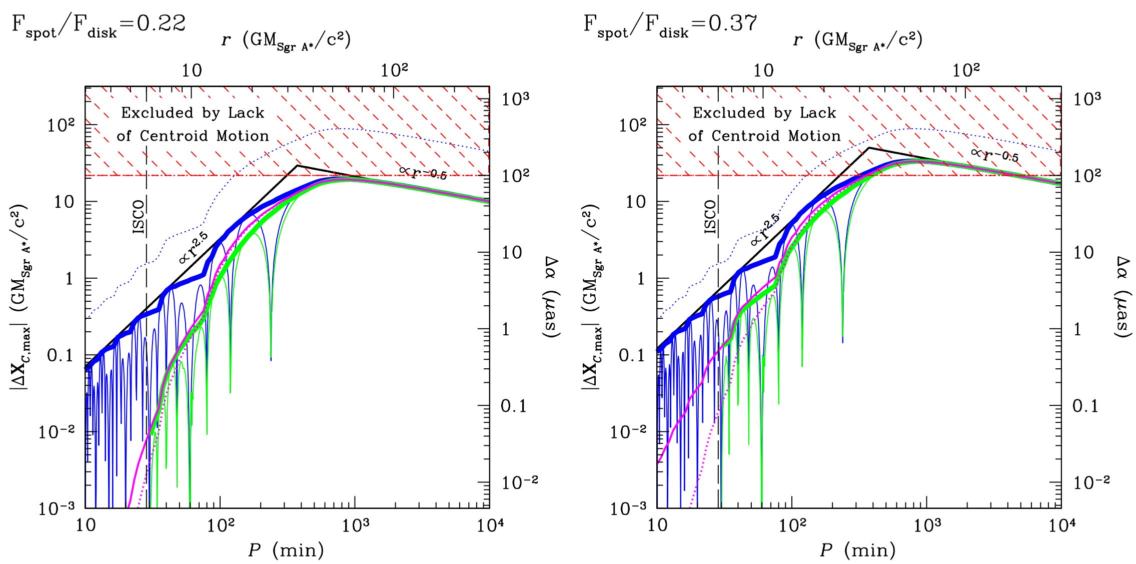

Figure 6: The centroid variations of Sgr A*as a function of flare period for a flare with a 7 mm amplitude variation of 22% (*left*) and 37% (*right*), as predicted by a simple Newtonian model (blue), detailed general-relativistic hot spot model (green), and that excluded by existing 7 mm observations (red, dashed region). A bright flare could be constrained by continued phase-referenced 7mm monitoring. (From Reid et al., 2008)

