CONSTRAINING THE SIZE OF THE DARK REGION AROUND THE M87 BLACK HOLE BY SPACE-VLBI OBSERVATIONS

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ABSTRACT

In order to examine if the next-generation space very long baseline interferometer (VLBI), such as VSOP-2 (VLBI Space Observatory Programme-2), will make it possible to obtain direct images of the accretion flow around the M87 black hole, we calculate the expected observed images by relativistic ray-tracing simulations under considerations of possible observational errors. We consider various cases of electron temperature profiles, as well various values for the distance, mass, and spin of the M87 black hole. We find it feasible to detect an asymmetric intensity profile around the black hole caused by rapid disk rotation, as long as the electron temperature does not rise steeply toward the black hole, as was predicted by the accretion disk theory and three-dimensional magnetohydrodynamic simulations. Further, we can detect a deficit in the observed intensity around the black hole when the apparent size of the gravitational radius is larger than $\gtrsim 1.5\, \mu$as. In the cases that the inner edge of the disk is located at the radius of the innermost stable circular orbit (ISCO), moreover, even the black hole spin will be measured. We also estimate the required signal-to-noise ratio $R_{SN}$ for achieving the scientific goals mentioned above, finding that it should be at least 10 at 22 GHz. To conclude, direct mapping observations by the next-generation space VLBI will provide us a unique opportunity to provide the best evidence for the presence of a black hole and to test the accretion disk theory.

Key words: accretion, accretion disks – black hole physics – galaxies: nuclei – Galaxy: center – radiative transfer – techniques: interferometric

Online-only material: color figures

1. INTRODUCTION

Elucidating the nature of space plasmas and their dynamical behavior in a strongly curved spacetime remains one of the greatest challenges of observational astronomy and astrophysics in this century. This requires a superb angular resolution, down to tens of microarcseconds and, hence, has been impossible up to now with any instruments at any wavelengths. Surprisingly, however, the situation is expected to be enormously improved in the near future thanks to the rapid progress of the very long baseline interferometer (VLBI) technique from the radio to submillimeter band. In many past studies, the observational feasibility of the direct imaging of the black hole shadow (or the black hole silhouette) with submillimeter interferometers on the ground has been investigated for the Galactic Center black hole Sgr A* (e.g., Falcke et al. 2000; Miyoshi et al. 2004, 2007; Fish et al. 2009; Doeleman et al 2009; Broderick et al. 2009; Huang et al. 2009) and the black hole in the elliptical galaxy M87 (Broderick & Loeb 2009). Following the same line, in this paper we elucidate a feasibility study of obtaining direct imaging of the black hole with a planned space-VLBI satellite.

It has long been believed that radio emission arises from bidirectional jets emanating from the accretion flow, and not from the accretion flow itself. This may not be the case, however, if there exist high-energy electrons with energy above 100 keV and if the magnetic field strengths are on average greater than about 1% of the equipartition value. If these two conditions are satisfied in accretion flow, we expect significant radio emission not only from the jets but also from the flow itself (see, e.g., Narayan et al. 1995; Narayan & Yi 1995). It is true that the radio emission from the flow is usually overwhelmed by that from jets owing to much higher antenna temperature of the jets, but it is nevertheless possible, in principle, to separately detect radio emission from the accretion flow if observed with instrumentation with good spatial resolution. Future direct imaging observations of the innermost region of active galactic nuclei with VLBI will provide unique and excellent opportunities to map the accretion flow plunging into black holes (e.g., Falcke et al. 2000; Miyoshi et al. 2004; Takahashi 2004, 2005; Broderick & Loeb 2006a, 2006b, 2009; Yuan et al. 2006; Noble et al. 2007; Huang et al. 2007, 2008; Nagakura & Takahashi 2010). Such observations will also prove the Kerr geometry (Bardeen 1972; Takahashi 2004, 2005) predicted by gravity theories, including general relativity (Psaltis 2008; Psaltis et al. 2008).

One of the leading, ongoing projects of the radio VLBI is the VSOP-2 with the ASTRO-G satellite, space VLBI program with the highest angular resolution of 38 $\mu$as at the observation frequency of 43 GHz (e.g., Hirabayashi et al. 2005; Tsuboi 2008, 2009). The minimum antenna temperature which can be detected by the VSOP-2/ASTRO-G is about a few times $10^8$ K, which is far exceeded by the expected temperature of optically thin accretion flow (e.g., Narayan et al. 1995; Narayan & Yi 1995; Esin et al. 1996; Nakamura et al. 1996; Manmoto et al. 1997; Yuan et al. 2003). For details, see the mission Web site (http://www.vsop.isas.ac.jp/vsop2e/). There is another ongoing space-VLBI mission called RadioAstron (for details, see http://www.asc.rssi.ru/radioastron/). We have mainly used the parameters of the space-VLBI satellite in VSOP-2/ASTRO-G as one example and the results presented in this paper can be applied to other similar space-VLBI missions.

