The Supermassive Black Hole in the Center of the Milky Way

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Abstract

A black hole is a region of space where so much mass is present, that the resulting gravitational forces have become so strong, that even light itself cannot escape from the region. The possible mass for a black hole in nature can range from as small as that of the sun to billions times larger. In the nuclei of galaxies, very large black holes have been suggested to exist. The nearest supermassive black hole is at the center of our Milky Way. Measuring very carefully the stellar motions around a point-like radio source in the middle, we find that a massive black hole of about four million times the mass of the sun is likely to be present. This source is called the Sagittarius A *. A team of Chinese astronomers, all in residence at some time at the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), have been measuring the size of this point-like radio source over the last decade. The ASIAA is part of the consortium building the Atacama Large Millimeter/submillimeter Array in Chile. Very Long Baseline Interferometry with ALMA may someday resolve the shadow cast by the supermassive black hole Sagittarius A*.

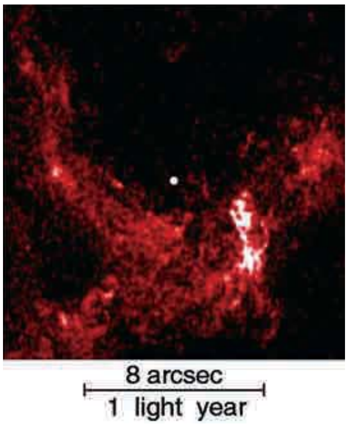

Figure 1. Radio continuum image of the center of the Milky Way. This image is made with the Very Large Array of the National Radio Astronomy Observatory in New Mexico. The point-like source is the black hole source SgrA*. (Image from NRAO/AUI Jun-Hui Zhao and W.M. Goss)

A black hole is a region of space where so much mass is present, that the resulting gravitational forces have become so strong, that even light itself cannot escape from the region. The defining feature is that the velocity of escape, as for the case of a rocket from earth, must exceed the speed of light. Since physics tells us that the speed of light, at 300,000 kilometers per second, cannot be exceeded, then matter, energy, light, and all forms of information, are trapped within a black hole once we pass through the boundary, known as the “Event Horizon” or “Schwarzschild Radius”. It is interesting to note that this escape velocity requirement depends on the ratio of mass to size scale and not the density which is the ratio of mass to volume. Hence, for a sufficiently large black hole, its size scale can be quite large, in which case the density is quite low and physics can be ordinary. However, as matter is compacted into smaller and smaller regions, the density will become very high, far exceeding what can be achieved in a labora-

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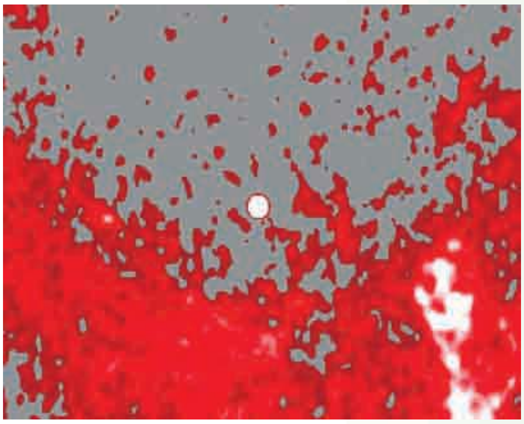

Figure 2. The very small bright point source in the picture is the radio emission from the central black hole source SgrA*. This is an enlargement of the previous Very Large Array Image. (Image from NRAO/AUI)

tory. New physics may then be required to describe the behavior of nature at that point.

As physicists and astronomers now understand, the possible mass for a black hole in nature can range from as small as that of the sun to billions times larger. Black holes with masses like the sun are recognized to be the products of the end of stellar evolution.

