Shedding Light on Darkness: **Imaging Black Hole Silhouettes**

Avery E. Broderick & Abraham Loeb

There is a famous TV commercial in which a cell phone technician travels to remote places and asks on his phone: “can you hear me now?”. Imagine this technician traveling to the center of our Milky Way galaxy and approaching the massive black hole there, Sagittarius A* (Sgr A*), which weights as much as four million Suns. As the technician will get within a distance of ten million kilometers from the black hole, his cadence would begin to slow and his voice would deepen and fade, eventually turning to a monotone whisper with diminishing reception. If we were to look, we would see him frozen in time, his image increasingly red and fading as he hovers around the so-called event horizon of the black hole. The horizon is the boundary of the region from where we can never hear back the technician, because even light cannot escape from the strong pull of gravity over there. The first indication the technician will have that he has passed the horizon is hearing us saying “no, we can’t hear you well!”, but he will have only a short while to lament his fate before being torn apart by tidal gravitational forces near the central singularity. But he will have no way of sharing his last impressions from his journey with us. In real life we have not yet sent a technician on such a journey, but astronomers have developed techniques that allow them, for the first time in history, to probe the immediate vicinity of a black hole.

In 1783 reverend Jon Michell, a part time astronomer, realized that were he to take Newton’s new theory of gravity seriously, a sufficiently massive and compact object must have an escape velocity that exceeds the speed of light. Should light gravitate it could never escape, and this “dark star” would be forever hidden from view, revealing itself only through its gravitational tugs on nearby visible stars. Today, what we call “black holes” are essentially the modern kin of Michell’s dark stars, but they carry an important qualitative distinction. The modern view was shaped by Einstein, who developed the *General Theory of Relativity* to describe gravity as a curvature of space and time. In Einstein’s theory, nothing can move faster than light. Thus, unlike Michell’s dark stars, from which escape is possible with a sufficiently fast ship, black holes represent the ultimate prisons: you can check in, but you

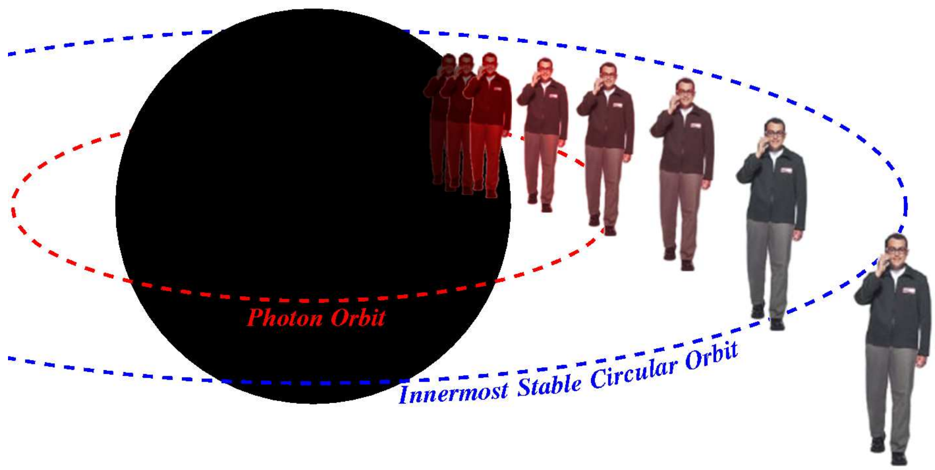

Figure 1: Our intrepid technician begins his exploration of a black hole space-time outside of the *Innermost Stable Circular Orbit* (ISCO). Once he crosses the ISCO, the surrounding material will no longer orbit around the black hole, but rather plunge towards it on ballistic trajectories. More notable to our technician will be the *Photon Orbit*, the radius at which his cell phone signal will execute closed orbits around the black hole and the technician will receive his own signal. Once inside, more than half of his outgoing phone signal will be lensed back to him. As he approaches the event horizon, his distant image will appear to freeze, redden and fade away, hovering over the horizon. From his perspective the only event of note as he passes the horizon will be us telling him that we can no longer hear him.

can never check out. This is guaranteed by the causal structure of space-time in the black hole's vicinity, with the "event horizon", denoting the boundary of the compact region from where no signal can reach the outside universe.

If you find the idea of horizons shocking, you are not alone. Einstein himself felt they were an unphysical solution to his equations, one that Nature must somehow conspire to forbid. More disturbing, horizons represent the primary sticking point in unifying the two great triumphs of 20th century physics, Quantum Mechanics and General Relativity. In the former, time-reversibility is an essential ingredient, i.e., all quantum processes have an inverse process, and thus in principle information is never lost. In the latter, this is manifestly impossible, i.e., there is no inverse process to falling into a black hole! This results in the often debated "Information Paradox", the need for a solution to which has been one of the primary motivations of *string theory*.

