

INTRINSIC SIZE OF SAGITTARIUS A*: 72 SCHWARZSCHILD RADII

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ABSTRACT

Recent proper motion studies of stars at the very center of the Galaxy strongly suggest that Sagittarius A*, the compact nonthermal radio source at the Galactic center, is a $2.5 \times 10^6 M_{\odot}$ black hole. By means of near-simultaneous multiwavelength Very Long Baseline Array measurements, we determine for the first time the intrinsic size and shape of Sgr A* to be $72 R_{sc}(\star)$ by less than $20 R_{sc}(\star)$, with the major axis oriented essentially north-south, where $R_{sc}(\star) (\equiv 7.5 \times 10^{11} \text{ cm})$ is the Schwarzschild radius for a $2.5 \times 10^6 M_{\odot}$ 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 multiwavelength mapping of Sgr A* with the same interferometer 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 emission models for Sgr A*. In particular, the advection-dominated accretion flow model may have to incorporate a radio jet in order to account for the structure of Sgr A*.

Subject headings: galaxies: active — Galaxy: center — scattering

1. INTRODUCTION

Sagittarius A*, the extremely compact nonthermal radio source at the Galactic center, has been for many years considered the signpost of a massive black hole (e.g., Lynden-Bell & Rees 1971; Lo et al. 1985). Recent proper motion and radial velocity measurements of the stars in the immediate neighborhood of Sgr A* have provided very compelling dynamical evidence for the existence of a compact dark mass of $2.5 \times 10^6 M_{\odot}$ located within 0.015 pc ($4.5 \times 10^{16} \text{ cm}$) of Sgr A*, supporting the hypothesis that Sgr A* is powered by a single massive black hole (Eckart & Genzel 1996, 1997; Ghez et al. 1998). Since Sgr A* would be the nearest example by far of such a system, determining its intrinsic source structure would be very important for probing the region immediately surrounding the massive black hole.

Up until now, very long baseline interferometric (VLBI) observations of Sgr A* have not been able to probe its intrinsic structure because of the scattering by the interstellar electrons (e.g., Davies, Walsh, & Booth 1976; Lo et al. 1981, 1985, 1993; Backer et al. 1993; Rogers et al. 1994; Krichbaum et al. 1997; Bower & Backer 1998). In this Letter, we report our efforts to image Sgr A* with the Very Long Baseline Array (VLBA) nearly simultaneously at five wavelengths ($\lambda = 6.0, 3.6, 2.0, 1.35 \text{ cm}$, and 7 mm). The *multiwavelength* imaging, with the same interferometer, is crucial for our differentiating interstellar scattering effects from the intrinsic source structure of Sgr A*. Finally, more than 20 years after its discovery (Balick & Brown 1974), we have for the first time determined that the intrinsic size of Sgr A* is asymmetric, being $72 R_{sc}(\star)$ by less than $20 R_{sc}(\star)$, where $R_{sc}(\star) (\equiv 7.5 \times 10^{11} \text{ cm})$ is the Schwarzschild radius of a $2.5 \times 10^6 M_{\odot}$ black hole. The new VLBA result is consistent with the latest millimeter wavelength VLBI results at 3.5 and 1.4 mm , sampled with 3 and 1 baseline

respectively, which suggest that the intrinsic size of Sgr A* may be $17 \pm 9 R_{sc}(\star)$ (Krichbaum et al. 1998).

2. OBSERVATIONS AND DATA ANALYSIS

The observations were carried out using 11 National Radio Astronomy Observatory² (NRAO) 25 m radio telescopes: 10 VLBA antennas and one Very Large Array antenna. The 7 mm observations were carried out on 1997 February 14, while the 1.35 cm observations were interlaced with the 2.0 cm observations on 1997 February 12 and the 3.6 cm observations were interlaced with the 6.0 cm on 1997 February 7, all at the same hour ranges of UT $12^{\text{h}}00^{\text{m}}\text{--}20^{\text{h}}00^{\text{m}}$. Quasars (NRAO 530 and PKS 1921–293) served as amplitude calibrators and fringe detection sources. The data recording was in the standard VLBA mode, with 32 MHz bandwidth for both circular polarizations at each telescope site. Correlation of the data was done with the VLBA correlator in Socorro, New Mexico. All of the postcorrelation reduction was carried out by using the NRAO Astronomical Image Processing System and the Caltech VLBI package including DIFMAP. With global fringe fitting, Sgr A* was detected on the short and intermediate baselines depending on the observed wavelength, whereas both calibrators (NRAO 530 and PKS 1921–293) were detected on all of the baselines. The visibility amplitude calibrations were done using system temperature measurements at each site. At $\lambda = 7 \text{ mm}$, special attention was paid to the elevation-dependent opacity corrections, while at $\lambda \geq 1.35 \text{ cm}$ the atmospheric opacity was not significant. Images of Sgr A* were produced for all five wavelengths using standard hybrid mapping.