The existence of a black hole in an accretion flow or a disk will manifest itself as a region with a deficit intensity, sometimes called a “black hole shadow” or “black hole silhouette”, in the...
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Figure 1. Diagram of the black hole mass, $M$, and the distance, $D$, with the observational data points of M87. Lines of 10 $GM/(c^2 D) = 10$ µas, 20 µas, 30 µas, 40 µas, and 50 µas are also indicated. The ranges of the black hole mass of and the distance to M87 reported in the past studies are plotted by the shaded region. For the black hole mass, we use $M = (2.4 \pm 0.7) \times 10^9 M_\odot$ (Ford et al. 1994 (F+94); Harms et al. 1994 (H+94)), $(3.2 \pm 0.9) \times 10^9 M_\odot$ (Macchetto et al. 1997 (M+97)), and $(6.4 \pm 0.5) \times 10^9 M_\odot$ (Gebhardt & Thomas 2009 (GT09)). The mass in GT09 is calculated by assuming $D = 17.9$ Mpc. For the distance to M87, we use $D = 14.7 \pm 1.0$ Mpc (Jacoby et al. 1990 (J+90)), 16.75 Mpc (Whitmore et al. 1995 (W+95)), 16.0 \pm 1.9 Mpc (Macri et al. 1999 (M+00)), and 17.0 \pm 0.3 Mpc (Tonry et al. 2001 (T+01)). The values of $M$ and $D$ adopted in the present study are denoted by A, B, and C, respectively (see also Table 1).

(A color version of this figure is available in the online journal.)

The Black Hole Mass of and the Distance to M87 Adopted in This Study

| Model | A | B | C |
|-------|---|---|---|
| Black hole mass $M (10^9 M_\odot)$ | 6.4 | 6.0 | 1.7 |
| Distance to M87 $D$ (Mpc) | 17.9 | 16.0 | 17.9 |
| Angular size corresponding to $10 GM/(c^2 D)$ (µas) | 35.0 | 18.5 | 9.3 |

Note. The corresponding apparent angular sizes are also listed.

Table 1

observed intensity map. The properties of the black hole shadow were investigated for optically thick disks (e.g., Luminet 1979; Fukue & Yokoyama 1988) and for optically thin flow (e.g., Falcke et al. 2000). The angular size and precise shape of the black hole shadow depend on the distance, black hole mass, spacetime geometry, and the optical depth of the accretion flow at the observed frequencies (e.g., Bardeen 1972; Luminet 1979; Fukue & Yokoyama 1988; Takahashi 2004, 2005).

There are good targets of supermassive black holes suitable for the VLBI imaging observations. For the observations at 43 GHz, the best target will be M87, which has the second largest angular size of the gravitational radius, $r_g/D \sim 1-3$ µas. Here, $r_g \equiv GM/c^2$, and $M$ and $D$ are the mass and the distance of the black hole, respectively. According to relativistic ray-tracing calculations under the Kerr geometry, the maximum size of the shadow ranges between 4 and 15 $r_g/D$ (see Figure 2 in Takahashi 2004) which corresponds to 6–24 µas for M87 when $M = 3 \times 10^9 M_\odot$ and $D = 16$ Mpc are assumed, where $M_\odot$ is the solar mass. Note that the black hole in the Galactic Center (Sgr A*), the largest black hole in terms of the apparent angular size of $r_g/D \sim 5$ µas, is not suitable for the observations at 43 GHz, since the image of the accretion flow around Sgr A* will be totally washed out at low frequencies, $\lesssim 100–150$ GHz, because of interstellar scattering. In fact, a rather broadened radio morphology with an elliptic shape was already obtained at the observed frequency 86 GHz (e.g., Shen et al. 2005, see also Doeleman et al. 2008 for the observations at 230 GHz).

In this study, we investigate how the accretion flow around the black hole in M87 will be observed and mapped by technically feasible space-VLBI observations at 43 GHz and 22 GHz. For the bolometric luminosity of $L_{bol} \approx 10^{41}$ erg s$^{-1}$ (Biretta et al. 1991; Reynolds et al. 1996; Di Matteo et al. 2003) and the black hole mass of $M \approx 3 \times 10^9 M_\odot$, the Eddington ratio of M87 is about $L/L_E \approx 10^{-6}$, much less than unity, indicating that the accretion flow is likely to be radiatively inefficient (see Chapter 9 of Kato et al. 2008). The observed multi-wavelength continuum spectrum of M87 from radio to X-rays can be explained in terms of the radiatively inefficient accretion flow (RIAF) model or its variant, advection-dominated accretion flow (ADAF) model (Di Matteo et al. 2003; Wang et al. 2008; Broderick & Loeb 2009; Li et al. 2009; Nakagura & Takahashi 2010). Further, powerful, relativistic jets are observed in M87, which seem to be produced in the innermost part of the accretion flow. To understand the rapid TeV $\gamma$-ray variability in M87 jets detected by the High Energy Stereoscopic System (HESS; Aharonian et al. 2006), it is suggested that the black hole in M87 may be rapidly rotating (Wang et al. 2008). On this ground, we calculate the expected images of the central region of M87 by radiative transfer calculations in the Kerr spacetime, basically adopting the same method as that used in Takahashi (2004), Takahashi & Watarai (2007), and Takahashi & Harada (2010) except that we employ the RIAF model, instead of the standard disk model, in the present study. The continuum emission at around 43 GHz will be of Rayleigh–Jeans spectrum because of the self-absorption of synchrotron radiation by the thermal electrons. We, therefore, assume that the accretion flow is optically thick to absorption at 43 GHz.

The plan of this paper is as follows. In Section 2, we explain the methods and models in this work. The results of numerical simulations are given in Section 3. The important issues are discussed in Section 4, and the conclusions are given in Section 5.

2. METHODS AND MODELS

We first need to specify the black hole mass $M$ and the distance $D$ to M87, but there are uncertainties in the observed values of $M$ and $D$. In Figure 1, we summarize the past reports for the mass and the distance measurements. In this figure, we plot three data for the mass measurements and four data for the distance measurements with uncertainties indicated by the shaded region (for the details of the data, see the caption of Figure 1). In this study, we adopt three data sets of combinations of $M$ and $D$ denoted as A, B, and C in Figure 1 and these values are summarized in Table 1. In contrast, the black hole spin is not so well constrained by the observations. Therefore, we consider two extreme cases: a black hole with spin parameter $a = 0$ (i.e., a Schwarzschild black hole) and one with $a = 0.998$ (i.e., an extreme Kerr black hole) where $a = J/GM^2 c^{-1}$, where $J$ is the angular momentum of the black hole.

