High-resolution Millimeter-VLBI Imaging of Sgr A*

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Abstract. We present the highest resolution VLBI imaging observations of Sgr A* made at both 7 and 3.5 mm. These data reveal wavelength-dependent intrinsic sizes with an intrinsic emitting region at 3.5 mm of about 1 AU (at a distance of 8 kpc to the Galactic Center). When combined with the lower limit on the mass of Sgr A*, these size measurements provide strong evidence that Sgr A* is a super-massive black hole. We also detected a structural variation which results in an intrinsically symmetrical structure that increases in its intrinsic size by more than 25% at 7 mm.

1. Introduction

Sgr A*, the extremely compact non-thermal radio source at the galactic center, is a best candidate for a single super-massive black hole (SMBH) from both the observational studies and the theoretical models (cf. [1]). The determination of the orbital motions of those early-type stars within the vicinity of Sgr A* reveal a central dark mass about $4 \times 10^6 M_\odot$ within a radius of about 45 AU [2, 3]. On the other hand, the upper limit to the intrinsic proper motion of Sgr A* itself sets a lower limit of $0.4 \times 10^6 M_\odot$ to the mass directly associated with Sgr A* [4]. Now we can say that we have known the mass of Sgr A* to a great extent, the main uncertainty being the exact distance to the galactic center. But how big it is, and what it looks like, are different questions.

VLBI observations can provide the highest angular resolution achievable with any astronomical instruments [5]. At a distance of 8 kpc to Sgr A* at the galactic center [6], an angular separation of 1 mill-arcsecond (mas) corresponds to a linear size of 8 AU. The Schwarzschild radius ($R_{sc}$) of a $4 \times 10^6 M_\odot$ SMBH is $1.2 \times 10^{12}$ cm, or 0.08 AU or 10 micro-arcsecond ($\mu$as) in angular size. Indeed, Sgr A* is the closest SMBH candidate with the largest angular size of its Schwarzschild radius on the sky, and thus one of the best prime targets for the VLBI observational study.

2. Millimeter-VLBI of Sgr A*

Attempts to measure the Sgr A* structure with high-resolution VLBI observations at centimeter (cm) wavelength have suffered from the angular broadening caused by the diffractive scattering by the ionized interstellar medium, which dominates the resultant images with a $\lambda^2$-dependence apparent size, that is, $\Theta_{\text{obs}} = \Theta_{\text{cm}}^\lambda \lambda^2$, where $\Theta_{\text{obs}}$ is the observed full-width at half-maximum (FWHM) in mas at a wavelength $\lambda$ in cm, and equals $\Theta_{\text{cm}}^\lambda$ at 1 cm. This tells us that the cm radio emission of Sgr A* comes from a region that extends to observers a much smaller

1 for collaborators see acknowledgments
angle than the scattering angular size. However, following the $\lambda^2$-dependent scattering law, the scattering angle decreases very fast with the observing wavelength. So it can be expected that VLBI observations at millimeter (mm) wavelength, where the pure scattering angular size could become small enough to be comparable to the intrinsic (finite) size of Sgr $A^*$, would show deviations of the observed apparent size from the scattering law.

Unlike the cm-VLBI observations, the mm-VLBI observations are severely limited by the atmosphere due to the fact that Sgr $A^*$ has a southerly declination ($\sim -30^\circ$) and most existing VLBI antennas are located in the Northern Hemisphere. Therefore, most of the observational data of Sgr $A^*$ were taken at low elevation angles ($10^\circ - 20^\circ$) where atmospheric effects are substantial. Furthermore, the short and variable coherence time at mm wavelength, combined with the compromised sensitivity due to the high system temperature and the lower antenna efficiency of mm VLBI antennas, seriously limits the high signal-to-noise-ratio (SNR) detections of mm-VLBI observations of Sgr $A^*$. As a consequence, there are large uncertainties in the results obtained from the conventional imaging process, i.e. the self-calibration technique for VLBI imaging, whose biggest drawback is non-uniqueness when the SNR is poor.