An elliptical Gaussian model was fitted by the least-squares method to both amplitudes and phases in the calibrated visibility data to yield a quantitative description of the source structure. Figure 1 illustrates the model fitting to the 7 mm data, showing both the amplitude as a function of visibilities

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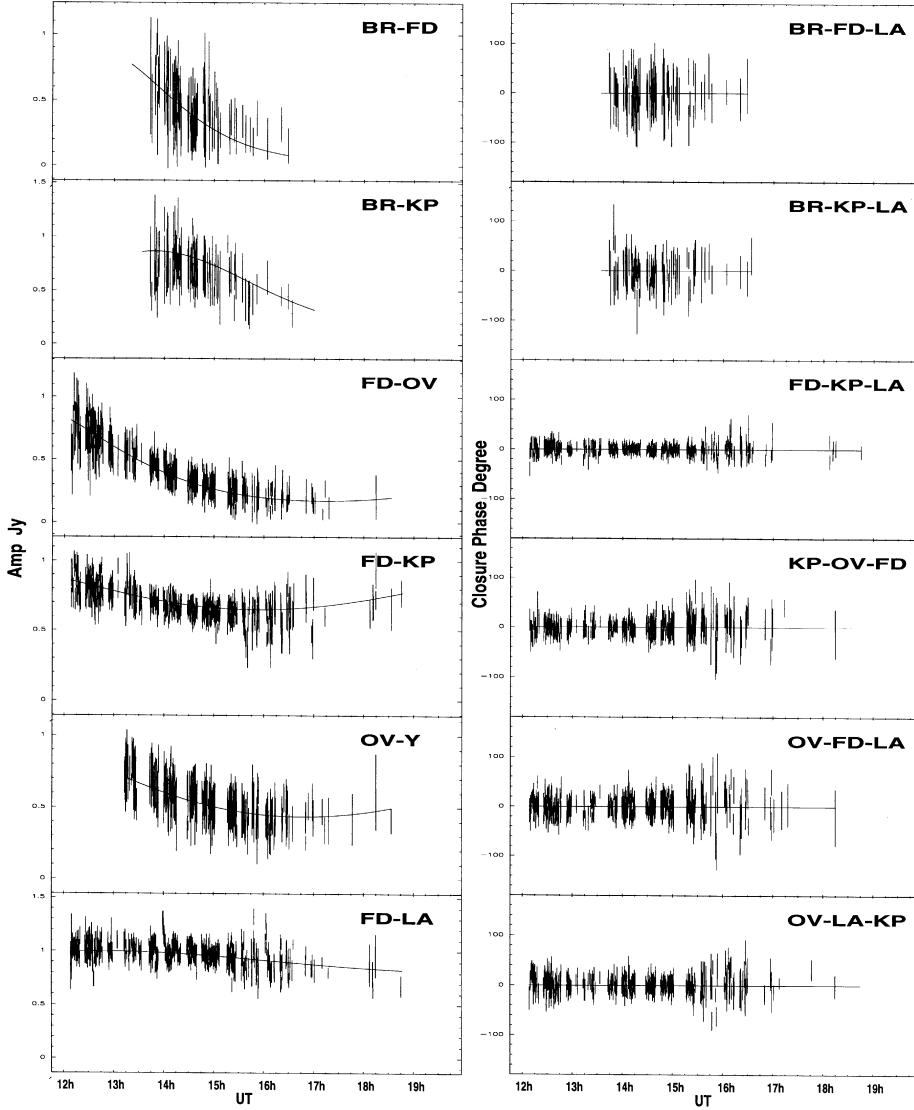