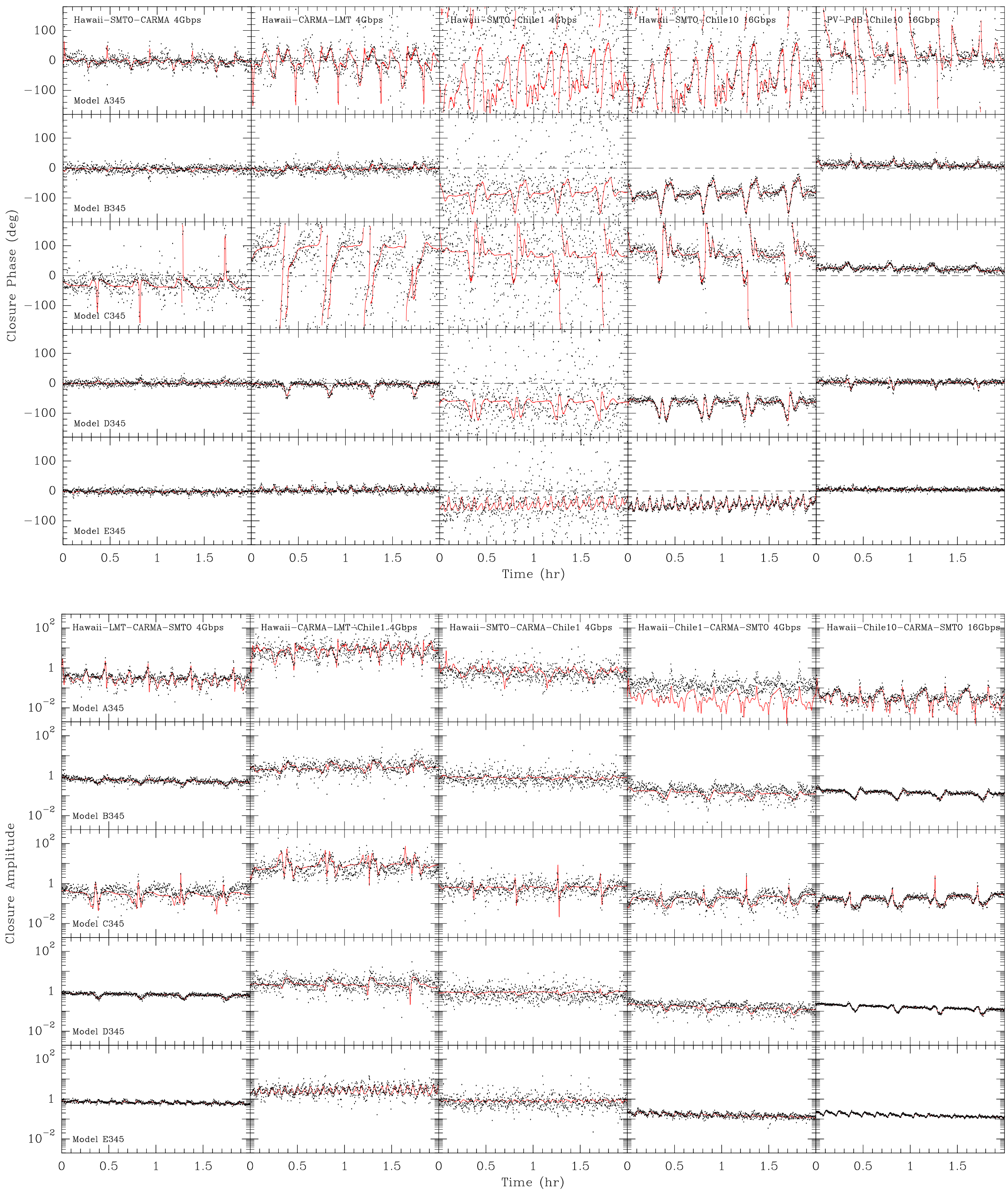

Figure 7: *Top:* The evolution of the closure phase for a number of different triangles of existing and upcoming telescopes and for a variety of orbital orientations and black hole spins. *Bottom:* The evolution of the closure amplitudes for a number of different quadrangles of existing and upcoming telescopes for the same models shown in the top panel. See Doeleman et al. (2008) for more detail on the modeling and analysis.