Despite their fantastic yet dark nature, black holes do appear to exist. Ironically, black hole environments are the brightest objects in the universe. Of course, it is not the black hole that is shining, but rather the surrounding gas that heats up by viscosity as it rubs against itself and shines as it spirals into the black hole, never to be seen again. The source of the radiated energy is the release of gravitational binding energy as the gas falls into the deep gravitational potential well of the black hole. As much as tens of percent of the mass of the accreting material can be converted into heat (more than an order of magnitude beyond the maximum efficiency of nuclear fusion!). Black holes appear to come in two flavors: stellar-mass black holes that form when massive stars die, and are observed as they accrete matter from a companion star in X-ray binaries, and the monstrous super-massive black holes that sit at the center of galaxies, reaching masses of up to 10 billion Suns. The latter type are observed as Quasars and Active Galactic Nuclei (AGN). It is by studying these accreting black holes that all of our observational knowledge of black holes has been obtained.

Although practically invisible, naked astrophysical black holes are extremely simple, being defined solely in terms of their mass and rotational spin. Complications arise when the black holes get dressed with accreting material. If this material is organized into a thin accretion disk, where the gas can efficiently radiate its released binding energy, then its theoretical modeling is straightforward. Less well understood are Radiatively Inefficient Accretion Flows (RIAFs), in which the inflowing gas obtains a thick geometry.

Hunting the Behemoth

Direct observations of the gas in the vicinity of a black hole are desparately needed to properly inform theoretical modeling. Unfortunately, such data is difficult to come by for a number of reasons. Black holes are extremely small by any astrometric measure; a black hole with the mass of our Sun would exhibit a city-size horizon of only 6 kilometers in diameter! Even the most massive black holes would fit within Jupiter's orbit about the Sun, and are located at a distance many thousands of times further than the scale of the Milky Way galaxy. The small size results in a correspondingly short dynamical timescales near the horizon, as short as microseconds for stellar mass black holes, requiring highly sensitive instruments to detect and observe the black hole's accretion flow before it changes. Of course, the biggest difficulty is that only the small subset of black holes that have large reservoirs of nearby gas to accrete are visible at all. For this reason the vast majority of black holes in the Milky Way are, as yet, undiscovered.

Rising to the challenge, astronomers have developed a variety of indirect techniques to probe black hole environments. Perhaps the most familiar method uses the orbits of stars near the black hole. In a similar way that astronomers weigh the Sun using the orbits of its planets, it is possible to weigh black holes using the orbits of stars in their vicinity. In distant galaxies, individual stars cannot be distinguished, and a measurement of their average velocity spread must be used. However, at the center of the Milky Way, it is possible to resolve individual stars using the largest (8-10 meter) telescopes on Earth, such as the Keck telescope in Hawaii and the Very Large Telescope in Chile. The closest star passes within a distance from the black hole of merely 45 times larger the Earth-Sun distance. Unfortunately, this still corresponds to a thousand times the size of the horizon.

Alternatively, astronomers search for signatures of general relativity in the time-variability of the radiation emitted by black hole environments. For example, Quasi-Periodic Oscillations (QPOs) are observed in the X-ray luminosity of some stellar mass black holes. Typically, these oscillations are at kilohertz frequencies and can persist for hundreds, if not thousands, of periods before finally being damped. While a single, satisfactory model for how such oscillations are produced has not yet been discovered, the high frequency of QPOs argue strongly for some connection to the orbital timescales of the gas near the inner edge of the accretion disk around the black hole. Such a disk is believed to be terminated at an inner radius where General

Relativistic orbital motion becomes unstable, the so-called Innermost Stable Circular Orbit (ISCO). Inside of the ISCO gas is inevitably plunges into the black hole over timescales short even compared to a single orbital period. The presence in a few black hole systems of more than one QPO, generally with a 2:3 ratio in their frequencies, inspired researchers to fit them with epicyclic models in which the QPOs are associated with different orbital periods or resonances among them. Alternative models employ disk-seismology, in which the oscillation modes of the disk are used to drive the QPOs. The lack of a unique theoretical interpretation, however, weakens the use of this observational tool for studying the vicinity of black hole horizons.

A variable luminosity is also a characteristic of massive black holes, the best studied of which is at the center of our galaxy, Sgr A*. A number of observations at radio, infrared and X-ray wavelengths have shown frequent oscillations in the brightness of Sgr A* over timescales commensurate with the orbital period near its ISCO. In one data set, as many as seven periods were observed, providing tantalizing evidence for the flaring emission's origin: orbiting bright spots in the accreting gas. Presumably, these spots could be generated by mechanisms similar to those that cause solar flares; namely, the entanglement and resulting reconnection of magnetic field lines, which transform turbulent energy from the bulk motion of the gas to energetic electrons that rapidly cool by emitting the observed radiation.

