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LETTERS

A size of ~1 AU for the radio source Sgr A* at the centre of the Milky Way

Zhi-Qiang Shen[1], K. Y. Lo[2], M.-C. Liang[3], Paul T. P. Ho[4,5] & J.-H. Zhao[4]

Although it is widely accepted that most galaxies have supermassive black holes at their centres[1–3], concrete proof has proved elusive. Sagittarius A* (Sgr A*)[4], an extremely compact radio source at the centre of our Galaxy, is the best candidate for proof[5–7], because it is the closest. Previous very-long-baseline interferometry observations (at 7 mm wavelength) reported that Sgr A* is ~2 astronomical units (AU) in size[8], but this is still larger than the 'shadow' (a remarkably dim inner region encircled by a bright ring) that should arise from general relativistic effects near the event horizon of the black hole[9]. Moreover, the measured size is wavelength dependent[10]. Here we report a radio image of Sgr A* at a wavelength of 3.5 mm, demonstrating that its size is ~1 AU. When combined with the lower limit on its mass[11], the lower limit on the mass density is $6.5 \times 10^{21} M_{\odot}\,\mathrm{pc}^{-3}$ (where $M_{\odot}$ is the solar mass), which provides strong evidence that Sgr A* is a supermassive black hole. The power-law relationship between wavelength and intrinsic size (size ∝ wavelength$^{1.09}$) explicitly rules out explanations other than those emission models with stratified structure, which predict a smaller emitting region observed at a shorter radio wavelength.

Past very-long-baseline interferometry (VLBI) observations[12–16] of Sgr A* have revealed an east–west elongated structure whose apparent angular size at longer wavelengths is dominated by the interstellar scattering angle, that is, $\Theta_{\mathrm{obs}} = \Theta_{\mathrm{obs}}^{1\,\mathrm{cm}} \lambda^2$, where Θ_{obs} is the observed size in milliarcseconds (mas) at wavelength λ in cm, and equals $\Theta_{\mathrm{obs}}^{1\,\mathrm{cm}}$ at 1 cm. Thus, VLBI observations at shorter millimetre wavelengths, where the intrinsic structure of Sgr A* could become comparable to the pure scattering size, are expected to show deviations of the observed size from the scattering law. This has been demonstrated by the recent detection of the intrinsic size at 7 mm (ref. 8). On 20 November 2002, we successfully carried out an observation of Sgr A* with the Very Long Baseline Array (VLBA) at its shortest wavelength of 3.5 mm (ref. 10). Our observation, with the steadily improved performance of the VLBA system, has produced the first (to our knowledge) high-resolution image of Sgr A* made at 3.5 mm (Fig. 1), which exhibits an elongated structure too.

To yield a quantitative description of the observed structure, we tried a model fitting procedure[17] in which the amplitude closure relation is applied. Compared to the conventional VLBI