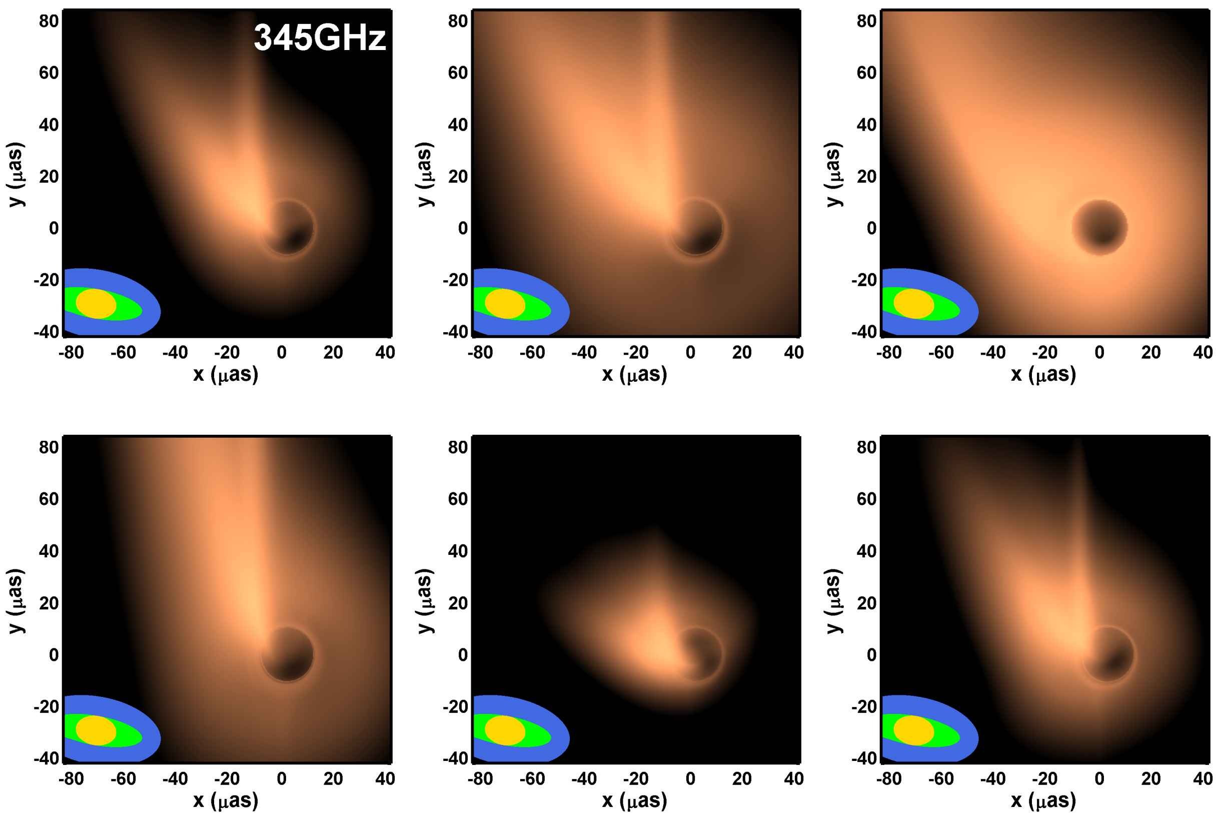

Figure 8: 0.87 mm images for a variety of possible M87 jets, corresponding to different spins, footprint sizes, orientations and collimation models. Clockwise from top-left, these correspond to the canonical model ($a = 0.998$, $\theta = 25°$, $r_{fp} = 10GM/c^2$ & $p = 1$), a fat jet ($r_{fp} = 20GM/c^2$), a non-rotating black hole ($a = 0$), an oblique jet ($\theta = 40°$), a nearly conical jet ($p = 0.75$) and a nearly cylindrical jet ($p = 1.25$). Model details are presented in Broderick and Loeb (2008).

Since interpreting Sgr A*'s flares as orbiting hot spots greatly simplifies efforts to separate the accretion physics from strong gravity physics, we have developed methods of observationally validating this model. These have thus far centered primarily upon looking for signatures of rapidly evolving asymmetry in the image of Sgr A*. At 7mm this can be done using high-precision phase-referenced centroid observations using the existing VLBA, originally obtained to measure the relative Galactic motion of Sgr A* (Reid et al., 2008). An example limit is shown in the right panel of Fig. 6. At shorter wavelengths this may be achieved with even very small arrays by analysis short-time variability in the closure phase and closure amplitude (Doeleman et al., 2008), which is sensitive to the changing symmetry of the source. This is seen in Figure 7, in which the short-timescale variability is indicative of the orbiting hot spot.

3.4 Imaging M87's Jet

Despite spanning an angular scale only half that of Sgr A*, M87 is a very interesting alternate target due to the presence of a powerful jet. High resolution imaging is poised to provide critical input into the existing widespread efforts to model the formation of the ultra-relativistic jets found in AGN. Outstanding questions include how rapidly to jet collimate, what is the size of the launching region, how important is black hole spin to the jet formation process and how rapidly does material acceleate along the jet. Each of these can be addressed by the mm and sub-mm imaging of M87. Figure 8 shows the 0.87 mm images for a variety of different values of these parameters for a jet capable of fitting M87's spectrum and the 7 mm image obtained by Junor et al. (1999).

Of particular importance for efforts to constrain the spin, the black hole silhouette is visible in all of these images. This implies that any variability in the underlying accretion flow or within the jet itself will also be easily seen. Note that in comparison to Sgr A*, the dynamical timescale of M87 is much larger, roughly 10 days, meaning that Earth aperture synthesis can easily be done in this source even when flares are present.

4 Proposed Work

We propose to refine and extend the investigations summarized in the previous section. Specifically, the improvements fall into four broad categories:

1. Improved and alternate accretion flow and outflow models,
2. Improved flare models,
3. Analyzing existing & upcoming millimeter VLBI observations and optimizing future observations for both Sgr A* and M87 separately,
4. Developing and assessing additional tools to separate aspects of GR from the astrophysics of the accretion flows, with the goal of testing GR in the strong field limit.