FIG. 1.—Gaussian elliptical model fitting (solid curves) to the visibility data at 7 mm (vertical bars). *Left:* Amplitude vs. baseline pairs (BR-FD, BR-KP, FD-OV, FD-KP, OV-Y, and FD-LA). The maximum baseline lengths of the pairs are 2346, 1914, 1508, 744, 1025 and 607 km, respectively. BR-FD is the longest baseline in NS. *Right:* Closure phase triangles.

and the closure phase triangles. We emphasize by this figure the good quality of the data, the availability of many baselines on which the structure can be fitted, and the robustness of the fit. The steadily improved performance of the VLBA played a pivotal role in the quality of this data set. The total flux density S_{ν} , FWHM major axis diameter θ_{major} , FWHM minor axis diameter θ_{minor} , axial ratio of minor to major axis diameters, and the position angle (P.A.) of the major axis of the model fit are given in Table 1, in which we also include previous 7 mm results from 1994.74 for comparison (Bower & Backer 1998). At wavelengths ≥ 1.35 cm, the mean P.A. of the major axis is $80^\circ \pm 3^\circ$ (essentially east-west) and the mean axial ratio is 0.53 ± 0.07 . At 7 mm, the axial ratio, 0.83 ± 0.11 , is significantly different from that at the longer wavelengths, while the P.A. is not.

3. THE INTRINSIC STRUCTURE OF SGR A*

Our near-simultaneous multiwavelength VLBA mapping of Sgr A* allows us to plot *both* the measured major and minor

axis diameters versus the observing wavelength in Figure 2. The measured major axis diameters (*open circles*) can be fit by $\theta_{\text{major}} = (1.43 \pm 0.02) \lambda^{1.99 \pm 0.03}$ mas (λ in cm), represented by the solid line. Within the accuracy of the experiment, such an index is indistinguishable from 2, so that the major axis diameters appear to follow a λ^2 law over a range of λ from 7 mm to 6 cm, in excellent agreement with the previous result of $1.42 \lambda^{2.0}$ (e.g., Alberdi et al. 1993). This λ^2 -dependence is consistent with the measured size being dominated by the scattering angle that is a result of the radiation from Sgr A* propagating through the interstellar medium with fluctuations in the electron density. The power spectrum of the density fluctuation of interstellar electrons is normally assumed to be $\propto k^{-\beta}$, where k is the wavenumber of the irregularities. The scattering angle scales as $\lambda^{1+2/(\beta-2)}$, where $[1+2/(\beta-2)] = 2, 2.2$ for $\beta = 4, 11/3$ respectively (Romani, Narayan, & Blandford 1986).

Along the minor axis, a fit to the measurements at all five wavelengths yields $\theta_{\text{minor}} = (1.06 \pm 0.10) \lambda^{1.76 \pm 0.07}$ mas, which appears inconsistent with interstellar scattering. A fit to all

TABLE 1
PARAMETERS OF ELLIPTICAL GAUSSIAN MODEL FIT

λ (cm)	ν (GHz)	S_p (Jy)	θ_{major} (mas)	θ_{minor} (mas)	Axial Ratio	P.A. (deg)
6.03	4.97	0.60 ± 0.09	49.6 ± 4.50	25.1 ± 2.00	0.51 ± 0.09	81 ± 3
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
0.69 ^a	43.2	1.28 ± 0.10	0.76 ± 0.04	0.55 ± 0.11	0.73 ± 0.10	77 ± 7

^a For comparison, the corresponding results at 43.2 GHz from 1994.74 (Bower & Backer 1998).

points for $\lambda \geq 1.35$ cm, however, yields a dependence of $(0.87 \pm 0.23) \lambda^{1.87 \pm 0.16}$ mas, which is consistent, within the errors, with the λ^2 -dependence expected for interstellar scattering. If we assume that the λ^2 -dependence derived for the major axis also applies to the minor axis, $\theta_{\text{minor}} = (0.76 \pm 0.05) \lambda^{2.0}$ for $\lambda \geq 1.35$ cm (Fig. 2). This dependence also agrees very well with $\theta_{\text{major}} = (1.43 \pm 0.02) \lambda^{1.99 \pm 0.03}$ and a constant axial ratio of 0.53.

This is the first time that the λ -dependence of the minor axis diameters has been determined directly by observations, the results of which strongly suggest interstellar scattering dominates the observed minor axis image size 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. The anisotropy in the electron fluctuations in the interstellar medium has been postulated to be due to turbulence in a magnetized plasma, and the mechanism to generate the density fluctuation has been proposed to be due to the specific entropy being mixed by shear Alfvénic turbulence that has “eddies” elongated in the direction of the magnetic field on small spatial scales (Higdon 1984; Goldreich & Sridhar 1995).