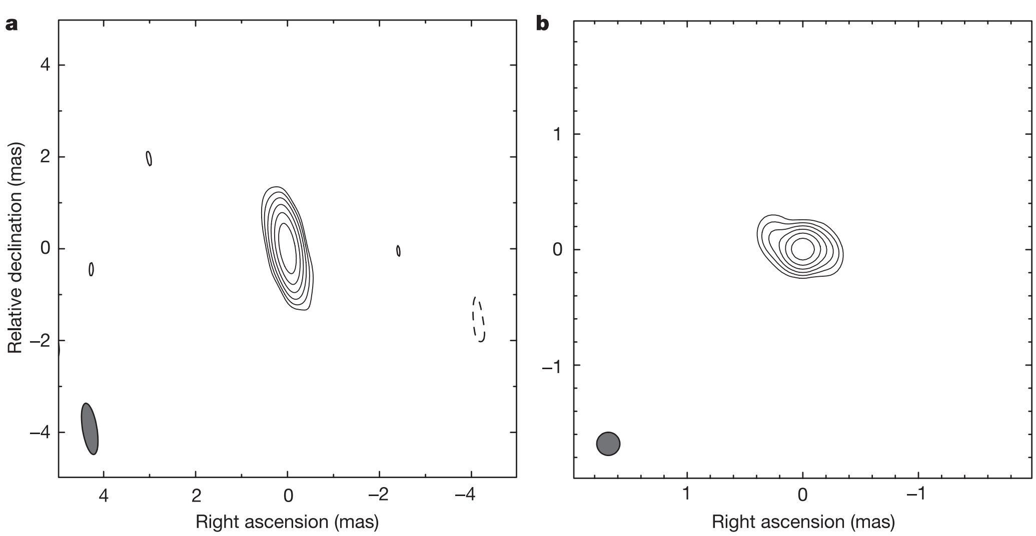

Figure 1 | High-resolution VLBI image of Sgr A* at 3.5 mm obtained with the VLBA on 20 November 2002. The observations were flexibly scheduled to ensure good weather conditions at most sites, and the data were recorded at the highest possible recording rate of 512 Mbit s^{-1}. Standard visibility amplitude calibration including the elevation-dependent opacity correction was done, and the final image was obtained after several iterations of the self-calibration and cleaning procedures. The calibrated total flux density is about 1.2 Jy. **a**, A uniformly weighted image with the restoring beam (indicated at the lower left corner) of 1.13 mas × 0.32 mas at 9°. The peak flux density is 1.08 Jy beam^{-1}. Contour levels are drawn at $3\sigma \times (-1, 1, 2, 4, 8, 16, 32)$; $3\sigma = 17.5$ mJy beam^{-1}. **b**, A super-resolution image with a circular beam of 0.20 mas from which an east–west elongated structure can be seen (see Table 1). Note the different scales. The contour levels are the same as that in **a** with the corresponding peak flux density of 1.01 Jy beam^{-1}.

[1]Shanghai Astronomical Observatory, 80 Nandan Road, Shanghai 200030, China. [2]National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, Virginia 22903, USA. [3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA. [4]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, Massachusetts 02138, USA. [5]Institute of Astronomy & Astrophysics, Academia Sinica, PO Box 23-141, Taipei 106, Taiwan, China.

self-calibration and imaging technique, this can improve on the calibration of current VLBI observations of Sgr A* (see Supplementary Information). We have applied this model fitting procedure to 12 sets of VLBA observations of Sgr A* made at a variety of wavelengths from 6 cm to 3.5 mm over the time range from 1994 to 2004. Two experiments at 7 mm in 1994 are from the VLBA archive. Table 1 lists the fitting results. A consistent position angle ($\sim$80°) of the scatter-broadened image can be seen in all the data sets, regardless of the observing epoch and wavelength. Furthermore, it is quite significant that in all seven experiments made at 7 mm, the fitted apparent major axis size is always larger than the largest known scattering size of 0.69 mas extrapolated from the existing scattering models. We thus perform weighted least-squares fits to the near-simultaneous angular size measurements (in February 1997) as a function of the observing wavelength (see Supplementary Information for more details). We conclude that the best-fit two-dimensional scattering structure is $\Theta_{\rm major} = (1.39 \pm 0.02)\lambda^2$ by $\Theta_{\rm minor} = (0.69 \pm 0.06)\lambda^2$ with a position angle of $\sim$80°. Here $\Theta_{\rm major}$ and $\Theta_{\rm minor}$ are respectively the full-width at half-maximum of major and minor axes in mas. This gives an even smaller scattering angle along the major axis direction. An immediate important conclusion is that the discrepancy seen in all seven VLBI observations made at 7 mm is real, implying the appearance of the intrinsic source structure at wavelengths of 7 mm and shorter (see Supplementary Fig. 1).

