The Sub-millimeter emission and the visibility of Sagittarius A*

Lei Huang1,3, Z-Q Shen2,3, S Liu1, F Yuan2,3, M Cai3, H Li1 and C L Fryer4

E-mail: mlhuang@ustc.edu.cn

1 Center for Astrophysics, University of Science and Technology of China, Hefei 230026, China
2 Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
3 Joint Institute for Galaxy and Cosmology of ShAO and USTC, Shanghai 200030, China
4 Los Alamos National Laboratory, Los Alamos, NM 87545
5 Academia Sinica, Institute of Astronomy and Astrophysics, Taipei 106, Taiwan

Abstract. We adopt the ray-tracing algorithm to simulate the emission from Sagittarius (Sgr) A* with three theoretical models, i.e., the radiatively inefficient accretion flow, jet model, and MRI-driven Keplerian accretion flow with highly-magnetized plasma. By compared to the millimeter VLBI imaging and polarization results, our simulation imposes some constraints on the orientation of the central black hole with regard to the accretion flow or jet. These models can further predict black hole shadow images and corresponding visibility profiles along specific sub-millimeter VLBI baselines, providing reasonable explanations for the preliminary data at 1.3mm.

1. Introduction

Sagittarius (Sgr) A*, the non-thermal radio source with a mass of $\sim 4 \times 10^6 M_\odot$, residing at the center of our Milky Way Galaxy, is the best super-massive black hole candidate that can be well studied by current observations. The updating observations suggest a stable geometry for the emitting plasma around the assumed black hole and provide orientation constraints. Various theoretical models with unique geometries are therefore in face of strict challenges. To test these models, we focus on recent size measurements [18] and polarization observations [2, 11, 13, 14, 15] in Section 2. We then show in Section 3 that some existing models can fit recent detection from high resolution sub-millimeter VLBI observations. We finally give simple discussion and instructive predictions on further detections to support the black hole nature of Sgr A* in the last Section.

2. Orientation Constraints of Theoretical Models

The structure of the dominant emitting region of Sgr A* is poorly known by VLBI observations in centimeter bands, since the images are significantly washed out due to the inter-stellar scattering. In millimeter bands, however, its intrinsic structure cannot be neglected to explain the apparent angular sizes. Considering the General Relativity effect by the ray-tracing simulation and the scatter broadening, we can simulate the emitting region in millimeter bands using a theoretical model with specific orientation. The simulated image might be chosen, or rejected, when compared with observations.
Adopting the observed images in elliptical Gaussian distribution with the position angle of 80°, and FWHMs of 0.724±0.001 mas by 0.384±0.013 mas (at λ 7mm) and 0.21±0.02 mas by 0.13±0.05 mas (λ 3.5mm) [18], we’ve constrained the RIAF (radiatively inefficient accretion flow [19]) model to be highly-inclined and nearly North-oriented by its central axis [8]. Here we choose two typical well-fit cases of RIAF with inclination angle (i) of 75° and position angle (Θ) of −10°, generating images in structure of ~ [0.72 mas × 0.37 mas, 80°] at λ 7mm and ~ [0.23 mas × 0.13 mas, 81°] at λ 3.5mm, and with i = 90°, Θ = −10°, in structure of ~ [0.72 mas × 0.38 mas, 80°] at λ 7mm and ~ [0.24 mas × 0.13 mas, 80°] at λ 3.5mm.

Markoff, Bower, & Falcke (2007) established 41 models with emission dominated by jet, and compared with closure quantities from the data at 7mm only [3]. They found that the data prefer those models with double jets, high inclination angle, and the position angle of 105° ± 15°. Here we choose three well-fit models, no.23, no.33 and no.41 from their 41 candidates all with i = 85°. We set the black hole spin a = 0.99 for no.33 and a = 0 for no.23 and no.41 in ray-tracing simulations in order to reproduce the spectrum. We further test the above observational structure constraints at λ 3.5mm. We find that a choice of Θ = 95° makes models no.23, no.33, and no.41 predict images in structure of ~ [0.22 mas × 0.09 mas, 81°], ~ [0.23 mas × 0.09 mas, 82°], and ~ [0.22 mas × 0.09 mas, 81°], respectively. Therefore, these three cases with specific orientations are considered as typical well-fit jet models.