Importantly, Figure 2 shows a significant deviation at 7 mm between the measured minor axis diameter θ_{minor} and the scattering angle θ_{sc} extrapolated from $0.76 \lambda^{2.0}$: $\Delta\theta \equiv \theta_{\text{minor}} - \theta_{\text{sc}} = (0.58 \pm 0.07) - (0.37 \pm 0.02) = (0.21 \pm 0.07)$ mas. The deviation of θ_{obs} from the λ^2 dependence is naturally expected when the intrinsic source diameter θ_{int} becomes comparable to the scattering angle, since $\theta_{\text{minor}} = (\theta_{\text{int}}^2 + \theta_{\text{sc}}^2)^{1/2}$ (Narayan & Hubbard 1988).

Thus, this implies that at 7 mm, $\theta_{\text{int}} = (0.45 \pm 0.11)$ mas for Sgr A* along the minor axis (P.A. = -10° ; nearly north-south) direction. If we use the measurements of Bower & Backer (1998), $\theta_{\text{minor}} = (0.55 \pm 0.11)$, $\Delta\theta = (0.18 \pm 0.11)$, and $\theta_{\text{int}} = (0.41 \pm 0.17)$ mas. Combining the two sets of measurements, we obtain $\theta_{\text{minor}} = (0.57 \pm 0.06)$, $\Delta\theta = (0.20 \pm 0.06)$, and $\theta_{\text{int}} = (0.44 \pm 0.09)$ mas. We note that this intrinsic size scale is larger than the value inferred at 1.4 mm by Krichbaum et al. (1998). In addition to a possible λ dependence on the intrinsic size, we note that the 1.4 mm measurements were based on a single baseline.

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, are (1) the scattering size along the minor axis is half that along the major axis, and (2) the near-simultaneous multiwavelength mapping of Sgr A* with the same instrument over the same hour angle and calibrated in a uniform manner makes it possible to extrapolate precisely the minor axis scattering angle at $\lambda = 7$ mm.

Conceivably, changes in the refractive properties of the interstellar medium could lead to the deviation indicated above, since the 7 mm refractive scattering timescale for Sgr A* (proportional to λ^2) could be short: $t_{\text{ref}} = \theta_{\text{sc}} D/V \leq 0.5 \times (10 \text{ km s}^{-1}/V) \text{ yr}$, where D and V are the distance to the scattering medium and the relative velocity of the scattering medium and the observer, respectively. However, since the 7 mm source parameters did not change over 2.4 yr and probably over a longer period, the deviation of the minor axis size from $0.76 \lambda^{2.0}$ is unlikely to be due to changing refractive scattering effects at 7 mm. Furthermore, other evidence suggests that the refractive scattering effects for the Galactic center must be very small (Romani et al. 1986).

Along the major axis (P.A. of 80° ; essentially east-west) direction, the measured diameter of 0.7 ± 0.01 mas and the extrapolated scattering size of 0.69 ± 0.01 mas imply that the intrinsic size along the same direction has to be ≤ 0.13 mas. Combined with the minor axis intrinsic diameter of 0.44 ± 0.09 mas derived above, this implies that the intrinsic source structure of Sgr A* could be elongated along an essentially north-south direction, with an axial ratio of less than 0.3. This also implies an intrinsic brightness temperature of greater than 1.3×10^{10} K.

Up until now, only limits to the intrinsic size of Sgr A* existed. Given that the intrinsic source size of Sgr A* can now be estimated at 7 mm, we can also ask whether there are constraints on the wavelength dependence of the intrinsic source size. At $\lambda = 3.5$ mm, the upper limit to the observed size is 0.2 mas, from which we can infer an upper limit to the intrinsic size along the minor axis of less than 0.18 mas (Rogers et al. 1994). At $\lambda = 1.4$ mm, the marginal detection with an inter-

