Relativity in Fundamental Astronomy
Proceedings IAU Symposium No. 261, 2009
S. A. Klioner, P. K. Seidelman & M. H. Soffel, eds.

doi:10.1017/S1743921309990500

Observing a black hole event horizon: (sub)millimeter VLBI of Sgr A*

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Abstract. Very strong evidence suggests that Sagittarius A*, a compact radio source at the center of the Milky Way, marks the position of a super massive black hole. The proximity of Sgr A* in combination with its mass makes its apparent event horizon the largest of any black hole candidate in the universe and presents us with a unique opportunity to observe strong-field GR effects. Recent millimeter very long baseline interferometric observations of Sgr A* have demonstrated the existence of structures on scales comparable to the Schwarzschild radius. These observations already provide strong evidence in support of the existence of an event horizon. (Sub)Millimeter VLBI observations in the near future will combine the angular resolution necessary to identify the overall morphology of quiescent emission, such as an accretion disk or outflow, with a fine enough time resolution to detect possible periodicity in the variable component of emission. In the next few years, it may be possible to identify the spin of the black hole in Sgr A*, either by detecting the periodic signature of hot spots at the innermost stable circular orbit or parameter estimation in models of the quiescent emission. Longer term, a (sub)millimeter VLBI "Event Horizon Telescope" will be able to produce images of the Galactic center emission to the see the silhouette predicted by general relativistic lensing. These techniques are also applicable to the black hole in M87, where black hole spin may be key to understanding the jet-launching region.

Keywords. black hole physics, accretion, accretion disks, Galaxy: center, submillimeter, techniques: interferometric, techniques: high angular resolution

1. Introduction

The Galactic center radio source Sagittarius A* is believed to host a massive ($\sim$4 $\times$ 10^6 $M_{\rm sun}$) black hole. Due to its proximity at $\sim$8 kpc (e.g., Reid 2008), Sgr A* has the largest apparent event horizon of any known black hole candidate: $r_{\rm Sch} = 2r_{\rm G} \approx 10$ μas.

There is active debate in the scientific community on whether the emission from Sgr A* is predominantly due to an accretion disk or a jet. Further data are necessary in order to disentangle the accretion/outflow physics from general relativistic effects.

There are several reasons to observe Sgr A* at millimeter wavelengths. The spectrum of Sgr A* peaks in the millimeter. Interstellar scattering, which varies as λ^2, dominates over intrinsic source structure at longer wavelengths, and the emission from Sgr A* transitions from optically thick to optically thin near $\lambda = 1$ mm (Doeleman *et al.* 2001). Finally, millimeter wavelengths permit observations by the technique of very long baseline interferometry (VLBI). The spatial scales accessible to millimeter VLBI range down to a few $r_{\rm G}$, providing angular resolution currently unachievable by any other means.

Recent VLBI observations by Doeleman *et al.* (2008) were successful in detecting Sgr A* on the long baseline between the James Clerk Maxwell Telescope (JCMT) in Hawai'i and the Arizona Radio Observatory's Submillimeter Telescope (SMT). Combining this result with a shorter-baseline detection from the SMT to the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California, Doeleman *et al.* were able to place a size limit of 37 μas on the emission if its distribution is a circular Gaussian. They conclude that the emission must be partially optically thin and offset from the center of Sgr A*, since an optically thick sphere centered on the black hole would be lensed to a larger size.

With only detections on two baselines, the data are insufficient to distinguish between other models such as a "doughnut" of emission as might be expected from a face-on accretion disk. In actuality, the structure of the emission from Sgr A* is likely to be much more complicated due to the inclination of the system and general relativistic effects, such as Doppler boosting of approaching emission and weakening of emission from in front of the black hole due to gravitational redshift. It is this complexity of source structure that drives the need for more data. The eventual goal is to produce an image of the quiescent emission in Sgr A*, from which many physical parameters (such as the spin of the black hole) can be derived. In the nearer term, nonimaging methods of data analysis can be used to produce scientific output from millimeter VLBI observations.