We considered another Keplerian accretion flow in MRI-driven mode [10]. We choose three typical cases with i = 30°, 40°, and 50°, all with Θ = 120° and other model parameters as β = 0.7, β = 0.4, C = 0.47, and M = 6×10^{17} g·s^{-1} (see [9] for details). All these three cases produce images in structure of ~ [0.69 mas × 0.38 mas, 79°] at λ 7mm and ~ [0.18 mas × 0.11 mas , 79°] at λ 3.5mm. These cases would predict larger sizes by introducing a jet/outflow component [10]. Moreover, with azimuthal-dominated magnetic field configurations involved and birefringence effects treated self-consistently, these typical cases succeed in explaining some observed polarization properties, including the high linear polarization in sub-millimeter bands, flips in position angle of electronic vector from radio to NIR bands, and a weak left-hand circular polarization detected in sub-millimeter bands.

3. Sub-millimeter Images and Visibility Predictions
We’ve chosen two cases of the RIAF, three cases of the jet model, and three cases of the Keplerian torus as our favorite models. These models can provide reasonable explanations for the observed images in millimeter band. However, the real geometry of Sgr A* is still concealed by the interstellar scattering screen. One has to decrease the observational wavelength to sub-millimeter band to further minimize the broadening. As shown in figure 1, our simulations generate different morphology for each model at λ 1.3mm. There is obvious structure of black hole shadow, which results from the light-bending, in the RIAFs (the top two panels) or Keplerian tori (the bottom three panels). The images of jets are dominated by the nozzles connecting the event horizon and the jet base. Although the shadow structure is not as clear as those two accretion flow dominated models, the existence of central black hole causes gap between the two nozzles, making the image quite different from a simple Gaussian component in millimeter bands.

To detect the shadow structure of Sgr A* has become one of the most important and promising missions for the high resolution sub-millimeter VLBI observations. The VLBI observation at λ 1.3mm has been reported recently to successfully detect fringes along two baselines SMT0-CARMA and JCM1-SMTO [4]. To compare with these detections, we performed a 2-d Fourier transform for each of the models shown in figure 1 and then took two visibility slices, one in position angle (P.A.) of 50°(−130°) which is similar to that of the SMT0-CARMA baseline of ~ 0.8×10^3 km (0.66GΔA), the other is in P.A. of −70°(110°) similar to that of the JCM1-SMTO baseline of ~ 4.5×10^3 km (3.5GΔA). In figure 2, these two visibility slices of each model are plotted in dashed line (50° direction) and solid line (−70° direction), respectively. In general,
Figure 1. Simulated images of at λ 1.3mm. Top: images based on RIAF with $i = 75^\circ$ (left), 90° (right), and $\Theta = -10^\circ$. Middle: image based on jet model no.23 (left), no.33 (middle), and no.41 (right), all with $i = 85^\circ$ and $\Theta = 95^\circ$. Bottom: images based on Keplerian tori with $i = 30^\circ$ (left), 40° (middle), 50° (right), and $\Theta = 120^\circ$.

almost identified profiles of both dashed and solid lines on baseline lengths $< 2G\lambda$ are predicted by RIAFs, while the solid lines in more sharply decreasing profiles by jets and Keplerian tori, mainly due to their specific structures and orientations. Valley structures are presented in solid lines in all the cases, but at somehow shorter baseline lengths in RIAFs than jets and Keplerian tori, due to the compactness in their morphology. In dashed lines, RIAFs and jets easily produce valleys, but Keplerian tori don’t. This is because the Doppler effect is much more significant in the Keplerian rotation than in both the symmetrical jets and the sub-Keplerian rotation in RIAFs.

Compared with those visibility profiles with the preliminary data detected by the JCMT-SMTO-CARMA array, a timely check can be made on the predicted emission geometry. Our results show that two cases are selected as preferred explanations, the jet model no.33 with $a = 0.99, i = 85^\circ, \Theta = 95^\circ$ (the middle panel in the middle row) and a Keplerian torus with
Figure 2. The corresponding visibility profiles of images in figure 1, in 50°(–130°) direction projected by SMTO-CARMA baseline (dashed) and −70°(110°) direction projected by JCMT-SMTO baseline (solid). The symbols represent preliminary data of total flux density (thick dash), visibility amplitudes detected by SMTO-CARMA baseline (rhombus) and JCMT-SMTO baseline (square).