All of these items may be included in a straightforward manner within the computational framework we have already developed. The proposed work will define the PhD thesis of a Harvard University student, to be supervised by Loeb. The student will work closely with Broderick on incorporating the required new elements into a numerical code and producing numerically simulated images and lightcurves for comparison with existing and planned observations. Loeb, Broderick and the dedicated student will interact frequently with Shep Doeleman (Haystack) and his postdoc, Vincent Fish, in examining the implications of existing mm-VLBI observations and optimizing future ones.

4.1 Accretion Flow & Outflow Models

We have thus far considered only a single class of accretion models in which the magnetic field was added in an ad hoc manner. Proposed improvements include:

- Surveying state-of-the-art theoretical accretion models which satisfy all known observational constraints, focusing in particular on identifying generic signatures of the black hole spin.
- Employing results from existing fully relativistic, three-dimensional, magnetohydrodynamic simulations. In particular, we have access to the HARM code described in Gammie et al. (2003).

Similarly, we have only considered a simple, qualitatively correct jet model for M87. While this has a variety of advantages, a more detailed study of existing jet simulations is warranted. Proposed improvements include:

- Surveying state-of-the art jet formation simulations that are appropriate for M87. In particular, considering the variety of existing GRMHD jet-formation simulations in the literature, focusing upon constraining the fundamental jet-formation parameters.
- Studying the consequences of jet variability for imaging and understanding the jet structure. In particular, studying the effects of bright spots both in the accretion flow and outflow.

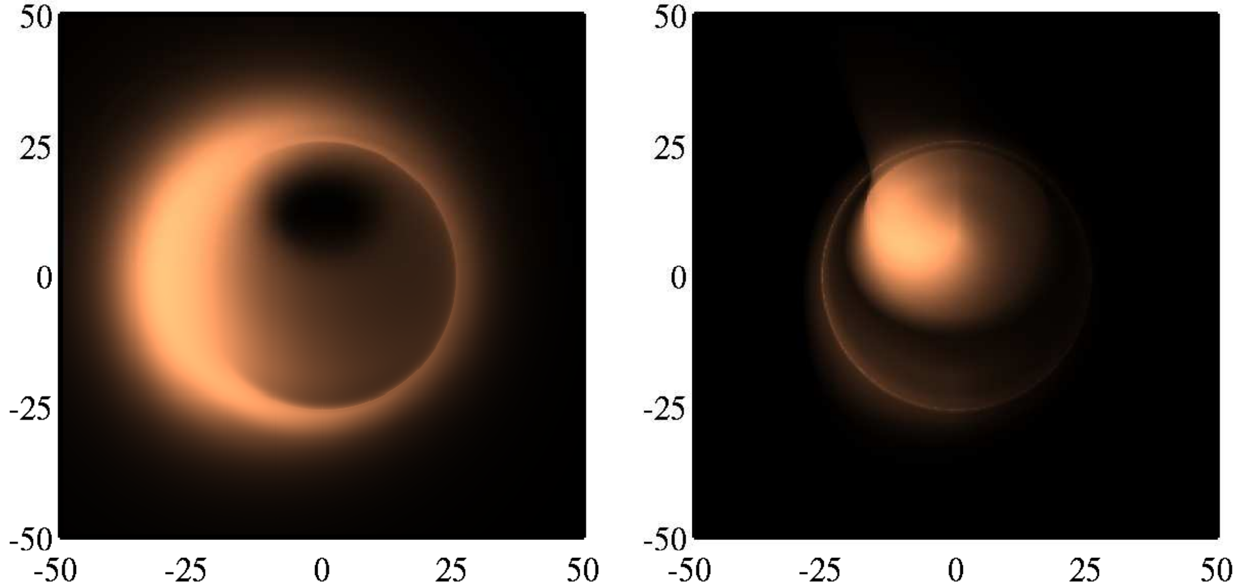

Figure 9: 345 GHz images for a RIAF (left), and a simple jet model (right, Falcke and Markoff (2000)) for the compact emission from Sgr A*. Both are viewed from 45° and show a region approximately 100 μas across.