At 7 mm, two measurements from the March 2004 observations are used to get averaged sizes of the major and minor axes of 0.724 ± 0.001 and 0.384 ± 0.013 mas, respectively, with position angle $80.6^{+0.5}_{-0.6}$ degrees. The difference between the measured and the extrapolated scattering sizes along the major axis is $\Delta\Theta = 0.053 \pm 0.010$ mas, significant at $>5\sigma$ level. By subtracting in quadrature the scattering angle, this suggests an intrinsic size of 0.268 ± 0.025 mas for the major axis. Similarly, we can derive an intrinsic size for the minor axis to be 0.190 ± 0.057 mas, comparable to the major axis size. However, it should be kept in mind that the deviation seen for the minor axis is only significant at the 1.6σ level. Note that the derived source size has greater statistical significance than the deviation, because the scattering size has been deduced with good accuracy.

At 3.5 mm, the fitted apparent source 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 of 79^{+12}_{-33} degrees (see Table 1). Thus, an intrinsic size of 0.126 ± 0.017 mas for the major axis can be obtained from the deviation $\Delta\Theta = 0.042 \pm 0.010$ mas (at $>4\sigma$ level) in the measured major axis size from that of the scattering angle at 3.5 mm. Mainly owing to the limited resolution, the minor axis measurement at 3.5 mm is, however, inadequate to make any firm claim on the determination of its intrinsic size. So, we defer any estimate of intrinsic minor axis size at 3.5 mm for future investigation. Past 3.5 mm VLBI observations with the heterogeneous Coordinated Millimeter VLBI Array, severely limited by its low sensitivity, could not warrant a model more complex than the circular one[18]. The best-fit circular gaussian has a diameter of 0.18 ± 0.02 mas, which is indistinguishable from the scattering size along the major axis and cannot give a meaningful estimate of the intrinsic structure[8].

Thus we have sampled a zone of the supermassive black hole (SMBH) closer to the event horizon than ever before, by detecting the intrinsic size of Sgr A* to be only 1.01 AU at a distance of 8.0 kpc, or $12.6R_{\rm sc}$, where $R_{\rm sc}(\equiv 1.2\times10^{12}$ cm) is the Schwarzschild radius of a $4\times10^6 M_\odot$ SMBH. By assuming a spherical structure, we obtain a lower limit to the mass density of Sgr A* of $6.5\times10^{21} M_\odot\,{\rm pc}^{-3}$. Here, we used the lower bound to the mass of Sgr A*, derived from the upper limit to the intrinsic proper motion of Sgr A* itself[11], which is about 10% of the $4\times10^6 M_\odot$ inferred from the stellar orbital motions[6–7], and the upper limit to the source intrinsic size (this work). This mass density is at least four orders of magnitude greater than that determined from dynamical measurements of stellar velocities[6]. This is because here we are probing directly the structure of Sgr A*, where the assumed mass estimate refers to the value within Sgr A*. We note also that this mass density is almost 12 orders of magnitude greater than the estimate for NGC 4258 (ref. 19), one of the best known SMBHs. Such an extraordinarily high mass density robustly rules out the possibility of Sgr A* being a compact dark cluster of stellar remnants as it would have an unreasonably short lifetime of less than 100 yr (ref. 20), and thus argues strongly in favour of the SMBH nature of Sgr A*. To prove that Sgr A* is indeed an SMBH requires an unambiguous demonstration that Sgr A* possesses an event horizon. It is intriguing that the detected intrinsic size at 3.5 mm is about twice the diameter of the shadow caused by