A star which is like our sun will eventually exhaust its supply of hydrogen, helium, and higher elements, so that the fusion process will cease to work. At that point, the dying sun will grow colder and colder, while contracting, as the stellar matter is pulled ever inward because of gravity. Because electrons are not allowed to occupy the exact same energy state, there is a residual pressure from the electrons in a star which can withstand the gravity. For a small enough star, like our sun, the end state is what we call a white dwarf, which will become stable against further contraction and will cool continuously over time. If the mass is somewhat larger, gravity will overcome the pressure of the electrons, and contraction will continue. These stars will pass through a supernova stage ejecting most of the stellar matter. However a remnant core remains where the electrons will actually be crushed into the protons to form neutrons. The neutrons, like the electrons, will also have a residual pressure, as they too cannot occupy the exact same energy state. This end state is called a neutron star, composed of all neutrons. If the mass is greater still, then gravity will once again exceed the neutron pressure. Then collapse cannot be prevented. Theory suggests that such large stars, perhaps eight times that of the sun, will be crushed inward irresistibly until they exceed the mass to size scale ratio which defines the black hole state. Some of these black holes exist in binary systems, and they are still devouring material from their

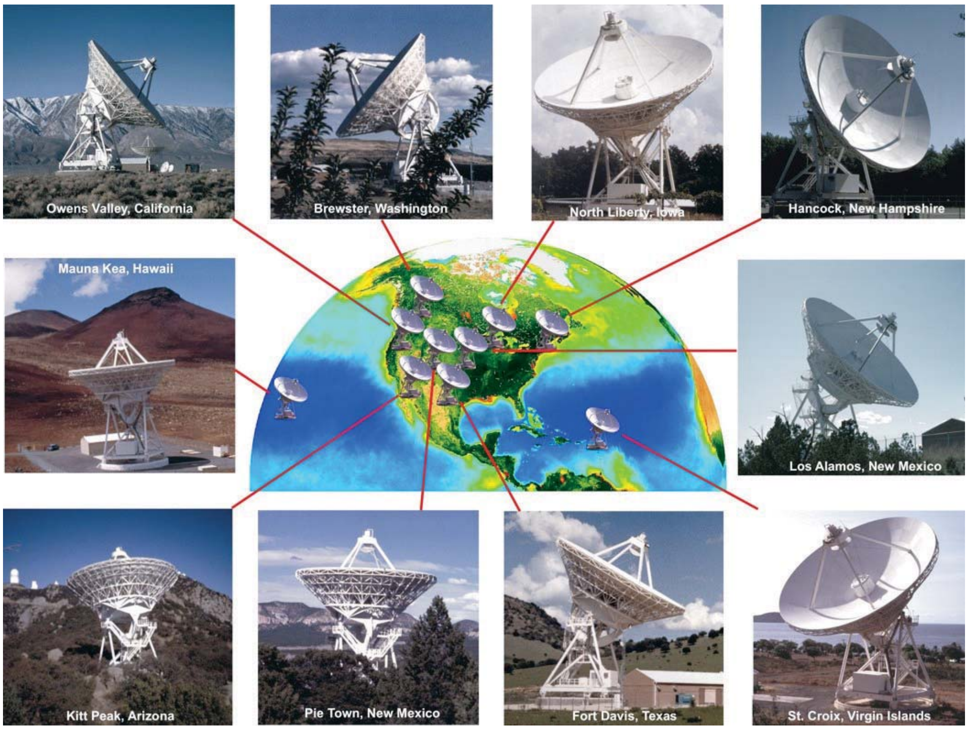

Figure 3. The Very Long Baseline Array is an intercontinental interferometer built by the National Radio Astronomy Observatory. It consists of ten telescopes spread across the globe. Very high angular resolution can be achieved, better than 1 mas (milli-arc second). This is enough resolution to resolve a strand of hair from one side of the United States to the other. (Image from NRAO/AUI and SeaWiFS Project NASA/GSFC and ORBIMAGE)