Thus far, the most fruitful avenue for probing massive black holes has utilized the fluorescence of iron atoms on the surface of the accretion disk. When a surrounding hot corona illuminates the disk surface, an energetic X-ray photon kicks an electron out of its most bound (K-shell) orbit and produces a characteristic emission line when another electron from the second most bound orbit (L-shell) replaces it. The shape of the fluorescence line is broadened and shifted by the motion of the gas (through the so-called Doppler effect) as well as by the gravitational redshift due to the strong gravity of the black hole. The spectral line obtains a characteristically asymmetric shape in the vicinity of rapidly spinning black holes. Thus, when an asymmetric broad iron line was observed by the ASCA satellite in MCG-6-30-15, a 3-4 million solar mass black hole located 120 million light-years away, it was immediately interpreted as direct evidence for a rapidly rotating black hole. Since that time the Japanese Suzaku satellite has found a number of asymmetric, broad iron fluorescence lines in other AGN.

Careful analysis of the X-ray spectra from stellar binary systems, where the black hole slowly feeds upon an ordinary stellar companion, has produced the first reliable assessments of spin for low-mass black holes. Here one essentially measures the area of the accretion disk A by comparing the total luminosity L to that predicted via the Stefan-Boltzmann (black-body) law, $L = A\sigma T^4$, for the temperature T determined by the fitting the X-ray spectrum. In practice, this involves detailed disk modeling, precise measurements of the binary orbital parameters (most importantly inclination) and very high signal-to-noise observations while the binary is in the so-called thermal state, during which it can very accurately be described by thin-disk models. This technique has yielded a handful of spin measurements for stellar-mass black holes, ranging from 65% to 100% of the maximum possible spin value.

When two black holes collide, they shake the fabric of space-time around them, producing "gravitational waves". Similar to the waves excited by a bouncing rock on the surface of a pond, these ripples of space-time propagate away from their source and can be detected at vast distances. They offer a fundamentally new way to observe the universe and promise to revolutionize astronomy and black hole science. The *Laser Interferometer Gravitational-wave Observatory* (LIGO), consisting of a pair of 4-kilometer interferometers on opposite sides of the US, is already operating at design efficiency and is sensitive to mergers of stellar-mass black holes. Similar observatories are planned and constructed around the globe, including VIRGO, GEO, & TAMA. In the more distant future, there are plans to build a space-based observatory, the *Laser Interferometer Space Antennae* (LISA), that will be sensitive to super-massive black holes. Should LISA observe a stellar mass black hole falling into a supermassive black hole, it would be possible to map out the structure of space-time with exquisite precision. This would allow a direct test of general relativity itself in the regime where it deviates most substantially from Newtonian gravity.