Table 1 | Parameters of the elliptical gaussian model for Sgr A*

λ (cm)	ν, bw, rate† (GHz) (MHz) (bits)	Epoch (d month yr)	$\Theta_{\rm major}$‡§ (mas)	$\Theta_{\rm minor}$‡§ (mas)	PA§ (°)
0.348	86.236, 128, 2	03 Nov. 2002	$0.21^{+0.02}_{-0.01}$	$0.13^{+0.05}_{-0.13}$	79^{+12}_{-33}
0.694	43.213, 32, 2‖	14 Feb. 1997	$0.71^{+0.01}_{-0.01}$	$0.42^{+0.05}_{-0.05}$	74^{+2}_{-2}
0.695	43.175, 128, 2	08 Mar. 2004	$0.722^{+0.002}_{-0.002}$	$0.395^{+0.019}_{-0.020}$	$80.4^{+0.8}_{-0.8}$
0.695	43.175, 128, 2	20 Mar. 2004	$0.725^{+0.002}_{-0.002}$	$0.372^{+0.020}_{-0.018}$	$80.8^{+0.6}_{-0.9}$
0.695	43.151, 64, 1	26 Apr. 1994	$0.72^{+0.01}_{-0.01}$	$0.39^{+0.07}_{-0.07}$	78^{+2}_{-2}
0.695	43.151, 64, 1	29 Sep. 1994	$0.72^{+0.01}_{-0.01}$	$0.42^{+0.03}_{-0.03}$	79^{+1}_{-1}
0.695	43.135, 32, 2	24 Apr. 1999	$0.69^{+0.01}_{-0.01}$	$0.33^{+0.04}_{-0.04}$	83^{+1}_{-1}
0.695	43.135, 32, 2	23 May 1999	$0.71^{+0.01}_{-0.01}$	$0.44^{+0.02}_{-0.02}$	79^{+1}_{-1}
1.350	22.229, 32, 1‖	12 Feb. 1997	$2.53^{+0.06}_{-0.05}$	$1.45^{+0.23}_{-0.38}$	83^{+4}_{-5}
1.953	15.361, 32, 1‖	12 Feb. 1997	$5.33^{+0.07}_{-0.07}$	$2.70^{+0.30}_{-0.44}$	83^{+3}_{-3}
3.564	8.417, 32, 1‖	07 Feb. 1997	$17.5^{+0.5}_{-1.0}$	$8.5^{+1.0}_{-1.0}$	87^{+3}_{-3}
6.020	4.983, 32, 1‖	07 Feb. 1997	$43.0^{+2.5}_{-1.0}$		

Results from the model fitting procedure, which implicitly uses the amplitude closure relation (see Supplementary Information for details). Also listed are some details of the VLBI observations. Except for five observations in February 1997 which used the VLBA and one VLA antenna, all the other observations were performed by the VLBA. λ, wavelength; ν, frequency; $\Theta_{\rm major}$, $\Theta_{\rm minor}$ and PA, parameters of gaussian model: respectively major and minor axes, and the position angle of the major axis.

†The observing frequency in GHz, the recording bandwidth in MHz, and the sampling rate (1 bit or 2 bits). With the same total bandwidth, the noise level from 2-bit quantization data is about $\sqrt{2}$ times lower than that from 1-bit quantization. The recording rate is two times the product of the bandwidth and the sampling rate.

‡Full-width at half-maximum (FMHM).

§In all cases, errors are 1σ.

‖Dual polarization observation. Both left and right circular polarization data have the same recording mode (listed), and both data were used in the model fitting.

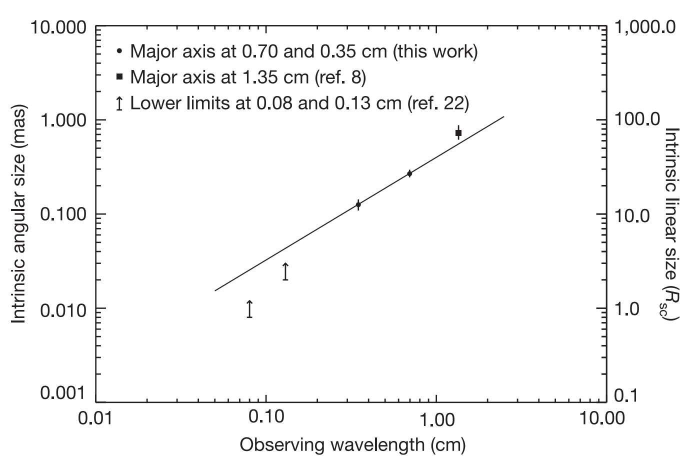

Figure 2 | Intrinsic major axis size versus observing wavelength. The solid line represents the two-point fit from the detected intrinsic sizes at both 3.5 and 7 mm (this work). Also plotted are the lower limits to the intrinsic sizes at 1.3 and 0.8 mm (ref. 22), and the reported detection at 1.35 cm (ref. 8). The extrapolated intrinsic sizes at 1.3 and 0.8 mm are about $4.3R_{\rm sc}$ and $2.5R_{\rm sc}$, respectively. Here $R_{\rm sc}(\equiv 1.2\times10^{12}$ cm) is the Schwarzschild radius for a $4\times10^6 M_\odot$ SMBH. The error bars represent 1σ standard deviation.