2.1. Revision of Scattering Law

To circumvent the large uncertainty in the commonly used amplitude calibration of VLBA observations of Sgr $A^*$, we have since 2001 developed a model fitting program in which the amplitude closure relation is applied to minimize the calibration errors and thus to improve the accuracy of the measurements [7]. We then applied this procedure to refine the apparent size measurements of the first near-simultaneous VLBA+Y1 data [8] observed at five wavelengths (6, 3.6, 2, 1.35 cm, and 7 mm). By performing the weighted least-squares fits to these sizes at different wavelengths, we conclude that the best-fit two-dimensional scattering structure is [9]

$$\Theta_{\text{major}}^{\text{sca}} = (1.39 \pm 0.02)\lambda^2,$$

and

$$\Theta_{\text{minor}}^{\text{sca}} = (0.69 \pm 0.06)\lambda^2,$$

with a position angle of $80^\circ$. Here, $\Theta_{\text{major}}^{\text{sca}}$ and $\Theta_{\text{minor}}^{\text{sca}}$ are FWHM of major and minor axes in mas. This newly revised wavelength-dependent two-dimensional scattering structure is consistent with that from directly fitting to the closure amplitudes of somewhat different databases [10]. Compared with previous one (cf. [8]), new scattering law shows an even smaller scattering angular size along the East-West major axis direction.

2.2. Detections of Intrinsic Size

On November 3, 2002, we successfully carried out the first VLBA imaging observation of Sgr $A^*$ at its shortest wavelength of 3.5 mm [9]. Compared to the past 3.5 mm VLBI observations with the CMVA [11], our VLBA observation, with its dynamic scheduling, the highest possible recording rate and more frequent pointing calibration, has for the first time determined its elliptical structure in the radio emission at 3.5 mm, consistent with the morphology seen at longer wavelengths. It should be pointed out that dynamic observing is crucial to minimize the atmospheric effects in the mm-VLBI observation of Sgr $A^*$. The exact observing date is not fixed, but depends on the weather condition at most antenna sites which usually are separated by a few thousand kilometers. While observing, a frequent antenna pointing check observations of compact and strong SiO maser sources, roughly in every 10 minutes, is necessary to maintain the best reference (offset) pointing and calibration.

The best fitted apparent structure from November 2002 VLBA observations is $0.21^{+0.02}_{-0.01}$ mas by $0.13^{+0.05}_{-0.13}$ mas with a position angle $79^{+12}_{-33}$ degrees. The major axis size is well determined while the fitted size of the minor axis has a quite big error mainly due to the poor resolution.
along the North-South direction. By subtracting in quadrature the scattering angle from Eq. (1), we obtain, for the first time, an intrinsic size of 0.126±0.017 mas along the major axis at 3.5 mm. In September 2003, we performed the second 3.5 mm VLBA imaging observation of Sgr A*, which confirms the results in November 2002 (Shen et al. 2006 in preparation).

Similarly, two 7 mm VLBA+GBT (Green Bank Telescope) observations with the highest recording rate were dynamically scheduled in March 2004 with the resultant averaged sizes of the major and minor axes of 0.724±0.001 mas and 0.384±0.013 mas, respectively with position angle 80.6±0.5 degrees. The inclusion of GBT can improve the resolution in North-South direction by a factor of 3 [7], and actually this is the first VLBI observations to make use of the GBT at 7 mm. The results are consistent with the previous ones, but with much better accuracies. A significant deviation of measured size from the scattering angle along the major axis indicates an intrinsic size of 0.268±0.010 mas for the major axis [9], consistent with the previously reported detection of intrinsic size at 7 mm [11].

2.3. Temporal Variation in the Structure of Sgr A*

On May 31, 1999, Sgr A* was observed simultaneously at three 7 mm bands (39, 43 and 45 GHz). It shows a larger deviation in the apparent source size from scattering angle than that observed a week ago on May 23, 1999 [9]. Such a deviation is significant at about 3σ along the minor axis direction. Thus, for the first time we can estimate an intrinsic size along the minor axis of 0.359±0.095 mas. The derived intrinsic size for the major axis is 0.334±0.042 mas. Therefore, within the error bars, the intrinsic structure detected at 7 mm on May 31, 1999 could be treated as a circular. Compared with the previously detected major axis size of 0.268 mas, such an intrinsic structure has increased in its size by at least 25% at 7 mm.