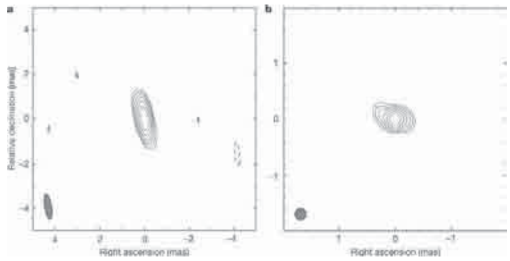

Figure 4. Left: Observed image of the Galactic Center black hole source SgrA* at a wavelength of 3 mm. The achieved resolution is shown in the lower left hand corner, and is 1.1 mas x 0.3 mas (milli-arc second). Right: Restored with a 0.2 mas resolution, the image shows an elongation in the East-West direction. When corrected for interstellar scattering effect, the intrinsic size appears to be about 1 Astronomical Unit (the distance from the earth to the sun). This size is about 12 times the Event Horizon radius of the black hole, where even light cannot escape. These results are made with the Very Long Baseline Array by Shen and his collaborators.

companions, emitting powerful X-ray in the process. We have good evidence of such black holes through X-ray observations, and precise orbital measurements of some binary systems are being used to determine their masses.

In the nuclei of galaxies, very large black holes have been suggested to exist. The reason is that very large orbital motions are sometimes seen, and very high energy outputs have been detected. Analysis suggests that a very efficient energy source must be present, and a very large concentration of mass must be present. The most efficient energy production process is recognized to be the infall of matter towards a central black hole. If matter lands close enough to the central black hole, the potential energy which can be extracted from the gravitational field approaches nearly the mass equivalent energy through the famous $E=mc^2$ equation. Even fusion or fission can only extract energy at one hundredth of the mass equivalent energy. Hence black hole accretion of matter is at least about a hundred times more efficient than all other known forms of energy sources.

The nearest supermassive black hole is at the center of our Milky Way. Measuring very carefully the stellar motions around a point-like radio source in the middle, we find that a massive black hole of about four million times the mass of the sun is likely to be present. This source is called the Sagittarius A*. A team of Chinese astronomers, all in residence at some time at the Academia Sinica Institute of Astronomy and Astrophysics, have been measuring the size of this point-like radio source over the last decade. We used the technique called Very Long Baseline Interferometry, to connect radio telescopes which are separated on intercontinental distances. This technique measures very precisely the arrival times of the signal at each telescope referenced to precise atomic clocks. The signals are then combined accurately, reconstructing the image as if the signals were collected by a single huge telescope spanning the longest separation of the individual telescopes. The Very Long Baseline Array, operated by the National Radio Astronomy Observatory in the United States, provides ten telescopes, extending from Hawaii, across the mainland of the United States, to St. Croix in the Virgin Islands. We used this array of telescopes to measure the size of Sagittarius A*. The achieved resolution at milli-arc

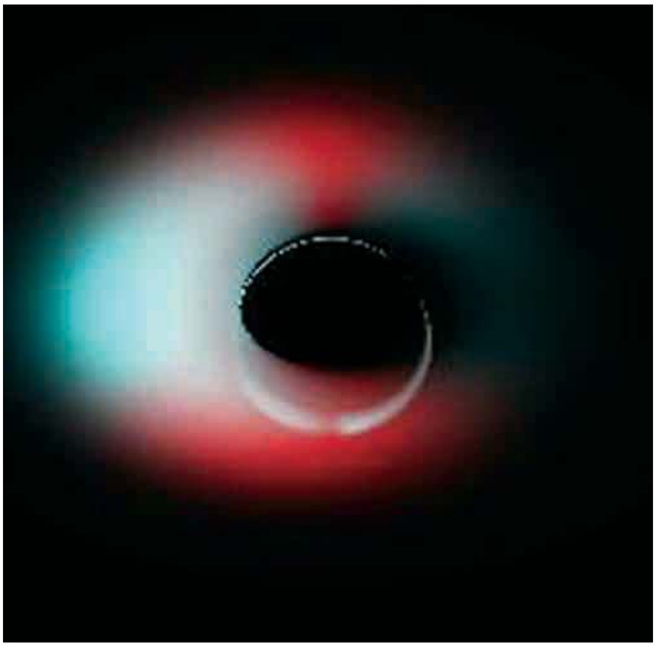

Figure 5. A model of what the shadow of the black hole might look like if more angular resolution can be achieved in the future. (Image from Liu et al, 2002)

second scale is able to resolve a fraction of a millimeter while standing in Taiwan looking at California.