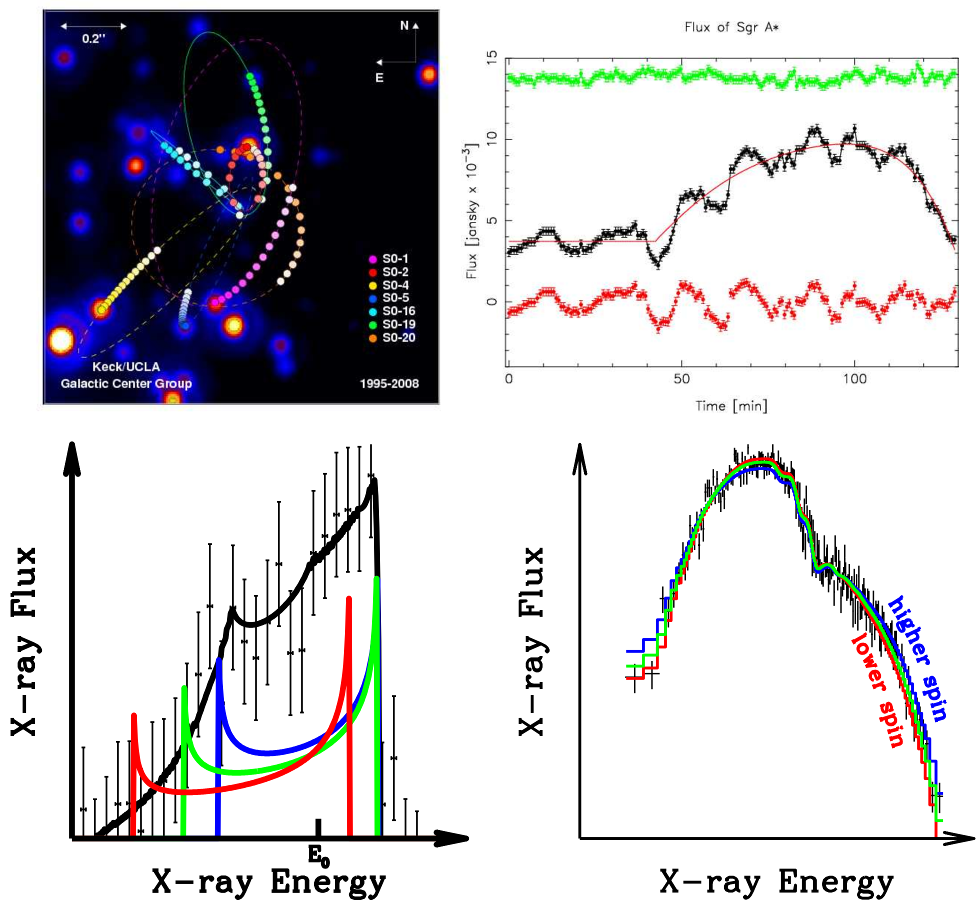

Figure 2: Various techniques for probing the environments of astrophysical black holes. **Upper Left:** Orbits of stars around the black hole at the center of the Milky Way, Sgr A*. Sequential snapshot observations are denotes by the colored circles, with the background showing the most recent near-infrared image. (*Image provided by Prof. Andrea Ghez (UCLA), based on data obtained with the W.M. Keck Telescopes.*) **Upper Right:** An infrared flare from Sgr A* (with the large scale trend removed), showing multiple oscillations (*adapted from Genzel et al. (2005).*) **Lower Left:** The relativistically broadened iron line in the active galaxy MCG 6-30-15, compared to the prediction from relativistic accretion disk models. The emission produced at a individual radii around the black hole, varying from close to the horizon (red) to far from the horizon (blue), are shown for comparison. The intrinsic line energy is $E_0 = 6.4$ keV. **Lower Right:** The X-ray spectrum of M33 x-7, a stellar mass black hole in the galaxy M33. The green line shows the best thin-disk model, corresponding to a spin of 77% of the maximum theoretical value. The red and blue lines show the best model for black hole spins that are 10% lower and higher, respectively.

A Third Way

Owing to very recent advances in technology, it has become just possible to directly image the horizon of a black hole. Astronomers have a deep affinity for beautiful pictures, as they frequently are the best tool we have for studying celestial objects. However, imaging a black hole is no mean feat, and there are a variety of difficulties with which any effort to image a black hole must contend.

Interestingly, the behemoth in our backyard, Sgr A*, occupies the largest angular scale on the sky of any known black hole. While bright in absolute terms (a thousand times the luminosity of the Sun), Sgr A* is extraordinarily underluminous in comparison to its maximum attainable luminosity, missing the mark by eight orders of magnitude. This has been used to argue for an anomalously low radiative efficiency, the rate at which liberated gravitational binding energy of the gas is converted into radiation. Weighing 4.3×10^6 solar masses, it is hundreds of thousands of times larger than stellar-mass black holes in our Galaxy, though thousands of times smaller than some of the truly enormous monsters that occupy the centers of other galaxies. Being only 24 thousand light-years away, though, Sgr A* is thousands of times closer than any other supermassive black hole. Nevertheless, even when the strong gravitational lensing is accounted for, which more than doubles the apparent size of the horizon, Sgr A*'s horizon is a putative 55 millionths (micro) of an arcsecond across. To put things in perspective, that is the angular scale of an average human hair in Los Angeles when viewed from Chicago!

The resolution of all modern telescopes, as impressive as they are, is fundamentally limited by diffraction, a wave-optics effect that occurs as light passes through the finite aperture presented by the size of the telescope. This effect dominates the astrometric uncertainty from telescopes like Keck and the VLT, where atmospheric effects can be corrected for via adaptive optics. Generally, the smallest angular scale that can be resolved is given by the ratio of the wavelength observed to the size of the telescope. Thus, the twin requirements of higher sensitivity and higher resolution are the primary motivations for pushing to increasingly larger telescopes. To reach an angular scale of 55 micro-arcseconds at infrared wavelengths (those observed at Keck that are relevant for Sgr A*) would require a telescope 7-km across! Alternatively, at millimeter radio wavelengths, this requires a telescope 5000-km across. While a 7-km infrared telescope is well beyond our present technological capabilities, an Earth-sized radio telescope is already operating.