Next, we need to prescribe electron temperature distribution. According to the RIAF model, ion temperatures are very high, close to the virial, and are several times $10^{12} (r/r_g)^{-1}$ K near the black hole, where $r$ is the radial distance from the center,
whereas the electron temperature will be much less and saturated around a few times $10^9$ K (which is about $m_e e^2/k$ with $m_e$ and $k$ being the electron mass and the Boltzmann constant, respectively) due to the enhanced cooling in the relativistic regimes (e.g., Narayan & Yi 1995, see Kato et al. 2008 for a review and references therein). Note that the accretion disk corona model also gives similar electron temperature profiles but with slightly lower values (e.g., Liu et al. 2003). As a result, the electron temperature is spatially uniform close to the black hole while the ion temperature increases in the central region of the disk. Such features are confirmed by three-dimensional MHD simulation (e.g., Ohsuga et al. 2005). The expected electron temperature of $>10^9$ K in the central part of the flow certainly exceeds the detection limit of VSOP-2/ASTRO-G at 22 GHz and 43 GHz. Hence, we prescribe electron temperature profile as $T_e = 5 \times 10^9 (r/r_b)^{-p} K$, where $p$ and $r_b$ are parameters. In this study, we calculate three cases of $p$: $p = 0.1, 0.5, and 1.0$. Note that the last model has the same temperature profile as that of ions. As for the parameter $r_b$, we determine the value so as to reproduce the observed energy spectrum, finding $r_b \sim 100 r_g$. Similar electron temperature profiles were used in past studies (e.g., Broderick & Loeb 2009; Nagakura & Takahashi 2010) and successfully reproduced the observed energy spectrum and images. At 22 GHz and 43 GHz, the energy spectrum is well explained by thermal synchrotron emission (e.g., Di Matteo et al. 2003; Wang et al. 2008; Li et al. 2009; Broderick & Loeb 2009; Nagakura & Takahashi 2010).

When the radiative cooling is not so efficient above $\sim 10^{10}$ K and/or the energy transportation from ions to electrons is very efficient, electron temperatures can increase with decreasing $r$. So, the radial profile of the electron temperature contains important information about the electron heating mechanism of the accretion flow. In this study, we show that the images obtained by the space-VLBI observations can put useful constraints on the electron temperature profile.

Further, we need to prescribe the inner edge and the velocity pattern of the accretion disk. We consider two cases for the inner edge of the luminous part of the accretion disk: one is at the innermost stable circular orbit (ISCO), $r_{\text{ISCO}}$, and the other is at the event horizon, $r_h$. In this study, we assume a sub-Keplerian velocity profile with the angular velocity given as $\Omega = \Omega_1 v / \sqrt{r}$ and the radial component of the four-velocity given as $u^r = u_1 v / \sqrt{r}$ where $\Omega_1$ and $u_1$ are the Keplerian angular velocity and the radial four-velocity component of the freely falling motion with zero angular momentum at infinity, respectively. We expect that the accretion disk in M87 has a sub-Keplerian velocity distribution near the black hole. As for the cases of different velocity profiles (such as freely falling motion and Keplerian rotation), see discussion in Section 4.

The viewing angle, $i$, between the direction of the observer and the rotation axis of the disk is assumed to be $i = 45^\circ$. Although in the past studies an inclination angle of $i = 30^\circ$ is used (e.g., Nagakura & Takahashi 2010), we have confirmed that the main results in this study do not change even if $i = 30^\circ$ is used. Based on the assumptions described above, we perform general relativistic ray-tracing calculations in the Kerr spacetime; that is, we fully incorporate the relativistic effects, such as frame-dragging, gravitational redshift, bending of light, and Doppler boosting. Our calculation methods are prescribed in our past papers, i.e., Takahashi & Watarai (2007), Nagakura & Takahashi (2010), and the appendix of Takahashi & Harada (2010).

After calculating the simulation images of the intensity $I_e$, with observed frequency at 22 GHz and 43 GHz by assuming the thermal synchrotron spectrum, we calculate the expected images smeared out by the spatial resolution of $\sim 38 \mu\text{as}$ with realistic $u-v$ coverage data created by the simulation tool, the Astronomical Radio Interferometer Simulator (ARIS; Asaki et al. 2007). In the left panel of Figure 2, we show a sample of the $u-v$ coverage of the VSOP-2 (ASTRO-G satellite and VLBA) for the observation of M87 within one day. By using this $u-v$ coverage, the synthesized dirty beam is calculated as shown in the right panel of Figure 2. The scale of the dirty beam shown in this figure is calculated based on model B.