the strong gravitational bending of light rays[9]. Thus, it is very likely that VLBI observations of Sgr A* at 1 mm or shorter will reach the region comparable to its shadow, which can be used to differentiate between the SMBH scenario and other supermassive non-baryonic stars[9,21].

The two-point fit to the well determined intrinsic sizes at 7 and 3.5 mm shows a λ^{β}-dependence of the intrinsic source size with $\beta = 1.09^{+0.34}_{-0.32}$ (Fig. 2). Also plotted in Fig. 2 are two inferred lower limits of 0.02 and 0.008 mas to the intrinsic size at 1.3 and 0.8 mm, respectively, from the absence of refractive scintillation[22]. These lower limits are consistent with the extrapolation of the λ^{β}-dependence. However, we note that these two lower limits are only about 2 and 0.8 R_{sc}, which are smaller than the last stable orbit (LSO) radius of $3R_{sc}$ for a non-rotating (Schwarzschild) black hole. There is some evidence that Sgr A* is a rotating black hole[23]. For a prograde maximally rotating Kerr black hole, the LSO radius is $0.5R_{sc}$. The LSO establishes the lower limit to the emission region size. Hence the λ^{β}-dependence will eventually reach a minimum. As such, the turn-over frequency[24] seen in the entire spectrum of Sgr A* might tell us the smallest size of the emission, which can be further used to constrain its spin, if any.

The extrapolated intrinsic size at 1.35 cm is $0.555^{+0.136}_{-0.115}$ mas. This, when compared to the scattering angle of 2.576 ± 0.036 mas, is consistent with the idea that the scattering effect dominates the observed source size at 1.35 cm. This deduced source size is also formally consistent with the reported detection of $0.726^{+0.152}_{-0.111}$ mas, to within the uncertainties[8].

The derived $\lambda^{1.09}$-dependence requires that the emission at different wavelengths is dominated by different emitting regions, and thus conclusively excludes those models without the stratified emission structure. Along with the detected intrinsic major axis size, we can derive a lower limit to the intrinsic brightness temperature as $T_b \geq 1.36 \times 10^9 \times \frac{S_\lambda \lambda^2}{\Theta^2_{int}}$ K; here S_λ is the flux density in Jy at wavelength λ in cm, and Θ_{int} is the intrinsic major axis size in mas. There is a wavelength dependence of the lower limit T_b as $\lambda^{-\alpha-0.18}$ (assuming $S_\lambda \propto \lambda^{-\alpha}$). Using the flux densities of 1.0 and 1.2 Jy at 7 and 3.5 mm, respectively, the corresponding minimal T_b is 0.9×10^{10} and 1.2×10^{10} K, greater than the prediction of the spherical accretion model[25]. However, this lower limit of 10^{10} K, and the spatial distribution of the radio emission, can be explained easily by the inhomogeneous jet model[26,27], in which the magnetic field and the electron number density vary with the distance (r) to the origin of the jet as r^{-1} and r^{-2}, respectively. On the other hand, the radiatively inefficient accretion flow (RIAF) model of Sgr A* (ref. 28) can also account for a brightness temperature of $>10^{10}$ K as well as the observed spectral energy distribution. The prediction of $\lambda^{0.9}$ from the hybrid thermal-nonthermal synchrotron radiation from RIAF (ref. 29) is in agreement with the estimated $\lambda^{1.09^{+0.34}_{-0.32}}$ relation. Here, the possible existence of strong outflows from the accretion disk was not taken into account. To further discern between them, it is important to study the correlation between the detected X-ray variability and the variations frequently seen in the radio to submillimetre wavelengths, which would yield further information on the intrinsic density structure of the emitting zone.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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