Very Long Baseline Interferometry (VLBI) is a technique whereby multiple radio telescopes, sprinkled around the globe, are joined together to synthesize an Earth-sized aperture, gaining angular resolutions unavailable in any other fashion (though without the commensurate gains in sensitivity that accompanies making a single-dish large telescope). For sufficiently bright radio objects two existing VLBI arrays (VLBA), one in North America and the other in Europe, have been operating at long wavelengths for decades. The same principle is implemented on a smaller scale at the Very Large Array in New Mexico, made famous in movies such as *Contact* and *2010*. Unfortunately, the VLBA is suitable only for wavelengths above 3.5 cm, corresponding to maximum resolutions of 500-1000 micro-arcseconds, an order of magnitude larger than what is required to image Sgr A*. Pushing to longer baselines would require space-based radio missions, and thus is both technologically difficult and extraordinarily expensive. Moreover, at these long wavelengths strong scattering by interstellar gas blurs the image of Sgr A* just as dense fog blurs the street lights overhead. The alternative is to implement a VLBI capability at shorter wavelengths.

Short-wavelength radio observations are limited by the increasing opacity of water vapor in the Earth's atmosphere. For this reason millimeter and sub-millimeter telescopes are placed in the highest elevation and driest sites available, such as atop Mauna Kea in Hawaii, on the Atacama desert in Chile and in Antarctica. Even so, it is rarely possible to observe wavelengths below 0.4 mm, leaving two atmospheric windows at 1.3 mm and 0.87 mm. Fortunately, an Earth-sized VLBI array at these wavelengths provides resolutions of 21 and 11 micro-arcseconds, respectively, sufficient to resolve the horizon of Sgr A*. A number of millimeter and sub-millimeter telescopes that could be phased into such an array already exist, in Hawaii, scattered throughout the southwestern US, Chile, Mexico and in Europe. Doing so entails technological difficulties, including obtaining stable and robust high-frequency time standards and reaching sufficient sensitivities to detect Sgr A* over short timescales (set by decoherence of the atmosphere). However, in 2007-8 these problems have been solved by S. Doeleman and collaborators, who successfully resolved Sgr A* on a small array (just three telescopes) at 1.3 mm. While the small number of telescopes used was insufficient to generate an image, the best fit size of the bright regions of Sgr A* to these observations was 37 micro-arcseconds, smaller than the full size of the horizon, implying

