World of Knowledge

Imaging of Black Holes in the Universe

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The concept of black hole was mentioned in the late 18th century by P.S. Laplace who defined it as an extremely massive and dense body that cannot radiate light outside of itself due to strong gravity. Until the 1960's, this issue had been mainly discussed as a theoretical concept. In the middle of the 1990's, Very Long Baseline Interferometry (VLBI) made an innovative discovery on the reality of the black hole. At the center of a galaxy, a massive object of 36 million Msol (solar mass = 2×10^{30} kg) was suggested, confined in a region less than 0.4 light years (4×10^{12} km) in radius [1]. The observation found a rotating disk that follows the Keplerian law. Although the central object was not observed, no objects could be supposed except a black hole under such a massive and compact situation. Soon after this, another new observation revealed a massive object at the center of our Milky Way Galaxy. The mass was estimated to be 3 million Msol, by monitoring stellar motions orbiting around it in the vicinity of about 0.3 light years (3×10^{12} km) [2]. Again, this massive object was suggested to be a black hole, although the massive object was also not seen.

Until then, black holes were candidates of the energy source for Active Galactic Nuclei (AGN). However, they are not classified as AGN, and these findings led to the idea that all galaxies have a Super Massive Black Hole (SMBH) at their center, the mass ranging 10^6-10^9 Msol. The formation mechanism of SMBH is one of the hot topics in recent astronomy.

As seen above, the existence of black holes has been recognized in recent astronomy. However, there is no direct evidence of it. What does it look like? An answer was given in the late 1970's; it would be seen like a black "shadow" against a bright accretion disk [3]. Due to the gravitational lensing effect, the size of the shadow image is estimated about 5 times of the Schwarzschild radius for a non-rotating black hole. Figure 1 shows an example of the shadow image [4]. When a SMBH is rotating, or has spin, the shadow size becomes smaller and deviates from a round shape. All these mean that we can derive two of the three black hole parameters, the mass and spin, from the shadow image, if the General Relativity under such a strong gravity field is correct. Thus, we could confirm the validity of the General Relativity. Furthermore, the observations of the immediate vicinity of a SMGB will reveal to us many new aspects of physics relating to the General Relativity: formation and accretion mechanisms of SMBH and accretion disk, formation mechanisms of relativistic jets, and fundamental black hole physics.

The tools are almost ready now for observing the shadow of SMBH. We can prove easily and simply the existence of a black hole when we observe it. In fact, we are now very close to obtaining the shadow image of SMBH with the present techniques. The only possible technique is VLBI at sub millimeter wavelengths. Why? The submm VLBI, in short, gives the highest spatial resolution among any telescopes at all wavelength regions from gamma-ray to radio. The Schwarzschild radius is proportional to the black hole mass, and it becomes 3 km for a black hole of 1 Msol. The closest SMBH is Sgr A* at the center of our Milky Way Galaxy, and the apparent shadow size is about 50 micro arc-seconds. This is due to the distance, although the mass is not so heavy. The next largest shadow size is 40 micro arc-seconds located at the center of an AGN, called M87, with the SMBH mass of 6 x 10^9 Msol. M87 is a dominant galaxy in the Virgo cluster of galaxies, and the huge mass with rather small distance yields the large apparent shadow size. All other SMBHs are less than half apparent size of these. As the achieved spatial resolution with the submm VLBI is around 40 micro arc-seconds [5], Sgr A* and M87 are the primary targets to identify the shadow image.

We made observations of Sgr A* and M87 with three VLBI elements in Hawaii, California, and Arizona. VLBI images are constructed by Fourier transformation of the interferogram by each interferometry pair, so that the image quality becomes higher with the number of interferometry pairs. Usually we need several elements to get an acceptable image of the target. We call the length of the pair a baseline length. The maximum baseline length corresponds to the spatial resolution of the VLBI system, as the spatial resolution is governed by the diffraction limit. For the case of above observation for Sgr A*, the number of baselines was only three, and two of them with Hawaii were almost the same. It was then impossible to construct a shadow image.

The observations have been conducted at 230 GHz (1.3 mm). This is the highest frequency obtained for successful VLBI observations. Yet there are several difficulties present in observation. The weather condition, particularly water vapor contents in the sky, affects observations very much. Until now, we do not have an indication of a shadow. To improve the situation, we need to build another observing site, preferentially in a distant place from the existing telescopes to improve the spatial resolution.