The calculation method of the observed image smeared by the spatial resolution of the VSOP-2/ASTRO-G observations is as follows. (1) From the dirty beam, the primary lobes of the clean beam can be calculated by fitting the primary component of the dirty beam by an elliptical Gaussian. (2) We calculate the visibility $V(u, v)$, that is, the Fourier components of the elliptic Gaussian beam $S(u, v)$ and the theoretical images. (3) The map of the spatially smoothed intensity $I_e$ is calculated as $I_e(x, y) = \int e^{2\pi i (x u + y v)} S(u, v)V(u, v)du dv$ (e.g., Clark 1999; Thompson et al. 2001, hereafter TMS). The image produced based on this procedure basically corresponds to the image produced by the CLEAN deconvolution algorithm if the algorithm works well and if the effects of the sidelobe can be

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completely removed, i.e., no deconvolution errors (see Section 4 for important discussion on the data deconvolution method for the image containing the dark region around the black hole). In the CLEAN deconvolution algorithm (e.g., Section 11.2 of TMS) which is usually used in radio data analysis, the clean map is calculated by first extracting the dirty beam components with some factor from the dirty map and then replacing the dirty beam with a Gaussian (or similar functions that are free from negative values). If this procedure works well, the effects of the sidelobe patterns can be removed and the resultant image made by the CLEAN deconvolution algorithm corresponds to the image which is obtained from the original image smeared with the Gaussian. Therefore, the image produced by the calculation method used in this study (as denoted above) corresponds to images with no deconvolution errors and no effects of the sidelobe in the CLEAN deconvolution algorithm. For possible problems in the application of the CLEAN deconvolution algorithm to images with a dark region around the black hole, see the discussions in Section 4.

In this study, we calculate the smeared images for 30 models (for model parameters see Table 2). We first prescribe the outer radius of (the luminous part of) the accretion disk as follows. According to the past observed images of M87 from radio interferometers the size of an emitting region is about a few to several hundreds of microarcseconds (e.g., Junor et al. 1999; Dodson et al. 2006). Note, however, that the actual length scale should depend on the distance, $D$, for a fixed value of the angular size, and the gravitational radius depends on the mass, $M$. In order that the emitting region size should be consistent with the past observational data, we adopt $r_{\text{out}} = 66, 110$, and 220 ($r_g$) for Models A, B, and C, respectively (see Table 2). As to the inner radius and the spin parameter, we consider three sets of their combinations: (1) $(a, r_{\text{in}}) = (0, r_{\text{ISCO}})$, (2) $(0, r_{\text{H}})$, and (3) $(0.998, r_{\text{H}})$. From the model names, we can get information on the assumed parameters, which include $M$, $D$ (from A, B, or C, see Table 1), $a$, $r_{\text{in}}$ (from (1), (2), or (3)), and $p$ (from p01, p05, and p1).

3. APPEARANCE OF THE ACCRETION DISK AROUND A BLACK HOLE

3.1. Overview

Figure 3 shows the results of the observed intensity distributions for the case of $p = 0.5$ (i.e., $T_e \propto r^{-0.5}$). From the left to right panels, we show the theoretical (unsmoothed) images (first column), images smeared with the $u-v$ coverage of the space-VLBI observations based on models A, B, and C in Table 1 (second, third, and fourth columns), and images smeared with an elliptical beam size of $0.3 \text{ mas} \times 0.2 \text{ mas}$ as in the past observations (Dodson et al. 2006; fifth column). From the top to bottom panels, we show the results for the above cases (a) top, (b) middle, and (c) bottom. In this figure, the normalized intensity variation along the horizontal line passing the center is also shown for each image (blue solid line). For other information, see the caption of Figure 3.

For all the cases of the space-VLBI observations (second, third, and fourth columns), the asymmetry of the observed intensity with respect to the vertical line passing the intensity peak can be clearly seen, while in the images smeared by the resolution of past observations (fifth column) such asymmetry cannot be seen. In all the cases of the space-VLBI observations except models of C(b)p05 and C(c)p05, furthermore, an underluminous region (i.e., deficit of the observed intensity) around the central black hole can be seen; that is, a second peak of the intensity can be clearly seen. The size of the underluminous region is nearly the same as that of the beam size (gray ellipse) for models of A(a)p05, A(b)p05, A(c)p05, and B(a)p05 and is smaller than the beam size for models B(b)p05, B(c)p05, and C(a)p05. On the other hand, the intensity contrast amounts to $\sim 40\%$ for A(a)p05, $\sim 30\%$ for A(b)p05, A(c)p05, and B(a)p05, $\sim 20\%$ for models B(b)p05 and B(c)p05, and $\sim 10\%$ for model C(a)p05. In terms of the black hole spin, we cannot see any difference between $a = 0$ and 0.998, in the smeared images of the cases of $r_{\text{in}} = r_{\text{H}}$ (compare middle and bottom), while we can see a difference with $\sim 10\%$ difference of the intensity in the case of $r_{\text{in}} = r_{\text{ISCO}}$ (compare top and bottom). Here, note $r_{\text{H}} \sim r_{\text{ISCO}}$ for $a = 0.998$.

Here, we define the size $\ell_{\text{BH}}$ as the length between the two peaks of the intensity profile in units of $GM/c^2$, which gives the size of the underluminous region around the central black hole, i.e., from the value of $\ell_{\text{BH}}$, the spatial size containing the black hole can be measured. When there is only one peak in the intensity profile, the size $\ell_{\text{BH}}$ cannot be defined. In Table 2, we summarize the values of $\ell_{\text{BH}}$ for all models. In the case of Sgr A*, the VLBI observations put constraints on the size of the region containing the black hole as $\sim 25.2 \text{ GM}/c^2$ from the size measurements of the observed intensity (Shen et al. 2005). In Table 2, we can see that models A(a)p05, A(b)p05, A(c)p05, B(a)p05, B(b)p05, and B(c)p05 give constraints of $\ell_{\text{BH}}$ around $\sim 25 \text{ GM}/c^2$ corresponding to the size obtained in Sgr A*. In all models with $p = 0.1$, we find $\ell_{\text{BH}} \gtrsim 100$. In models of A(a)p1, A(b)p1, A(c)p1, B(a)p1, B(b)p1, and B(c)p1, on the other hand, the size $\ell_{\text{BH}}$ is smaller than $\lesssim 19 \text{ GM}/c^2$, which gives a more stringent constraint than the case of Sgr A*. If this is the case, the space-VLBI observations can put useful constraints on the size $\ell_{\text{BH}}$ of the region containing the black hole. In Table 2, we also indicate whether the asymmetry (ninth column) and the deficit (tenth column) in the intensity profile can be seen or not for all the calculated models. Although the asymmetric signature can be seen (or marginally seen) for all the models, the deficit cannot be seen for some models.