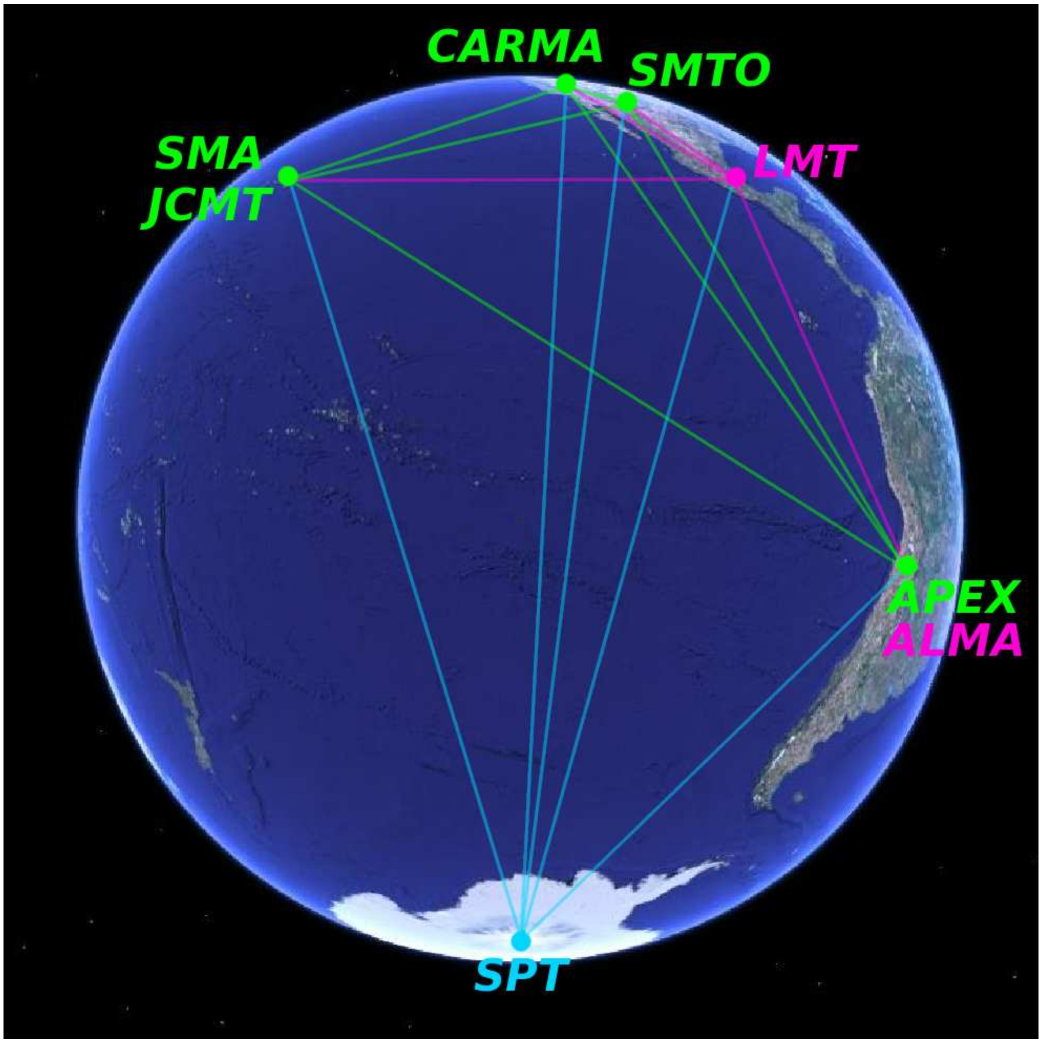

Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The *Large Millimeter Telescope* (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The *Atacama Large-Millimeter Array* (ALMA) is scheduled to be completed by 2012, though it will begin taking data in 2010. Already at the ALMA site, the *Atacama Pathfinder EXperiment* (APEX) is presently operating. Finally, the *South Pole Telescope* (SPT) needs only a millimeter receiver to be adapted for sub-mm VLBI. The projected baselines associated with these telescopes are shown in green for telescopes that exist, magneta for upcoming telescopes and cyan for the SPT. Note that a telescope in New Zealand would improve baseline coverage considerably!

that many such telescopes would be capable of resolving the silhouette of the black hole horizon itself.

Of course, while high resolution is necessary, it is not all that is required. In order to image the horizon we must also be able to see through the intervening material. This includes the surrounding accretion flow as well as interstellar electrons which blur our view of the Galactic center. In the case of Sgr A* we find ourselves the happy beneficiaries of a fortunate coincidence: at millimeter wavelengths the accretion flow around Sgr A* becomes transparent, and the blurring due to interstellar electrons becomes sub-dominant. Remarkably, the requirements necessary to image Sgr A*: sufficient resolution, transparency of the accretion flow, and the sub-dominance of interstellar blurring, are *all* satisfied when we view it at sub-millimeter wavelengths.

Already, the recent sub-millimeter VLBI observations place strong constraints upon the existence of a horizon. The crucial observational difference between black holes and objects that do not have horizons, like neutron stars, is that in the latter all of the gravitational binding energy liberated by the infall of accreting material is eventually emitted as radiation since the material eventually comes to rest while it is visible to outside observers. For black holes, material may carry large quantities of binding energy into the horizon where it is hidden forever. Because the emission from a surface is different from that in the rest of the accretion flow, it is possible to carefully search the spectrum for signatures of such a surface. Tight limits upon the size of the inner-edge of the accretion flow as well as upon the luminosity (in the case of Sgr A*, in the infrared) are particularly powerful. For a horizon to be absent, the most recent constraints require the accreting material to lose more than 99.7% of its binding energy to radiation before it hits any surface. This limit makes the existence of surface implausible, since the required radiative efficiency is much higher than the values of 10-30% found in other AGN and vastly larger than the putative efficiencies implicated in Sgr A* itself.

Portrait of a Monster

We, among other theorists, have been very busy trying to predict what observers might see when images of Sgr A* are produced in the next few years. The expected image of a black hole is shaped by a variety of relativistic effects, including the Doppler boosting and beaming due to the extreme velocities of the orbiting gas (approaching the speed of light), as well as the strong gravitational lensing which bends light-rays so much that material directly behind the black hole is also partially visible.

Generally, the black hole casts a silhouette upon the wallpaper of emission by the accreting gas. The black hole "shadow" arises from light rays that originate near the horizon, and pass through only the half of the translucent accretion flow in front of the black hole. In essence, this silhouette is what is meant by a "portrait of a black hole", a fitting picture in which the black hole truly is black. Even though the accretion flow has a thick disk geometry in all of these images, frequently only a crescent is visible as a consequence of the relativistic orbital motion of the gas. At high inclinations (when the disk is nearly edge-on) the asymmetry is most pronounced, and conversely, disappears entirely when the black hole is viewed face-on.

Apart from providing a striking validation of one of the most exotic predictions of general relativity, such images will allow astronomers to determine the direction and magnitude of the black hole spin and the inclination of the accretion disk. Equally important for astrophysics, they will provide invaluable observational input into accretion theory, settling once and for all the gas density and geometry at the inner edge of the accretion flow. Comparisons between images of Sgr A* and M87, a distant supermassive black hole that is the second best target for imaging and exhibits a vigorous jet, will doubtlessly provide critical empirical input into theoretical efforts to understand how narrow, ultra-relativistic jets are formed around black holes.

