Intrinsic Size and Shape of Sgr A*: 3.6 AU by <1 AU

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Abstract. By means of near-simultaneous multi-wavelength VLBA measurements, we determine for the first time the intrinsic size of Sgr A* to be 3.6 AU by <1 AU or 72 R_{sc}(\star) by <20 R_{sc}(\star), with the major axis oriented essentially north-south, where R_{sc}(\star) = 7.5 \times 10^{11} \text{ cm} is the Schwarzschild radius for a 2.5 \times 10^{6} \text{ M}_{\odot} black hole. Contrary to previous expectation that the intrinsic structure of Sgr A* is observable only at \lambda \leq 1 \text{ mm}, we can discern the intrinsic source size at \lambda 7 \text{ mm} because (1) the scattering size along the minor axis is half that along the major axis, and (2) the near simultaneous multi-wavelength mapping of Sgr A* makes it possible to extrapolate precisely the minor axis scattering angle at \lambda 7 \text{ mm}. The intrinsic size and shape place direct constraints on the various theoretical models for Sgr A*.

1. Introduction

Recent proper motion studies of the stars in the vicinity of Sgr A* have provided compelling evidence for the existence of a compact mass of 2.5 \times 10^{6} \text{ M}_{\odot} at Sgr A* (Eckart et al. 1997; and Ghez et al. 1998). Based on theoretical modeling, Narayan et al. (1998) have also shown that the spectral energy distribution (SED) of Sgr A* from radio up to \gamma-ray can be explained by an advection dominated accretion flow (ADAF), in which the presence of an event horizon would indicate that Sgr A* is in fact a massive black hole.

Over the past two decades since the discovery of this compact nonthermal radio source at the Galactic center (Balick & Brown 1974), VLBI observations of Sgr A* have revealed that the observed sizes follow a \lambda^2 dependence, and that the apparent source structure can be described by an elliptical Gaussian brightness distribution (e.g. Davies et al. 1976; Lo et al. 1981, 1985, 1993; Backer et al. 1993; Rogers et al. 1994; Krichbaum et al. 1998; Bower & Backer 1998). The corruption of the visibility function of Sgr A* due to the scattering by

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the interstellar electrons has been a persistent problem in resolving its intrinsic structure.

In this paper, we review the results from our recent work (Lo et al. 1998) in which we imaged Sgr A* with the Very Long Baseline Array (VLBA) nearly simultaneously at five wavelengths ($\lambda = 6.0, 3.6, 2.0, 1.35$ cm and $7$ mm). The multi-wavelength imaging, with the same interferometer array, is crucial for our differentiating interstellar scattering effects from the intrinsic source structure of Sgr A*. After taking out the scattering effect extrapolated from the long-wavelength data, we have for the first time determined that the intrinsic size of Sgr A* at 7 mm is asymmetric, being 3.6 AU by $<1$ AU, assuming a distance of 8.0 kpc to the Galactic center. The elongation is nearly N-S.

In addition, we also discuss the constraints of the radio observations on the existing theoretical models.

2. Observations and Data Reductions

The observations were made with 10 VLBA antennas and 1 VLA antenna at wavelengths 6.0, 3.6, 2.0 and 1.35 cm and 7 mm in February 1997. The hour angle coverage was UT12$^h$-20$^h$. A standard VLBA mode with BW of 32 MHz for both RCP and LCP was used. The visibility data were produced using the VLBA correlator at the Array Operation Center of the National Radio Astronomy Observatory (NRAO). The data reduction and calibration were discussed in Lo et al. (1998). We emphasize that the calibration is critical to the VLBA measurements, in particular, at the short wavelengths. With global fringe fitting, Sgr A* was detected on the short and intermediate baselines depending on the observed wavelengths while both calibrators NRAO 530 and PKS 1921-293 were detected on all the baselines. The amplitude calibrations of the visibility were done using the system temperature measurement at each site. The elevation dependent opacity corrections were done at the short wavelengths.

3. Data Analysis and Results

3.1. Measurements of The Angular Size and Structure of Sgr A*

An elliptical Gaussian model was fitted by the least-square method to both amplitudes and the phases of the calibrated visibility data to yield a quantitative description of the source structure. Table 1 summarizes the measurements at all five wavelengths. Fig. 1 shows the visibility data as a function of time and the fitted model in both amplitude and closure phase. The robustness of the fit is ensured by the good quality of the data and the availability of many baselines where the structure can be determined. The steadily improved performance of the VLBA played a pivotal role in the quality of this data set.