- Identifying signatures of spin in the black hole silhouette and variability. Of particular importance is determining the relationship between the jet orientation and the black hole spin vector.
- Exploring the distinctions between radiatively-inefficient accretion flow models(Yuan et al., 2003) and jet models (Falcke and Markoff, 2000) for the emission of Sgr A*. At 20 μas resolution, these are clearly distinguishable, as apparent in Fig. 9.
- Finally, comparing and contrasting images of Sgr A* and M87 in an attempt to ascertain those elements critical to jet production and why they are absent (or if they are absent) in Sgr A*.

4.2 Flare Models

In addition to the underlying accretion flow, of additional significance is to find generic features of black hole spin in the lightcurves and images of the flaring emission. Thus, we propose to:

- Investigate the generic features of hot-spots in outflows, e.g., those associated with jets and/or trans-relativistic winds.
- Identify generic signatures of black hole spin for orbiting and outflowing models amongst the various underlying accretion disk models we propose to study in the previous subsection.
- Employ the results of existing fully relativistic, three-dimensional, magnetohydrodynamic simulations in which hot spots are produced self-consistently at shocks and reconnection sites. In particular, we plan to utilize the HARM code described in (Gammie et al., 2003).

4.3 Analyzing Existing and Optimizing Future VLBI Observations

Already, we have begun to use our simple accretion flow and jet models to specify which combinations of existing telescopes are optimal for constraining the properties of Sgr A* and M87. This has taken the form of using our models to produce synthetic data for simulated VLBI experiments, and comparing against existing data sets as they become available. This remains to be done for the more advanced models described in §4.1. Of particular interest is whether or not those models make qualitatively different predictions for the optimal arrays.

Additional mm-VLBI observations will be performed over the next decade, with increasing sensitivity and more complete baseline coverage. Despite this, we will be faced with interpreting sparse data sets (as in Broderick et al., 2008). Applying our theoretical modeling will be critical to analyzing the implications for fundamental black hole and astrophysical properties of these systems. This will require considering a large suite of models, such as those described in §4.1, with a standardized set of tools.

Thus, we propose to

- Study the optimal mm and sub-mm VLBI arrays for constraining accretion flow and jet formation parameters from Sgr A* and M87. Including the study of the black hole silhouette and signatures of variability around the black hole.

- Develop tools, including software, to systematically constrain these different parameters given the sparse data sets we expect from mm and sub-mm VLBI experiments in the near future. Such parameters would include black hole spin, disk inclination, orientation, jet footprint, jet collimation rate, etc.

- Compare the systematic uncertainties introduced by the variety of existing accretion flow models and jet models. In particular, ascertain how significant these are to attempts to discern the underlying accretion/jet-formation physics.

- Develop tools to separate aspects of GR from the astrophysics of the accretion flow and jet formation, with the goal of providing methods to test GR in the strong field limit.

4.4 Testing Modified Theories of Gravity

Our implementation is unique in that it allows us to image plasma distributions in any geometric theory of gravity. In particular, we are not limited to only studying general relativistic spacetimes, or even only stationary, axisymmetric spacetimes. As such, we are in a position to begin to not only asses the ability of high-resolution imaging to provide internal consistency checks of GR, but determine how sensitive such imaging is to deviations from GR.

Unfortunately, unlike weak gravity, which admits the Parametrized Post-Newtonian framework, there is no general framework in which to consider deviations in the strong-field limit. Nevertheless, we can asses the ability of images to constrain the existence of anomalous high-order multipoles in the spacetime curvature. A controlled formalism for doing this has been developed by Collins and Hughes (2004), the so-called “bumpy black holes”. In practice, this is determining the ability of images to directly test the no-hair theorems of classical GR.

5 Summary: Significance of proposed work NSF

5.1 Intellectual Merit

The development of the capability to perform millimeter and sub-millimeter Earth-scale interferometric observations has made it possible for the first time to directly image a black hole (Sgr A* & M87) with sufficient resolution to notice structure on the scale of the horizon (Doeleman et al., 2008). This advance will make possible the detailed study of accretion and emission physics in strongly gravitating environments, and even of the nature of strong gravity itself. As has been demonstrated in (Broderick and Loeb, 2006a, 2005, 2006b), direct imaging in conjunction with spectropolarimetric and variability measurements provide methods by which Sgr A*'s mass and spin can be measured and the properties of the of its accretion flow can be studied at horizon scales. These studies have shown that multiple flare observations may be used to probe the spacetime at a variety of radii, thus providing a method to directly test of the Kerr metric specifically, and the characteristics strong gravity generally. Recent polarization measurements at near-infrared (Eckart et al., 2006) and sub-millimeter (Marrone et al., 2006) wavelengths, are consistent with the polarized light curves predicted by Broderick and Loeb (2005, 2006b) for a hot spot at the innermost stable circular orbit, and thus suggests that significant observational constraints upon models for the variability will exist in the near future.