3.2. Temperature Profiles

Next, Figure 4 compares the cases of different electron temperature profiles: $p = 0.1$ (green solid line), 0.5 (blue solid line), and 1 (pink solid line). In this figure, we show the normalized intensity variation along the line passing the center for 27 models listed in Table 2. All the lines for $p = 0.5$ are the same as those of Figure 3 and the lines for $p = 0.1$ and 1 are calculated in the same way as those in Figure 3. For all the cases of the space-VLBI observations (second, third, and fourth columns) except for models of C(b)p1 and C(c)p1, the asymmetry of the observed intensity with respect to the vertical line passing the intensity peak can be clearly seen, while in the cases of C(b)p1 and C(c)p1, the asymmetry can be only marginally seen.

On the other hand, we can clearly see the underluminous region around the black hole for all models except C(b)p05, C(c)p05, B(b)p1, B(c)p1, C(a)p1, C(b)p1, and C(c)p1. In general, the steeper the radial temperature profile is (e.g., $p = 1$), the more difficult it becomes to see the asymmetry of the intensity and the underluminous region around the black hole. This is because the size of the effectively emitting region for $p = 1$ is smaller compared with other cases ($p = 0.1$ and 0.5) and so the luminous part of the image tends to be smeared out. The observational feasibility of the effects of the
Figure 3. Images of an accretion flow surrounding a black hole with the characteristics of M87. The emitting accretion flow is assumed to have a sub-Keplerian velocity field with an electron temperature profile of $T_e = 5 \times 10^9$ K $(r/r_g)^{-p}$ with $p = 0.5$ and $r_g = 100 r_g$. From the left to right panels, the theoretical (unsmeared) images for models A, B, and C (in Table 1) (second, third, and fourth columns), and the images smeared by the beam size of the past observation (with 0.3 mas × 0.2 mas; Dodson et al. 2006; fifth column), respectively. The black hole is either (a, b) non-rotating ($a = 0$) or (c) maximally rotating ($a = 0.998$). The viewing angle is fixed to be $i = 45^\circ$ in this figure. The inner edge of the accretion flow is either at (a) the radius of the innermost stable circular orbit (ISCO) $r_{\text{ISCO}}$ or (b, c) at the event horizon $r_H$. The left panels show the results based on models A(a)p05, A(b)p05, and A(c)p05, while the right panels are based on models B(a)p05, B(b)p05, and B(c)p05. These model parameters are summarized in Table 2. The rotation axis of the accretion flow and the black hole is also shown (green dotted lines) in the left panels. The normalized intensity variations along the horizontal line passing the black hole center are overlaid (blue lines). The vertical and horizontal width of images is $100 \frac{GM}{(c^2D)}$ which corresponds to about 295 µas (A), 185 µas (B), and 93 µas (C). (A color version of this figure is available in the online journal.)

Figure 4. Normalized intensity variations along the line passing the black hole center for $p = 0.1$ (green lines), 0.5 (blue lines), and 1 (pink lines), respectively. All the lines for $p = 0.5$ are the same as those in Figure 3. The normalized intensity variations are shown for the theoretical (unsmeared) images (first column), the images smeared with the $u$–$v$ coverage of the next-generation space-VLBI observations for models A, B, and C (in Table 1; second, third, and fourth columns), and the images smeared with the resolution of the past observation, respectively. The lines of $p = 0.5$ are the same as those in Figure 3 (fifth column). The vertical width is $100 \frac{GM}{(c^2D)}$ which corresponds to about 295 µas (A), 185 µas (B), and 93 µas (C). See Table 2 for model parameters of the plotted 27 models. (A color version of this figure is available in the online journal.)
black hole spin is basically the same as that in the case of $p = 0.5$ described above, i.e., in the smeared images of the cases with $r_{in} = r_H$ (compare middle and bottom), we cannot see a difference between the cases with $a = 0$ and 0.998, while in the case with $r_{in} = r_{ISCO}$ (compare top and bottom) we can.

### 3.3. Observational Errors

So far, we implicitly neglected the effects of the noise introduced by the observations. Even when wide $u$-$v$ coverage is achieved by the space-VLBI satellite, the observational features investigated above if noise is large will not be completely obtained. The noise is caused by several factors, e.g., deviations of the antenna surface from the ideal profile (for details, see TMS). The complex visibility $V$ is affected by the noise as $Z = V + \bar{\epsilon}$, where $Z$ is the measured visibility (including the effects of the noise) and $\bar{\epsilon}$ is the noise components (see Figure 6.8 in TMS). The effects of the noise can be included. In this paper, we take the effects into account if noise is large will not be completely obtained.

Based on the probability distribution of the noise (in Section 9.3 of TMS) and the assumed value of $R_{SN}$, the effects of the noise can be included. In this paper, we take the following procedures to include the noise effects.