Fig. 2 shows both the major and minor axis diameters determined from our near-simultaneous multi-wavelength VLBA observations of Sgr A*. Fig. 3 shows the images of Sgr A* at the five wavelengths. The apparent major axis diameters can be fit by

$$\theta_{\text{maj}} = (1.43 \pm 0.02) \lambda^{1.99\pm0.03} \text{ mas},$$  \hspace{1cm} (1)
Figure 1. A plot shows the Gaussian elliptical model fitting (solid curves) to the visibility data at 7 mm (vertical bars). Left panels: amplitude vs. baseline pairs (BR-FD, BR-KP, FD-OV, FD-KP, OV-Y, and FD-LA). The maximum baseline lengths of the pairs are 2346, 1914, 1508, 744, 1025 and 607 kilometers, respectively. BR-FD is the longest baseline in NS. Right panels: closure phase triangles.
Figure 2. A log-log plot of measured (FWHM) source size versus observing wavelength for Sgr A* (7–14 February 1997). The solid line represents a $1.43 \lambda^{1.99}$ fit to the major axis sizes (open circles), while the dashed line a $0.76 \lambda^{2.0}$ fit to the minor axis sizes (filled circles).

which is in good agreement with the previous results of $1.42 \lambda^{2.0}$ mas (e.g. Alberdi et al. 1993). This result is also consistent with the value $\beta = 4$ for the power spectrum of the density fluctuations in the interstellar electrons ($\propto k^{-\beta}$, where $k$ is the wavenumber of the irregularities).

Along the minor axis, a fit to the measurements at all five wavelengths yields $\theta_{\min} = (1.06 \pm 0.10)\lambda_{\text{cm}}^{0.76 \pm 0.07}$ mas, which is inconsistent with the interstellar scattering. For a fit to the four points at $\lambda \geq 1.35$ cm, the apparent minor axis size $\theta_{\min} = (0.87 \pm 0.23)\lambda_{\text{cm}}^{1.87 \pm 0.16}$ mas, which is consistent, within the errors, with the $\lambda^2$–dependence expected from the interstellar scattering. If we assume that the $\lambda^2$–dependence derived for the major axis also applies to the minor axis, we obtain

$$\theta_{\min} = (0.76 \pm 0.05)\lambda_{\text{cm}}^{2.0} \text{ mas},$$

(2)

and a constant axial ratio of 0.53.

This is the first time that the $\lambda$–dependence of the minor axis diameter is determined directly by observations. Our results strongly suggest that interstellar scattering dominates the observed minor axis image at $\lambda \geq 1.35$ cm. The elongation of the scatter-broadened image can be caused by an anisotropic scattering medium in the vicinity of the Galactic center.
Figure 3. VLBA images of Sgr A* at wavelengths 6.0, 3.6, 2.0, 1.35 cm and 7 mm made with DIFMAP. These images are smoothed to a circular beam of FWHM = 2.62 $\lambda_{cm}^{1.5}$ mas as shown on the left-bottom corner on each image. At 7 mm, FWHM beam = 1.5 mas $\sim$ mean synthesis beam size; and at 6 cm FWHM beam = 38 mas that is close to the mean scattering size at this wavelength. The contours are 2 mJy beam$^{-1} \times (2, 4, 8, 16, 32, 64, 128, 256)$. 
Table 1. Parameters of Elliptical Gaussian Model Fit

| $\lambda$ (cm) | $\nu$ (GHz) | $S_\nu$ (Jy) | $\theta_{\text{major}}$ (arc s) | $\theta_{\text{minor}}$ (arc s) | Axial Ratio | P.A. ($^\circ$) |
|---------------|-------------|--------------|-----------------|-----------------|-------------|----------------|
| 6.03          | 4.97        | 0.60±0.09    | 49.6±4.50       | 25.1±2.00       | 0.54±0.09   | 84±8          |
| 3.56          | 8.41        | 0.73±0.10    | 18.0±1.53       | 9.88±1.68       | 0.55±0.14   | 78±6          |
| 1.96          | 15.3        | 0.68±0.06    | 5.84±0.48       | 3.13±1.14       | 0.54±0.21   | 73±14         |
| 1.35          | 22.2        | 0.74±0.04    | 2.70±0.15       | 1.50±0.59       | 0.56±0.25   | 81±11         |
| 0.69          | 43.2        | 1.03±0.01    | 0.70±0.01       | 0.58±0.07       | 0.83±0.11   | 87±8          |

3.2. The Intrinsic Structure of Sgr A* 

Comparing the measurement at $\lambda$ 7 mm with Eq. (2), we find a significant deviation of the observed minor axis diameter ($\theta_{\text{min}}$) from the scattering angle ($\theta_{\text{sc}}$) which is extrapolated from Eq. (2)

$$\Delta \theta_{\text{min}} \equiv \theta_{\text{min}} - \theta_{\text{sc}} = 0.21 \pm 0.07 \text{ mas.}$$  

(3)