\( i = 40°, Θ = 120° \) (the middle panel in the bottom row). The other two jet models (the left and right panels in the middle row) overestimate the data in the JCMT-SMTO projected direction (in square). Notice that the central black hole is set rapidly rotating only in case no.33. This makes its image more compact than other two jets (see figure 1), predicting a farther valley then lower amplitude on longer baselines in the visibility. The three Keplerian tori (the bottom panels) all fit the data in SMTO-CARMA projected direction (in rhombus), with the middle case preferred, and marginally fit the data in JCMT-SMTO projected direction. The preferred Keplerian torus would provide better fittings with slightly more compact morphology, which might be achieved by setting a non-zero black hole spin inspired by the jet model results. The RIAFs (the top panels) seems to significantly underestimate the flux density (in thick dash at zero baseline ). However, this underestimation can be explained by that the Sgr A* was detected.
in its flaring state in this epoch.

4. Discussion
Sgr A* presents many relativistic properties associated with the assumed central black hole. However, only the detection of its black hole shadow in sub-millimeter VLBI observations would provide a first strong support for its black hole nature. Special valleys in limited visibility profiles are characteristics of a shadow structure and can be analyzed to determine the geometry of its emitting region at an early stage (see [4] for details).

In the presentation of the VLBI detection at $\lambda$ 1.3mm [4], it has been reported that the preliminary data result in a size of $\sim 37\mu$as if fitted by a single Gaussian component, as done in millimeter bands. However, such fitting might be controversial since the size is much smaller than the predicted shadow size ($\sim 50\mu$as). It’s reasonable to consider valley structures in the visibility profiles, caused by the black hole shadow. We perform timely tests on the existing models associated with a central black hole, and first select a jet model with $i = 0.99$, $i = 85^\circ$, $\Theta \approx 95^\circ$ and a Keplerian torus with $i \approx 40^\circ$, $\Theta \approx 120^\circ$.

However, the observations cannot exclude other models of Sgr A* associated with black hole, or even other objects with solid surfaces at all. According to the descriptions of visibility profiles predicted by our favorite models, the important characteristics haven’t been detected yet. In order to unveil the black hole nature we are most interested in, we plot in figure 3 all the possible data that predicted by the preferred jet (left) and Keplerian torus (right) and could be detected by the JCMT-SMTO-CARMA array, with the uv-coverage of $\sim [3.5, 4.5] \times 10^3$km and $\sim [-45^\circ, -90^\circ]$ by JCMT-SMTO in the filled regions, of $\sim [2.9, 4.0] \times 10^3$km and $\sim [-45^\circ, -82^\circ]$ by JCMT-CARMA in the dotted regions, and of $\sim [0.2, 0.8] \times 10^3$km and $\sim [50^\circ, 70^\circ]$ by SMTO-CARMA in the dashed regions. From these plots, we make some instructive predictions for further observations as follows: (i) As a result of shadow structure, the detection at a shorter JCMT-CARMA baseline (dotted regions) should be less than, or comparable to the detection at a longer JCMT-SMTO baseline (filled regions). This would be quite different from a sharply deceasing Gaussian profile. (ii) The valley would present with greatest possibility in JCMT-CARMA baseline (dotted regions). (iii) Since the visibility amplitudes decrease more quickly in SMTO-CARMA baseline (dashed regions) in the jet prediction than the Keplerian torus
prediction, detections in a better accuracy would help to make further selections.

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References
[1] Bower G C et al. 2001 ApJ 555 L103
[2] Bower G C et al. 2003 ApJ 588 331
[3] Bower G C et al. 2004 Sci 304 704
[4] Doeleman S et al. in this proceedings
[5] Eckart A et al. 2006 A&A 455 1
[6] Marrone D P, Moran J M, Zhao J-H, Rao R 2007 ApJ 654 57
[7] Ghez A M et al. 2005 ApJ 620 744
[8] Huang L et al. 2007 MNRAS 379 833
[9] Huang L et al. 2008 ApJ 676 L119
[10] Liu S. et al. 2007 ApJ 668 L127
[11] Macquart J-P et al. 2006 ApJ 646 111
[12] Markoff S, Bower G C and Falcke H 2007 MNRAS 379 1519
[13] Marrone D P et al. 2006 ApJ 640 308
[14] Marrone D P et al. 2007 ApJ 654 57
[15] Meyer L et al. 2007 A&A 473 707
[16] Melia F and Falcke H 2001 ARA&A 39 309
[17] Schödel R et al. 2002 Nature 419 694
[18] Shen Z-Q et al. 2005 Nature 438 62
[19] Yuan F, Quataert E and Narayan R 2003 ApJ 598 301