1. First, we calculate the average flux density $\bar{\sigma}_{source}$ for each model in Table 2.
2. Next, we prescribe a single value of $R_{SN}$, e.g., $R_{SN} = 50$, and calculate the standard deviation of the noise $\sigma_{noise} = \bar{\sigma}_{source}/R_{SN}$ based on the calculated value of $\bar{\sigma}_{source}$ and the assumed $R_{SN}$.
3. Here, we injected a single noise value and input the noise effects into $(u, v)$-points. For the single value of $\sigma_{noise}$ calculated in the last stage and the Gaussian probability distribution function of the noise (given in Sections 6.2 and 9.3 of TMS), we can produce random Gaussian noises. In this stage, we randomly input the Gaussian noise on each $(u, v)$-point of the measured visibility which is calculated from the theoretical image by Fourier transformation, i.e., we have a noisy visibility map in this stage. It is noted that at this stage since the noise is randomly produced for each

| Model  | M&D | $a$ | $i$ | $r_{in}$ | $r_{out}$ | $\ell_{BH}$ | Asymmetry | Deficit | Figure |
|--------|-----|-----|-----|----------|----------|----------|-----------|---------|--------|
| $p = 0.5$ | A(ap05) | A | 0 | 45$^\circ$ | $r_{ISCO}$ | 66 | 20 | Yes | Yes | 3, 4 |
|        | A(bp05) | A | 0 | 45$^\circ$ | $r_H$ | 66 | 20 | Yes | Yes | 3, 4, 7 |
|        | A(cp05) | A | 0.998 | 45$^\circ$ | $r_H$ | 66 | 20 | Yes | Yes | 3, 4 |
|        | B(ap05) | B | 0 | 45$^\circ$ | $r_{ISCO}$ | 110 | 26 | Yes | Yes | 3, 4 |
|        | B(bp05) | B | 0 | 45$^\circ$ | $r_H$ | 110 | 24 | Yes | Yes | 3, 4, 5 |
|        | B(cp05) | B | 0.998 | 45$^\circ$ | $r_{ISCO}$ | 110 | 25 | Yes | Yes | 3, 4 |
|        | C(ap05) | C | 0 | 45$^\circ$ | $r_{ISCO}$ | 120 | 28 | Yes | Yes | 3, 4 |
|        | C(bp05) | C | 0 | 45$^\circ$ | $r_H$ | 220 | 39$^b$ | Yes | No | 3, 4 |
|        | C(cp05) | C | 0.998 | 45$^\circ$ | $r_{ISCO}$ | 220 | 38$^b$ | Yes | No | 3, 4 |

Notes.

$^a$ In units of $r_g \equiv GM/c^2$.

$^b$ Marginal value.
visibility point, the noise values are different at different
\((u, v)\)-points.
4. From the noisy visibility calculated at stage 3, we convolve
the sampling function calculated from the \(u–v\) coverage of the
space-VLBI satellite and the ground-based interferometers. We then calculate a noisy image by inverse Fourier
transformation.
5. We make 10 independent noisy images in this stage, i.e.,
stages 3 and 4 are repeated 10 times based on different
Gaussian random noise patterns.
6. Finally, we average the 10 noisy images.

In this procedure, we calculate the noisy image from the
theoretical original image for an assumed value of \(\mathcal{R}_{\text{SN}}\). It is
noted that the value of \(\mathcal{R}_{\text{SN}}\) represents the SN ratio for the
averaged value of the source flux density (from the definition of
\(\mathcal{R}_{\text{SN}}\)) and the actual SN ratios at different points of the image (or
the visibility) are different. In general, around the most luminous
part of the image where the value of the flux is larger than the
averaged flux, the SN ratios are much higher than \(\mathcal{R}_{\text{SN}}\) which
represents the average SN ratio.

In the left panel of Figure 5, for the observed frequency
43 GHz, we show the normalized intensity variations for model
B(b)p05 with \(\mathcal{R}_{\text{SN}} = 10, 50\), and without noise. These curves
with noise are calculated by the average of the 10 curves with
different noise patterns. In this way, we find that a deficit of the
intensity can be measured for \(\mathcal{R}_{\text{SN}} \gtrsim 10\). In the curves of
\(\mathcal{R}_{\text{SN}} = 10\) and 50, another deficit of the intensity caused
by the noise can be seen around \(x\). The depths of these
deficits (around \(x \sim 40\)) are comparable to those of the deficit
caused by the center caused by the existence of the black hole. We
also calculated the case for \(\mathcal{R}_{\text{SN}} = 100\) and confirmed that the
deficits around \(x \sim 40\) disappear.

Here, for the ASTRO-G satellite, we estimate the value of
\(\mathcal{S}_{\text{E}}\) satisfying the condition of \(\mathcal{R}_{\text{SN}} \gtrsim 10\) or \(\gtrsim 100\). By using
the values of \(\mathcal{S}_{\text{E}} \gtrsim 1 \text{ Jy for M87, } \mathcal{S}_{\text{E}} \gtrsim 1500 \text{ Jy for the}
\text{Very Large Baseline Array (VLBA), } \eta_0 = 0.7, \Delta v = 256 \text{ MHz}
\text{and } \tau_a = 60 \text{ s, the SEFD required for the observations satisfying}
\mathcal{R}_{\text{SN}} \gtrsim 10 \text{ is } \mathcal{S}_{\text{E}} \gtrsim 1.0 \times 10^5 \text{ Jy, and for } \mathcal{R}_{\text{SN}} \gtrsim 100, \text{the}
\text{required SEFD is } \mathcal{S}_{\text{E}} \gtrsim 1.0 \times 10^8 \text{ Jy. At 43 GHz, the nominal and the}
\text{possible worst values of } \mathcal{S}_{\text{E}} \text{ are 28,000 Jy and 190,000 Jy for the}
\text{ASTRO-G satellite. Therefore, we can expect the SN value around}
\mathcal{R}_{\text{SN}} \sim 10–100 \text{ for the nominal value of } \mathcal{S}_{\text{E}} \text{ (~28,000 Jy). For the worst value}
\text{of } \mathcal{S}_{\text{E}} \text{ (~190,000 Jy), the SN value is } \mathcal{R}_{\text{SN}} < 7, \text{ and then}
\text{useful images cannot be obtained.}