2. Parameter Estimation

The Doeleman *et al.* (2008) detections measure correlated flux densities on certain spatial scales and orientations, which can be used to constrain parameters in ensembles of models. For instance, Broderick *et al.* (2009) generate an ensemble of radiatively inefficient accretion flow (RIAF) models of disk emission from Sgr A* meeting certain prior constraints (such as the multiwavelength spectrum of emission from Sgr A*) and then use the Doeleman *et al.* (2008) detections to estimate probable values of the black hole spin, inclination of the spin axis, and orientation of the accretion disk on the plane of the sky. Within the RIAF ensemble, it is found that low-inclination (i.e., nearly face-on) models are strongly disfavored. Prospects are excellent for observations in the near future, which are likely to include a telescope in Chile, to be able to place strong constraints on the orientation of the disk within the RIAF context (Fish *et al.* 2009). As additional telescopes are added to the millimeter VLBI observing array, the constraints provided by the detections may be able to obtain a value for the black hole spin even before a high-quality image can be created.

It will be necessary to distinguish amongst different models of the mechanism of emission from Sgr A* (e.g., jets, fully general relativistic magnetohydrodynamic simulations, etc.), both in order to understand the accretion/outflow physics in general and because each model will have different particular predictions for parameter values such as the black hole spin. Thus, there is a need for similar analyses to be carried out in order to interpret present and future millimeter VLBI results.

3. Imaging with an Event Horizon Telescope

As additional telescopes are added to the millimeter VLBI array, it will become possible to produce an image of the emission from Sgr A*. Current observations have used the SMT, CARMA dishes, and a phased array of the JCMT, Caltech Submillimeter Observatory, and Submillimeter Array dishes on Mauna Kea. In the near future, it may be possible to extend this array by including the Atacama Submillimeter Telescope Experiment (ASTE) or Atacama Pathfinder Experiment (APEX) in Chile, the Large Millimeter Telescope (LMT) under construction in Mexico, the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope at Pico Veleta in Spain, and the IRAM Plateau de Bure interferometer in France.

https://doi.org/10.1017/S1743921309990500 Published online by Cambridge University Press

With upgrades to some of these telescopes (§5), it will be possible to produce an image that shows the general morphology of the emission from Sgr A* (Figure 1), possibly including the "shadow" of the black hole (e.g., Falcke *et al.* 2000). Unfortunately, image fidelity will be limited by the placement of these telescopes. Effectively, VLBI baselines are sensitive to the Fourier transform of the sky emission, where the Fourier components are parameterized by u and v, the projected baseline lengths (in wavelengths) as viewed from Sgr A*. Longer baselines provide higher angular resolution. As the Earth rotates, the projected baselines sweep out arcs in the (u, v) plane, allowing an image to be produced by an inverse Fourier transform and deconvolution. However, the lack of intermediate-spacings in some directions means that large parts of the (u, v) plane are unsampled. Reconstructing a high-fidelity, model-independent image of Sgr A* will require the addition of a few telescopes to fill in these holes in the (u, v) plane. Several existing telescopes, such as the South Pole Telescope, the Haystack 37 m in Massachusetts, and the Swedish-ESO Submillimeter Telescope in Chile, could be upgraded for use in a millimeter VLBI array. It may also be desirable to place additional telescopes in geographically favorable locations such as South Africa, Kenya, and New Zealand (Figure 2). Expanding the millimeter VLBI array by upgrading existing telescopes and adding a few new ones would allow very high quality imaging of Sgr A*.

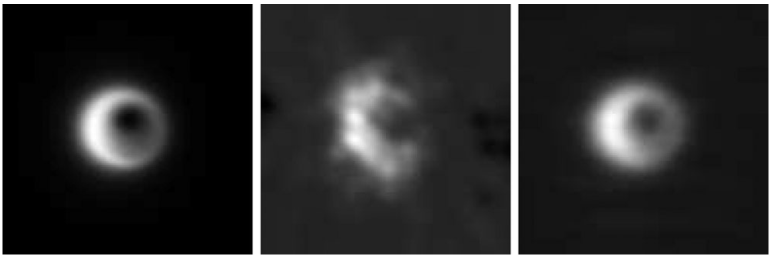

Figure 1. *Left:* Model of RIAF emission (345 GHz, $a = 0$, $i = 30°$), courtesy A. Broderick. *Center:* Simulated image from 7-telescope array of the near future. The black hole shadow is easily detected. *Right:* Simulated image from the 13-telescope array described in the text.