It turns out the radio signals from the center of the Milky Way are blurred by the scattering effects of interstellar electrons along the way. The effect is small but significant. Hence, before the time of this experiment, it was not possible to determine the intrinsic size of Sagittarius A*. However, this blurring effect decreases with the wavelength of light. Finally, operating at the shortest wavelength possible with the VLBA, 3 millimeters, we are able to measure the radio emission as having an intrinsic size scale of about one thousandth of an arc second. This sets the size scale to be about one astronomical unit, the separation between the sun and the earth, or equivalent to about twelve times the Schwarzschild radius for a 4 million solar mass black hole. Hence the emission is coming from very close to the Event Horizon of the central supermassive black hole. These measurements suggest a matter density of at least 10^{22} solar masses per cubic parsec, or about 1 gram per cubic centimeter. These results constitute the best arguments yet for the identification of a supermassive black hole. An intrinsic shape for Sagittarius A* may be due to some outflow phenomenon.

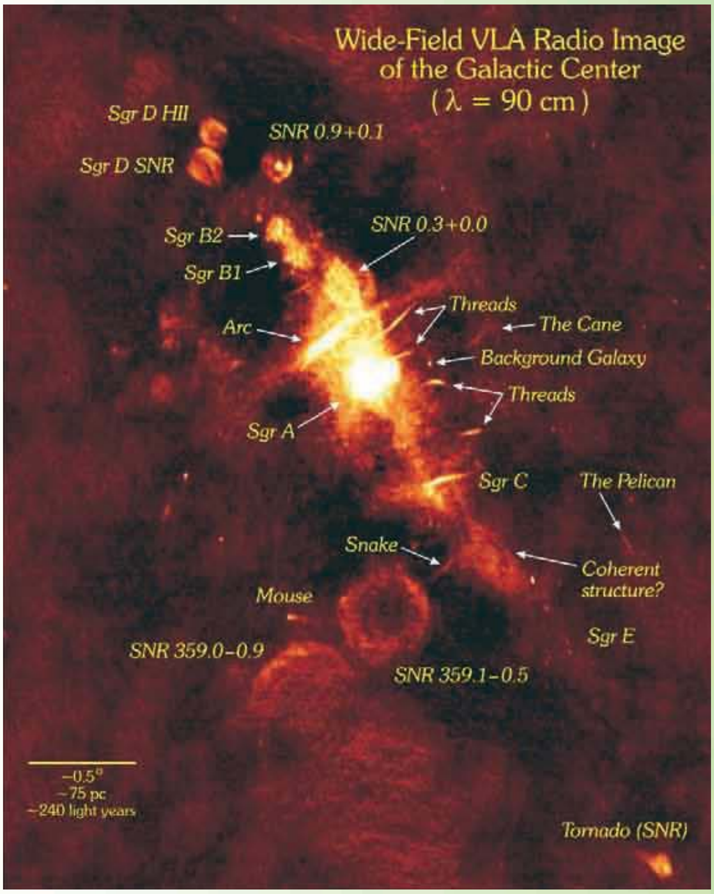

Figure 6. Big picture of the central region of the galaxy, the inner few hundred light years. (Image from NRAO/AUI N.E. Kassim)

These experiments were led by Shen Zhi-Qiang, now at the Shanghai Astronomical Observatory, together with Lo Kwok-Yung, past ASIAA Director, and now Director of the National Radio Astronomy Observatory, Liang Mao-Chang of Caltech, Zhao Jun-Hui of the Smithsonian Astrophysical Observatory, as well as Paul Ho. The ASIAA is engaged in many different kinds of studies of the Galactic Center black hole, utilizing also the Submilllimeter Array in Hawaii. The ASIAA is part of the consortium building the Atacama Large Millimeter/submillimeter Array in Chile. Very Long Baseline Interferometry with ALMA may someday resolve the shadow cast by the Supermassive black hole Sagittarius A*.

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