We also investigate the effects of the noise for the case of
22 GHz for model B(b)p05 (see the right panel of Figure 5).
The asymmetric brightness profile can be seen for the cases of
\(\mathcal{R}_{\text{SN}} = 50\) and 100. From these curves, we can marginally put a
constraint on the size \(\ell_{\text{BH}}\) as \(\ell_{\text{BH}} \sim 30 \text{ GM}\!/c^2\) for \(\mathcal{R}_{\text{SN}} \sim 100\)
and \(\sim 35 \text{ GM}\!/c^2\) for \(\mathcal{R}_{\text{SN}} \sim 50\). In these cases, however, we
cannot see a deficit of the observed intensity around the black
hole. In the same way as we did for 43 GHz, we estimate the
value of \(\mathcal{S}_{\text{E}}\) satisfying the condition of \(\mathcal{R}_{\text{SN}} \gtrsim 50\). By using
the values of \(\mathcal{S}_{\text{E}} \gtrsim 500 \text{ Jy for the VLBA, } \tau_a = 120 \text{ s and the same values for other parameters, the SEFD at 22 GHz}
\text{required for the observations satisfying } \mathcal{R}_{\text{SN}} \gtrsim 50 \text{ becomes}
\mathcal{S}_{\text{E}} \gtrsim 2.4 \times 10^4 \text{ Jy. At 22 GHz, the nominal and the possible}
\text{worst values of } \mathcal{S}_{\text{E}} \text{ are 5000 Jy and 8200 Jy for the ASTRO-
G satellite.}\text{ Even for the worst case, we can expect the SN value larger than } 100, \text{ i.e.,}
\mathcal{R}_{\text{SN}} \gtrsim 100. \text{ Therefore, the observations at 22 GHz by the VSOP-2/ASTRO-G will be able to detect the}
\text{asymmetric brightness profile of the accretion flow around the}
\text{black hole. This means that such observations will give new}
\text{evidence for the existence of a black hole within the size of}
\mathcal{\ell}_{\text{BH}} \sim 30 \text{ GM}\!/c^2\text{ in M87.}

4. DISCUSSION

In this study, we aim at extracting the essential features of
the M87 image to be observed with a technically feasible space-
VLBI satellite. For the purpose of calculation, we have made
several assumptions and simplifications. Here, we discuss how
realistic our numerical treatments are.

As is well known, bright jets emerge from the M87 black
hole. In this study, we implicitly neglected their contribution to
the radio emission at 43 GHz and 22 GHz. We also neglected the
nonthermal electron component. These treatments can be
justified, since the outflow component can be negligible at
43 GHz compared with the disk component (Junor et al. 1999; Di
Matteo et al. 2003; Dodson et al. 2006), although it should be
included in the other energy bands (Broderick & Loeb 2009;

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Li et al. 2009). Further, the observed energy spectrum can be fitted by the thermal synchrotron as was already mentioned in the previous section. Furthermore, since the electromagnetic radiation from the jets is likely to be generated by internal processes (e.g., Broderick & Loeb 2009), the Keplerian rotation model typically shows sub-Keplerian rotation. In the past studies (e.g., Broderick & Loeb 2009), the Keplerian rotation model is considered. Since the Doppler boosting effects become much stronger in the case of Keplerian rotation, we expect that the asymmetry of the intensity variation shown in Figures 3 and 4 will be more prominent. In the case of freely falling motion, conversely, the asymmetry of the intensity variation will be less pronounced compared with the sub-Keplerian cases considered in this study.

In this study, we also neglected the effects of a finite disk thickness. Since in the case of M87 the viewing angle is not large, i.e., \( i \lesssim 45^\circ \), the effect of the disk thickness is negligible and we have confirmed this by including the effects of the thickness for some samples. Concerning the viewing angle, some past studies used smaller value, such as \( i = 15^\circ \)–\( 20^\circ \) (e.g., Broderick & Loeb 2009, and references therein). We have confirmed that the main results in this study will not be changed even for such small viewing angles. In Figure 6, we plot the normalized intensity variations along the line passing the black hole center for \( i = 15^\circ \) (models B(a)p05i15, B(a)p05i15, and B(c)p05i15) and \( 45^\circ \) (models B(a)p05, B(a)p05, and B(c)p05). The curves for the cases of \( i = 45^\circ \) are the same as those plotted in Figures 3 and 4. From these plots, we can clearly see asymmetric signatures and central dark regions for the cases with \( i = 15^\circ \) as in the cases of \( i = 45^\circ \). For the cases with \( i = 15^\circ \), the size \( \ell_{BH} \) which is the length between the two peaks of the intensity profile is also calculated and is summarized in Table 2. The differences in the intensities of the two peaks in the cases of \( i = 15^\circ \) are smaller than those in the cases of \( i = 45^\circ \). This is because in the cases of \( i = 15^\circ \) the Doppler boosting effects become smaller than for \( i = 45^\circ \). For the cases with \( i = 15^\circ \)–\( 45^\circ \), we expect similar features (e.g., the asymmetric intensity profile, the central dark region) as shown in Figures 3 and 4.