Perhaps more exciting in the long run are the prospects for imaging the variable emission of Sgr A*. If the observed flares are in fact due to bright spots orbiting the black hole, they can be used to map out the space-time around the horizon. The image of each spot will be accompanied by a number of additional images, corresponding to rays that reach the observer by circuitous routes, the secondary image due to rays which pass behind the black hole, the tertiary image generated by rays which complete a full orbit prior to reaching Earth, and so forth. Within the structure of these higher order images, and their relationships to each other, is encoded the structure

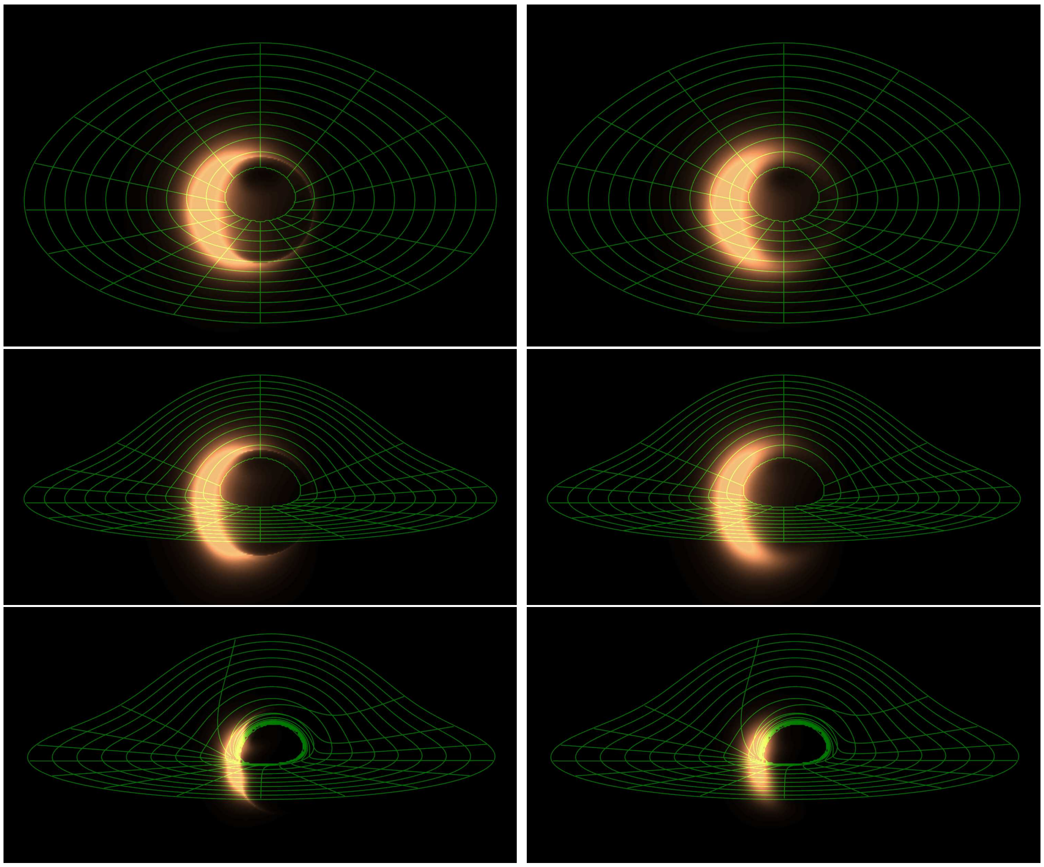

Figure 4: Theoretical images of the accretion flow around Sgr A* (adapted from Broderick & Loeb 2005). The lensed equatorial plane is shown by the green grid. **Top:** Non-rotating black hole viewed from 30° above the equatorial plane (the most common inclination). **Middle:** Non-rotating black hole 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 gas. Nevertheless, the silhouette of the black hole is clearly visible.