The ASIAA VLBI group has been making a site survey for the new submm VLBI station, so as to facilitate observations of black hole shadows. The requirements for the station are (1) a dry area which has a good atmospheric transparency at submm wavelengths, and (2) a place to provide good baselines with existing telescopes, preferably longer baselines. As we are planning to make observations at shorter wavelengths up to 0.86 and 0.46 mm (350 and 650 GHz), the dry condition with stable atmosphere is an essential requirement for our purpose. Shorter wavelength observations give us higher spatial resolution, although the observations become increasingly difficult both in technical and atmospheric terms. For the second requirement, we gave a high priority to the two existing telescopes, the Atacama Large Millimeter/submm Array (ALMA) in Chile and the Sub-Mm Array (SMA) in Hawaii. ALMA has very high sensitivity at submm wavelengths, and the baseline with ALMA should be very sensitive. In addition, the ASIAA is one of the key members participating in the construction and operation of ALMA, and the VLBI application is a quite natural extension for ASIAA to lead this exciting submm VLBI project. SMA is also a sensitive telescope. It is well known that the ASIAA is deeply committed to SMA. The ASIAA is thus a unique research institute which conducts extensive research using two of the most powerful telescopes in the world.

We found a promising site on Greenland. The site is 3,000 m high above sea level with an average temperature of circa -30°C. In the summer of 2011, we will bring a sky monitoring system to measure the sky transparency of the potential site. We cannot observe Sgr A* from the Greenland site. On the other hand, the site produces the longest baselines to ALMA for M87, and also good baselines to SMA and some European telescopes. M87 has a prominent relativistic jet, and the almost North-South extension of the baselines greatly facilitates a detailed investigation of this jet.

Recently, the ASIAA VLBI group was awarded a very powerful telescope for the submm VLBI from the National Science Foundation (NSF) in the US (see Figure 2). NSF called upon scientists to submit project proposals for the usage of the ALMA prototype telescope. We proposed the submm VLBI project, collaborating with international VLBI partners, and won the competition [6]. We have to retrofit it for the cold climate of Greenland, and hopefully we will ship it to the Greenland site within a couple of years. Furthermore, we hope to be able to identify the first image of the SMBH shadow in M87 with this antenna.

There are already some infrastructures in the Greenland site. We have come to the realization that the site condition for submm observations may be competitive or even better than the ALMA site in Chile, presumably due to the low temperature. It is then very promising for us to play a key role to observe the black hole shadows with this site. Further, the telescope would be very productive for single telescope observations at shorter wavelengths, because of the largest aperture of 12 m for submm region and good atmospheric conditions. In fact, some submm research groups are already showing an interest in collaborating with us for the single telescope applications. Thus, the ASIAA is making steady progress with the submm VLBI project, and also the single antenna observations of this project.

References

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FIGURE CAPTIONS

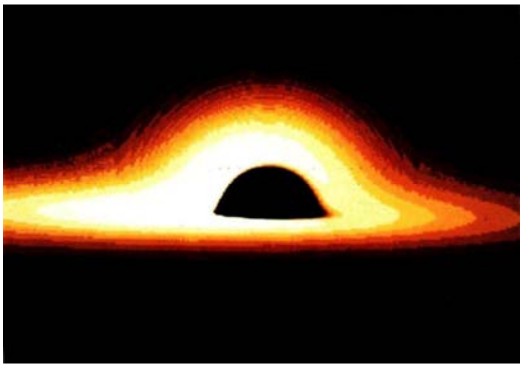

Figure 1. An image simulation of a black hole shadow [4]. The inclination angle of the accretion disk is 5°, rotating anticlockwise seen from the top. Due to the Doppler effect of the rotation, the left side (approaching side) becomes brighter than the left side.

Figure 2. The ALMA prototype telescope made by the North America group. The picture was taken in April 2011 during a workshop on how to re-activate and retrofit the telescope in order to use it as a submm VLBI antenna. The antenna had been left unattended for 3 years. Based on the discussions in Socorro, New Mexico, we have started re-testing and checking its present status in