The deviation of the apparent angular diameter ($\theta_{\text{obs}}$) from the $\lambda^2$-dependence is naturally expected when the intrinsic source diameter ($\theta_{\text{int}}$) becomes comparable to the scattering angle, since the observed apparent angular diameter $\theta_{\text{obs}} = \sqrt{\theta_{\text{int}}^2 + \theta_{\text{sc}}^2}$ (Narayan & Hubbard 1988). The deviation described by Eq. (3) implies that the intrinsic angular diameter at 7mm would be $\theta_{\text{int}} = 0.45 \pm 0.11$ mas for Sgr A* along the minor axis (PA = –10°, nearly N-S). From the measurements conducted by Bower and Backer (1998), we would have $\theta_{\text{min}} = 0.55 \pm 0.11$ mas, $\Delta \theta_{\text{min}} = 0.18 \pm 0.11$ mas, and $\theta_{\text{int}} = 0.41 \pm 0.17$ mas. Combining the two sets of measurements from both this paper and Bower and Backer, we obtain

$$\begin{align*}
\theta_{\text{min}} &= 0.57 \pm 0.06 \text{ mas}, \\
\Delta \theta_{\text{min}} &= 0.20 \pm 0.06 \text{ mas}, \\
\theta_{\text{int}} &= 0.44 \pm 0.09 \text{ mas},
\end{align*}$$  

(4)

The reasons that we can discern the intrinsic source size at $\lambda$ 7 mm, contrary to previous expectations that intrinsic source size is observable only at $\lambda \leq 1$mm, can be highlighted by the following two facts. First, the scattering size along the minor axis is half that along the major axis. In addition, the near simultaneous multiwavelength imaging of Sgr A*, with the same instrument, over the same hour angle coverage, and calibrated in a uniform manner, makes it possible to extrapolate precisely the minor axis scattering angle at $\lambda$ 7 mm.

Along the major axis (PA = 80°, essentially E-W), the observed angular diameter ($\theta_{\text{maj}} = 0.70 \pm 0.01$ mas and the extrapolated scattering diameter ($\theta_{\text{sc}} = 0.69 \pm 0.01$ mas imply

$$\theta_{\text{int}} \leq 0.13 \text{ mas.}$$  

(5)

Combined with the intrinsic diameter along the minor axis (Eq. (4)), this result suggests that the intrinsic source structure of Sgr A* could be elongated along an essentially N-S direction with an axial ratio of <0.3. The derived intrinsic
angular size also implies an intrinsic brightness temperature exceeding 1.3×10^{10} K at \( \lambda \approx 7 \) mm.

Finally, the intrinsic size along the minor axis derived at 7 mm appears to be larger than the value inferred at \( \lambda = 1.4 \) mm by Krichbaum et al. (1998). At \( \lambda = 1.4 \) mm, using the marginal detection of Sgr A* with an interferometer with a single baseline, they derived \( \theta_{\text{int}} = 0.11 \pm 0.06 \) mas. Taking our \( \lambda = 7 \) mm result and the 1.4 mm measurement together, a preliminary wavelength dependence of the intrinsic source size can be inferred:

\[
\theta_{\text{int}} = 0.08\lambda_{\text{mm}}^{0.9} \text{ mas} \quad (6)
\]

4. Discussion

At a distance of 8 kpc, the intrinsic angular size of Sgr A* corresponds to a linear size of 3.6 AU by <1 AU. The angular size is also equivalent to 72 \( R_{\text{sc}}(*) \) by <20 \( R_{\text{sc}}(*) \), where \( R_{\text{sc}}(*) = 7.5 \times 10^{11} \text{ cm} \) is the Schwarzschchild radius of a 2.5×10^6 M_\odot black hole. The elongation is nearly north-south.

Numerous models, typically involving synchrotron emission, have been proposed for the structure and mechanism of radio emission from Sgr A*. A model proposed by Reynolds & McKee (1980) based on a pulsar wind that is confined by the ram pressure in the Galactic center region can be ruled out due to the fact that Sgr A* is apparently associated with a massive black hole (2.5×10^6 M_\odot).

The rest of the models do involve a massive black hole. Melia (1994) modeled Sgr A* as synchrotron radiation from thermal electrons, heated by the dissipation of magnetic energy, as a result from the Bondi-Hoyle accretion process of the mass loss in the winds from the stars in the vicinity of Sgr A*. A jet in a coupled jet-disk system was also proposed to account for Sgr A* (Falcke, Mannheim, & Birnbaum 1993). A dynamically self-consistent model involving a rotating advection-dominated accretion flow (ADAF) suggests that Sgr A* arises from thermal electrons of a two-temperature plasma near the massive black hole (Narayan et al. 1998). In fact, none of the models has predicted both the intrinsic shape and size of Sgr A* as observed at 7 mm. Among these models, ADAF has naturally explained the spectral energy distribution as observed from radio to \( \gamma \)-ray, and predicts a very sensible X-ray limit. The ADAF model may have to incorporate a radio jet or a wind in order to account for the structure of Sgr A*.

Further observations are clearly indicated, especially at wavelengths shorter than 7 mm. Repeated observations are also important to monitor any variation in the intrinsic structure of Sgr A*.

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