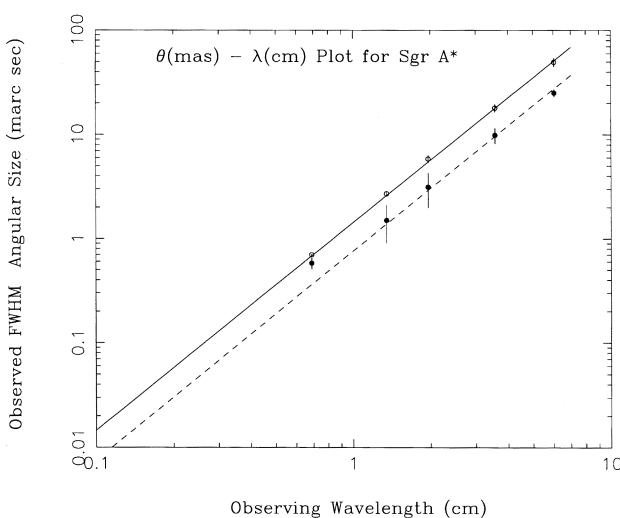


FIG. 2.—A log-log plot of measured (FWHM) source size vs. observing wavelength for Sgr A* (1997 February 7–14). The solid line represents a 1.43 $\lambda^{1.99}$ fit to the major axis sizes (open circles), while the dashed line a 0.76 $\lambda^{2.0}$ fit to the minor axis sizes (filled circles).

ferometer with a fringe spacing of ~ 0.3 mas suggests a size scale of 0.05–0.15 mas (Krichbaum et al. 1997, 1998). From the absence of refractive scintillation due to focusing and defocusing of the scattered image by large-scale plasma fluctuations (Gwinn et al. 1991) at $\lambda = 1.3$ and 0.8 mm, the respective lower limits to the intrinsic size are 0.02 and 0.008 mas. Taken all together, a λ^α -dependence of θ_{int} with $1.9 > \alpha > 0.7$ is not inconsistent with the above limits, at least along the minor axis direction. Clearly, this very preliminary determination of the wavelength dependence of the intrinsic source size has to be improved with further observations.

4. THE EMISSION MECHANISM FOR SGR A*

There have been several models for the structure and mechanism of radio emission from Sgr A*. They typically involve synchrotron emission from a pulsar wind that is confined by ram pressure (Reynolds & McKee 1980); from thermal electrons heated by the dissipation of magnetic energy as the mass-loss in the winds from stars in the vicinity of Sgr A*, such as IRS 16, is spherically accreted by a massive black hole (Melia, Jokipii, & Narayan 1992; Melia 1994); from a jet in a coupled jet-disk system (Falcke, Mannheim, & Biermann 1993); or from the thermal electrons at an electron temperature of $\sim 10^{9.5}$ K of a two-temperature plasma in a rotating advection-dominated accretion flow (Narayan et al. 1998).

Until now, in the absence of the intrinsic source structure, for confirmation the various models relied on comparison to the spectral energy distribution (SED) of Sgr A* from the radio wavelength to the γ -ray (Melia 1994; Narayan et al. 1998; Duschl & Lesch 1994; Serabyn et al. 1997; Falcke et al. 1998). However, because of the insufficient angular resolution in the wavelength bands shortward of $\lambda = 1$ mm, it is uncertain that

all of the radiation in the SED actually originates from Sgr A*, making the comparison less than definitive. In contrast, the intrinsic source structure derived here provides direct spatial constraints on the various models. Specifically, the spherical accretion model (Melia 1994) predicts a $\lambda = 7$ mm size too large to be consistent with the results here, while the coupled disk-jet model (Falcke et al. 1993) predicts a jet size scale smaller than the $72 R_{\text{sc}}(\star)$ obtained here. The advection-dominated accretion flow (ADAF) model for Sgr A* can naturally account for the luminosity far below that implied by the estimated accretion rate (Narayan et al. 1998). However, if the $\lambda = 7$ mm radiation from Sgr A* originates as thermal synchrotron radiation from the inner part of the advection-dominated accretion disk, the current model has difficulty explaining the elongated shape with an axial ratio less than 0.3 and the brightness temperature of greater than 1.3×10^{10} K. An additional component—a radio jet—may be needed in the ADAF model to account for the intrinsic elongation of Sgr A*. Obviously, observations of the intrinsic source structure at $\lambda < 7$ mm will probe ever closer to the event horizon of the massive black hole and will provide further constraints and stimuli for the models of Sgr A*.

Given the proximity of the center of our Galaxy, understanding the radio emission from Sgr A* provides a unique opportunity for probing the physical conditions to within less than $20 R_{\text{sc}}(\star)$ of a $2.5 \times 10^6 M_\odot$ black hole.

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