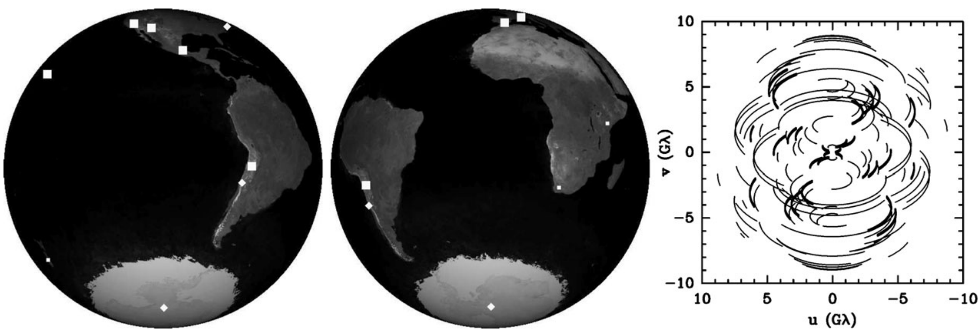

Figure 2. *Left two panels:* Current and future millimeter VLBI arrays. Large squares show telescopes that exist or are under construction. Medium diamonds show existing telescopes that could be refitted for VLBI. Small squares show other potential sites. *Right:* The (u, v) coverage produced by these arrays at 230 GHz. The bold curves show the coverage obtainable from the 7-telescope array described in the text. The curves in normal weight show the additional coverage that would be provided by the 13-station Event Horizon Telescope. High-fidelity imaging requires minimizing the gaps in (u, v) coverage.

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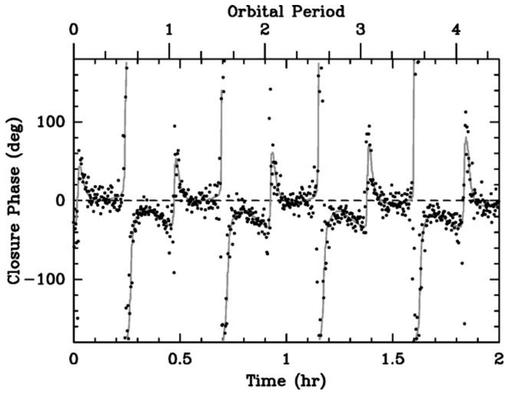

Figure 3. Simulated 230 GHz closure phases of a hot spot orbiting at the ISCO embedded in a quiescent RIAF disk ($a = 0, i = 30°$). The grey curve shows the model values for an array consisting of phased Mauna Kea (JCMT + CSO + 6 SMA dishes), phased CARMA (8 dishes), and the SMT. Black points represent simulated 10 second integrations at 8 Gbit s^{-1}.

4. Tracking Flaring Structures in Real Time with VLBI

While very high angular resolution millimeter imaging awaits the availability of additional VLBI telescopes, millimeter VLBI visibilities are already producing useful science. Indeed, the scientific implications of the Doeleman *et al.* (2008) detection stem from measuring the visibility amplitude on the JCMT-SMT baseline, which is a measure of the correlated flux density on small spatial scales. As Sgr A* is detected with larger arrays, it will also be possible to produce closure quantities, good observables that are very sensitive to the source structure of Sgr A* but independent of most calibration errors. The closure phase $\phi_{123} = \phi_{12} + \phi_{23} + \phi_{31}$, the sum of visibility phases around a closed triangle of three antennas, is robust against most phase errors, especially those caused by a variable troposphere. A nonzero closure phase implies source structure asymmetry. Similarly, a closure amplitude $A_{1234} = |A_{12}||A_{34}|/(|A_{13}||A_{24}|)$, the ratio of visibility amplitudes at 4 telescopes, is robust against systematic gain calibration errors. The number of independent closure quantities grows quickly with the number of antennas in an array.