As shown in the previous section, the effects of the black hole spin can be seen by the space-VLBI observations at 43 GHz for the case of \( r_{in} = r_{ISCO} \) as far as the stationary accretion disk model is concerned. However, the realistic accretion flow shows significant time variability. For the black hole in M87, the Keplerian rotation timescale, \( T \), at \( r_{ISCO} \) is \( T \sim 9.2 \times 10^4 \) s \( \left( \frac{r_{ISCO}}{r_g} \right)^{3/2} + a \left[ \frac{M}{(3.0 \times 10^9 M_\odot)} \right] \) for a distant observer. This timescale corresponds to 16 d and 2.1 d for a non-rotating and a maximally rotating black hole, respectively, and both are longer than the typical duration of a VLBI observation. Thus, intensity inhomogeneities in the M87 accretion disk and time-variable signatures (i.e., flares) will be detected by continuous observations with the space-VLBI satellites. If such observations are performed, the black hole spin will be measured from the variation timescale of the observed flux, and the space-VLBI observations will be able to confirm the claim by Wang et al. (2008) that the M87 black hole is rapidly rotating. Moreover, such inhomogeneity will produce a transient deficit of the observed flux, which is similar to that around the black hole. However, the former will be time-variable while the latter will be stable both in time and position. It is thus easy to discriminate one from the other. We will investigate the details of these topics in the near future.

We should also discuss what information we can extract if no deficits nor asymmetry were detected in the observed intensity profile. In such cases, it is expected that the velocity patterns should nearly be free-fall as long as the disk is luminous, or that only the jet component can be seen and the accretion disk is not luminous due to a low mass accretion rate and/or weak magnetic field strength, i.e., radiative efficiency is very small. In the present study we calculated the smeared images by the convolution of the visibility of the theoretical image and the Fourier component of the elliptic Gaussian beam. When actual observational data are obtained, however, radio observers usually make images by other traditional procedures, such as the method based on the CLEAN deconvolution algorithm (see Section 11.2 of TMS and references therein). We can, in principle and if successful, produce similar images to what we calculated here by the CLEAN deconvolution algorithm, but we should be aware in actual data analyses that spurious artifacts or some spurious structures are often generated in the image during the course of the CLEAN deconvolution algorithm (see discussion in TMS). When the CLEAN deconvolution algorithm is not successful, therefore, the effects of the sidelobe pattern cannot be completely removed, i.e., deconvolution errors remain. If this is the case, the calculated images do not reproduce the true images, and so we cannot correctly extract scientific information from the data. In order to see this explicitly, we...
have obtained the following results. In this study, we applied to other similar space-VLBI missions. In this study, we of the ASTRO-G as an example, the results obtained can be M87. Although in this paper we mainly used the parameters of the intensity map caused by the disk’s rotation can be determined and this gives additional evidence for the existence of the supermassive black hole in M87.

5. CONCLUSIONS

To summarize, we investigate the observational feasibility of the central structure of the accretion disk, including the black hole shadow, with the space-VLBI observations at 22 GHz and 43 GHz by solving the radiative transfer equation in the Kerr spacetime and adopting the accretion flow model proposed for M87. Although in this paper we mainly used the parameters of the ASTRO-G as an example, the results obtained can be applied to other similar space-VLBI missions. In this study, we have obtained the following results.

1. Our simulations have demonstrated that the asymmetry of the intensity map caused by the disk’s rotation can be detected by space-VLBI observations both at 22 GHz and 43 GHz. That is, the position of the black hole can be determined and this gives additional evidence for the existence of the supermassive black hole in M87.

2. In order to achieve these scientific goals and those described below, the signal-to-noise ratio $R_{SN}$ of the observations should be larger than at least 10 and desirably 50–100 for the observation at 43 GHz. If the nominal value of the SEFD of the ASTRO-G satellite at 43 GHz is achieved, i.e., $S_E^{satellite} \sim 28,000$ Jy, we can expect such SN ratios, while for the worst case (i.e., $S_E^{satellite} \sim 190,000$ Jy), such SN ratios cannot be expected. At 22 GHz, the required SEFD to detect the asymmetric profile is larger than the planned value of the VSOP-2/ASTRO-G by several factors even for the worst SEFD value (i.e., $S_E^{satellite} \sim 8200$ Jy). The results at 22 GHz will be applied to the observations by the RadioAstron.

3. From the asymmetric profile, we can put a constraint on the size of the spatial region containing the black hole in M87 within $30 \, GM/c^2$, which is closer to the event horizon than ever before. If not, the viscosity mechanisms usually proposed by the accretion disk theory and the MHD/kinetic simulations should be largely altered or be strongly constrained.

4. We have shown that in the cases that the apparent size of the gravitational radius is $r_g/D \gtrsim 15$ mas (models A or B in Table 1) or that the electron temperature profile is not so steep (i.e., $p \lesssim 0.7$), the underluminous region around the central black hole can also be detected by the space-VLBI observations at 43 GHz. Such a relatively flat ($p \lesssim 0.7$) electron temperature profile is predicted by the accretion disk theory and the three-dimensional MHD simulations. If the underluminous region is detected, this gives very strong evidence for the existence of the black hole shadow (or black hole silhouette) around the central black hole and may become the first direct test of general relativity in the strong gravity region around the supermassive black hole.

5. We have also shown in the case of $r_m = r_ISCO$ that the black hole spin can also be detected by the space-VLBI observations at 43 GHz. If such observation is performed, the spin value proposed by the past studies (Wang et al. 2008; Li et al. 2009) will be independently checked and the observation by the space-VLBI observations at 43 GHz gives more direct evidence for black hole rotation.

Finally, since the observational features of the intensity map (including the asymmetry and the underluminous region) depend on the electron temperature profile (see Figure 4), the space-VLBI observations at 43 GHz will give important information on the electron heating mechanism which is now one of the biggest unsolved problems of relativistic plasmas in curved spacetime.

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