5.2 Broader Impacts

This work is critical to efforts to take full advantage of recent millimeter VLBI observations, and expected to help motivate additional, more comprehensive millimeter and sub-millimeter VLBI experiments. It is also expected to motivate interferometric experiments at infrared wavelengths (GRAVITY).

Observational input obtained by careful modeling of these observations will play a critical role in calibrating and validating the large class of GRMHD black-hole accretion and jet-formation computations. At this time this is especially important given the expense in time and resources that such calculations require.

In addition, the method for testing strong gravity proposed here is complimentary to current and planned gravitational wave detectors (e.g., *LIGO* and *LISA*), and probes an entirely different class of black holes than observations of broad iron-lines. Direct tests of strong field general relativity have immediate implications for a number of fields in high-energy astrophysics, including current models of neutron stars, X-ray binaries, gamma-ray bursts, and active galactic nuclei, black hole outflows and feedback on galaxy formation. In addition, tests of strong field gravity, and especially observational constraints upon the existence of black hole horizons, will impact the search for unified theories, such as superstring theories. Testing general relativity with high-resolution imaging will provide a historic and easily accessible visual for generating public interest in black holes specifically, and the physical sciences more generally. Black holes are known to attract much interest from the general public. We intend to distribute our images of black hole silhouettes to the general public through popular-level articles and movies that would be provided freely to museums and the popular media. Broderick & Loeb are currently completing a Scientific American article, entitled "Imaging Black Holes".

Finally, we note that advances in radio imaging technology will likely have spin-offs with possible practical applications to both the civil and the defence industry.

6 Supporting Documentation

Our proposed theoretical investigations are directly relevant to current experimental work aimed at building instruments of sufficient angular resolution and sensitivity to image the accretion environments of Sgr A* and M87. As an example, we have attached a letter of support from MIT's Haystack Observatory, describing a program to develop new instrumental capabilities for high frequency (sub-mm) VLBI, and the impact our proposed research would have upon the optimization of the design and analysis of forthcoming experiments.

7 Results from Prior NSF Support

Past activity of the PI has been supported by the following NSF grants:
(i) **Evolution of Structure in the Universe from** $z = 30$ **to** $z = 3$ *(AST-0071019; ended in April 2004)*
(ii) **Observable Signatures of Reionization** *(AST-0204514; ended in August 2005)*

Results from these projects were summarized in 85 papers that were written by the PI and his colleagues over the past four years. Among these, are four major review papers on reionization (published in *Annual Reviews of Astronomy & Astrophysics*, *Reports on Progress in Physics*, *Physics Reports* and to appear in a forthcoming book by Springer for the 2006 SAAS-Fee winter school), and 6 papers by the PI were published in Nature (with 3 News & Views articles commenting on their significance). Some of the results derived in these papers were summarized as background material throughout this proposal. A complete list of all relevant publications can be found at http://cfa-www.harvard.edu/∼loeb/

The PI has supervised four graduate students on the topics covered by these two proposals (Dan Babich, Pinaki Chatterjee, Loren Hoffman, and Steve Furlanetto).

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BUDGET JUSTIFICATION

We are requesting support for scientific computing and graphics workstation. This is typically comprised of a high-performance multi-processor system with significant storage capacities (on the order of many Tb). This will be essential for performing the simulations and visualization tasks required by this proposal. The grant will primarily support a Harvard graduate student, whose PhD thesis will be dedicated to the proposed research. We allocate $10k for extended (1-2 months long) visits of Dr. Avery Broderick to Harvard. We also request two months of summer salary for Prof. Loeb to work on the proposed research. No funding from other sources are available to the PI. Finally, the budget allocates funds for page charges of related papers based on the typical expenses encountered by the PI/co-I over the past year.

Note that the overhead is 64% and the Fringe benefits for faculty are 27% for all 3 years. By Harvard's regulations, overhead does not apply to computer hardware greater than $5000.