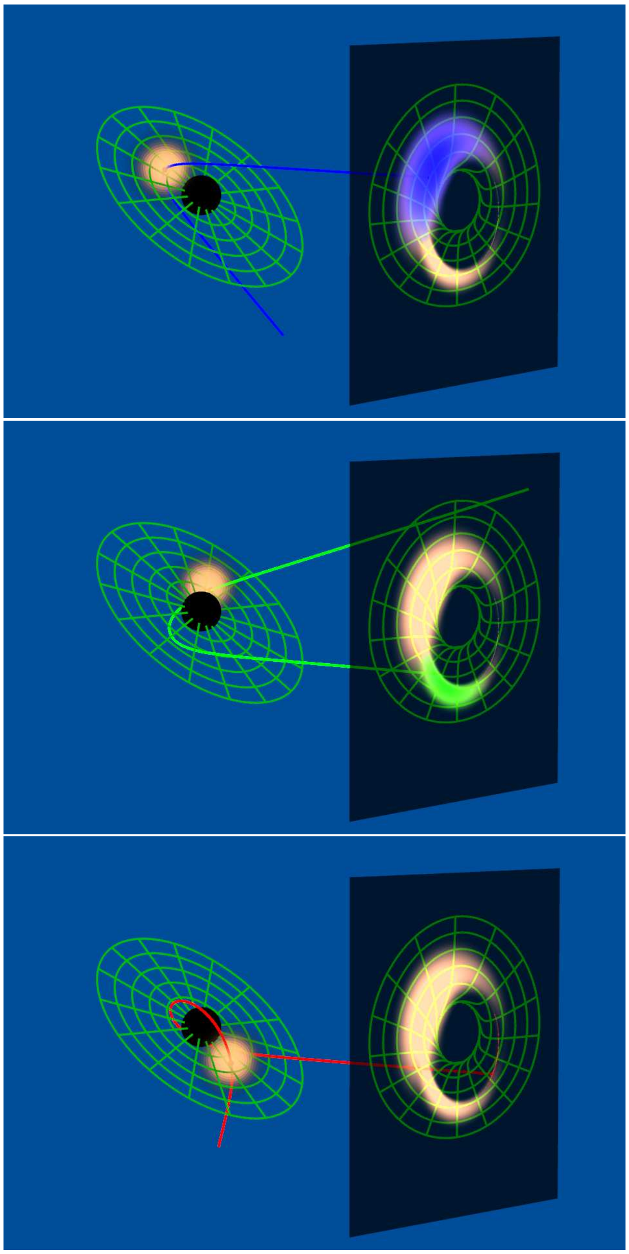

Figure 5: Snapshots of a bright spot orbiting a moderately rotating black hole, along with the class of light-rays that produce each part of its image. **Top:** The primary sub-image is the brightest, corresponding to the most direct path taken by photons as they travel from the bright spot to a distant observer. **Middle:** The secondary sub-image is the next brightest component (delayed by approximately a quarter orbit), and is produced by rays which are bent around the black hole. **Bottom:** The tertiary sub-image (just barely visible in the image), is produced by rays which execute a complete orbit around the black hole before reaching a distant observer, and are thus even further delayed. In practice an infinite number of sub-images are produced, though only the first three contain a significant radiation flux.

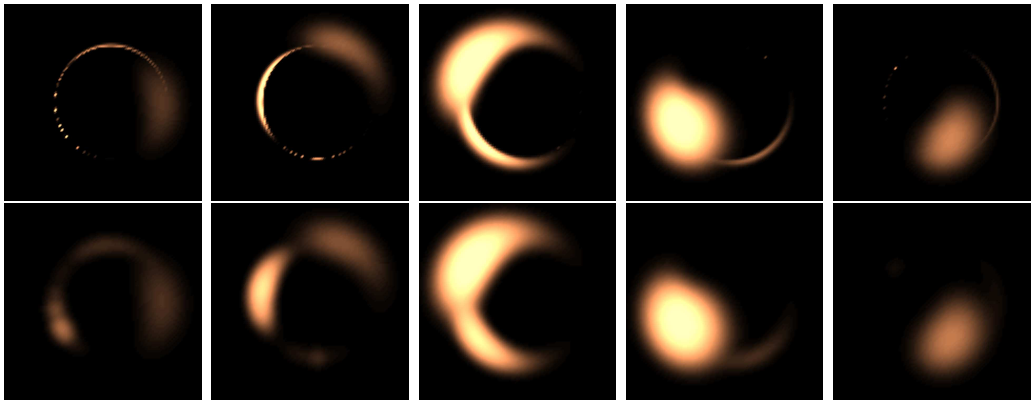

Figure 6: **Top:** Instantaneous theoretical images of a bright spot orbiting a moderately rotating black hole, viewed at 45° above the orbital plane. **Bottom:** The same images including the bluring effect of interstellar electrons.

of the space-time near the black hole. Careful analysis of lensed bright spots will allow the determination of the magnitude of Sgr A*'s spin, as measured *locally* by the bundle of rays connecting the bright spot to observers on Earth. Observations of multiple bright spots would provide a number of *local* measurements of the space-time near the black hole, which when taken together represent a test of general relativity's predictions for the behavior of strong gravity around black holes.

A New Era

Black hole observations are entering a new golden era. Less than a century after Einstein conceived of General Relativity, we might be in a position to test whether this theory correctly describes strong gravity in the extreme environments of black holes. When images of Sgr A* become available, we will be able to investigate in detail its space-time. And once this region will be mapped, cell phone technicians will not need to risk their life any more to test this hazardous environment.

Additional Reading

Testing General Relativity with High-Resolution Imaging of Sgr A*. *A. Broderick and A. Loeb*, 2006, http://arxiv.org/abs/astro-ph/0607279

Event Horizon Scale Structure in the Super Massive Black Hole at the Galactic Centre. *S. S. Doeleman, et al.*, Nature, 2008 .