The frequent flaring of Sgr A* implies that its source structure changes rapidly. Simulations by Doeleman *et al.* (2009) show that the sensitivity of VLBI combined with a time resolution much shorter than the natural orbit period make it very likely that time-variable structures during flares can be detected over the course of a single night of observing. Within the next few years, millimeter VLBI will have the sensitivity to probe r_{Sch}-scale structural changes on time scales of 10 seconds (Figure 3). This time resolution will be critical for detecting source structure periodicity, as might be expected in orbiting hot spot models (Broderick & Loeb 2005). Rapid periodicity may provide strong evidence that the black hole in Sgr A* has spin, since the period of the innermost stable circular orbit (ISCO) decreases rapidly with increasing spin. Depending on the spin of the black hole, the ISCO period may be as long as nearly half an hour or as short as approximately 4 minutes.

5. Future Enhancements

Several technological advancements are currently in progress to increase the sensitivity of the millimeter VLBI array. A phased array processor to sum the collecting

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area on Mauna Kea (Weintroub 2008) has been tested. Similar hardware could be used to increase sensitivity at CARMA, Plateau de Bure, and the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. Digital backends (DBEs) have been developed to process 1 GHz of data (4 Gbit s^{-1} with 2-bit Nyquist sampling), and next-generation DBEs will improve upon this by a factor of four. Mark 5B+ recorders can already record 2 Gbit s^{-1} data streams (presently requiring two at each site per DBE), and the Mark 5C recorders currently being developed will be able to handle even faster data rates. Cryogenic sapphire oscillators are being examined as a possible frequency standard to supplement or replace hydrogen masers to provide greater phase stability, which may improve coherence at higher frequencies.

Future observations will initially focus on improving sensitivity by observing a wider bandwidth and using phased array processors. Dual polarization observations will become a priority not only for the $\sqrt{2}$ improvement in sensitivity for total-power observations but also to allow full polarimetric VLBI of Sgr A*. Higher frequency observations, such as in the 345 GHz atmospheric window, will provide even greater spatial resolution in a frequency regime where interstellar scattering and optical depth effects are minimized.

The timing is right to move forward on building an Event Horizon Telescope to produce high-fidelity images of Sgr A* as well as other scientifically compelling sources, such as M87. Receivers currently being produced en masse for ALMA could be procured for other millimeter VLBI stations, in many cases providing substantial improvements in sensitivity. Studies of climate and weather will be necessary to provide information on the astronomical suitability of prospective sites for future telescopes, such as those at the present ALMA Test Facility or additional telescopes constructed specifically for millimeter VLBI (which would mesh well with present ALMA construction). Some existing telescopes will require improvements to their systems, such as increasing the bandwidth of the intermediate frequency signal after mixing. It will also be highly desirable to install permanent VLBI hardware at all sites to allow turnkey VLBI observing in order to maximize the efficiency of VLBI observations in terms of personnel time and transportation costs.

6. Conclusions

Millimeter VLBI offers an unparalleled ability to probe the emission from Sgr A* at angular scales of a few $r_{\rm G}$ and on timescales of a few seconds. Current 1.3 mm VLBI observations have established that the millimeter emission emanates from a compact region offset from the center of the black hole. These data are already being used to constrain key physical parameters (e.g., spin, inclination, orientation) in models of the emission (e.g., RIAF models). Future additions to the VLBI array would allow the millimeter emission to be imaged directly. In the meantime, closure quantity analysis may allow the spin of the black hole to be inferred from source structure periodicity. The technical advancements necessary to realize these goals are already in progress.

Acknowledgements

VLBI work at MIT Haystack Observatory is supported through grants from the National Science Foundation. VLBI at (sub)millimeter wavelengths is made possible through broad international collaborative efforts and the support of staff and scientists at all participating facilities.

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