3. Discussion

We have sampled a zone of the SMBH closer to the event horizon than ever before, by detecting the intrinsic size of Sgr A* to be only 1 AU, or 12.6 R_{sc}. Assuming an intrinsically spherical structure of Sgr A* and using the lower limit to the mass of Sgr A* of 4×10^5 M_{⊙} from the absolute proper motion work [4], we can easily derive a lower limit to the dark mass density of Sgr A* of 6.5×10^{21} M_{⊙} pc^{-3}. This is the highest mass density ever measured in any SMBH candidates, and thus strongly supports the SMBH nature of Sgr A*.

It is intriguing that the detected intrinsic size at 3.5 mm is about twice the diameter of the shadow caused by the strong gravitational bending of light rays [12]. Regardless of the exact emission model, the characteristic diameter of shadow is always about 5R_{sc}, which is nearly 50 μas for Sgr A*. So, Sgr A* will be the most important target for the future sub-mm VLBI experiment to test the general relativity in the strong field regime. Such kind of shadow, if confirmed, would be the most direct evidence for the existence of SMBH. The success of earlier single baseline 1.3 mm VLBI experiments [13] has already demonstrated the feasibility of capturing an image of the shadow around the edge of Sgr A* at sub-mm wavelengths in the near future.

From the two well determined intrinsic size at 7 [9, 11] and 3.5 mm [9], we can derive a λ^{β}-dependence of the intrinsic size with $β = 1.09^{+0.34}_{-0.32}$ using the two-point fit. This intrinsic size versus wavelength relation is consistent with the two lower limits of 0.02 and 0.008 mas at 1.3 and 0.8 mm, respectively, from the absence of refractive scintillation [14].

Such a wavelength dependence of the intrinsic major axis size provides a strong constraint on emission and accretion models for Sgr A*. It explicitly rules out explanations other than those models with stratified structure. It has been shown that the radiatively inefficient accretion flow (RIAF) model, after taking into account the interstellar scattering, can predict the observed sizes at both 7 and 3.5 mm quite well [15]. The extrapolated size of emitting region at 1 mm will reach the last stable orbit (LSO) radius of 3R_{sc} for a non-rotating SMBH. For a rotating
SMBH, the radius of LSO could be only $0.5R_{sc}$. Therefore, a break in the wavelength-dependent intrinsic size is inevitable with the decreasing wavelength, which can be used to constrain the spin of SMBH.

The radio flux density of Sgr A* is known to be variable at all the observable wavelengths on time scales of days to months. The variability appears to be more pronounced at shorter wavelengths with a relatively large amplitude fluctuation. For example, an intra-day variability (IDV) in the 2 mm flux density of Sgr A* has been found by the Nobeyama Millimeter Array (NMA) observations, indicating a very compact emitting region [16]. The correlation between flux density at 7 mm and spectral index suggests that the variation at the short radio wavelengths is intrinsic rather than due to the interstellar scintillation [17]. As such, it seems inevitable that the variability in the radio flux density of Sgr A* would be accompanied by the structural change. Our simulation seems to suggest that the detected structural variability on May 31, 1999 could be related to an outburst/flare occurred at about $50R_{sc}$ from the central SMBH (Shen et al. in preparation).

4. Conclusions
We have revised the scattering law, which gives a smaller scattering size along the East-West major axis direction. With the dynamic scheduling, we successfully carried out two 3.5 mm VLBA imaging observations, which reveal a consistent East-West elongated apparent structure. We also performed two-epoch new 7 mm VLBA+GBT observations with a better sensitivity and resolution. These new data show that the intrinsic size has come to play with the scattering effect at both 3.5 and 7 mm. The inferred intrinsic size is about 1 and 2.1 AU at 3.5 and 7 mm, respectively. The derived extraordinarily high (dark) mass density of Sgr A* strongly argues that Sgr A* is indeed a super-massive black hole.

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