97. Lederer, W. J. & Nichols, C. G. *J. Physiol.* **419,** 193-211 (1989).
98. Lopatin, A. N. & Nichols, C. G. *J. Pharmac. exp. Ther.* (in the press).
99. Sanger, F., Nicklen, S. & Coulson, A. R. *Proc. natn. Acad. Sci. U.S.A.* **74,** 5463-5467 (1977).
100. Kyte, J. & Doolittle, R. F. *J. molec. Biol.* **157,** 105-132 (1982).
101. Noda, M. *et al. Nature* **320,** 188-192 (1986).
102. Hanks, S. K. *Curr. Opin. struc. Biol.* **1,** 369-383 (1991).

ACKNOWLEDGEMENTS. We thank M. Lombardi for help with preparation and microinjection of oocytes; P. Kofuji and D. Schulze for cRNA used in patch clamp studies; R. G. Wells, G. Gamba and R. Lyons for advice on cDNA cloning; K.-D. Wu for RNA samples; F. M. Ashcroft and S. J. H. Ashcroft for discussion; W. Wang, G. Giebisch, L. Heginbotham and R. MacKinnon for suggestions and for single channel experiments; and B. M. Brenner for comments on the manuscript. This work was supported by grants from the NIH.

---

## LETTERS TO NATURE

# High-resolution VLBA imaging of the radio source Sgr A* at the Galactic Centre

**K. Y. Lo*, D. C. Backer†, K. I. Kellermann‡, M. Reid§, J. H. Zhao||, W. M. Goss|| & J. M. Moran§**

* Astronomy Department, University of Illinois, 1002 West Green Street, Urbana, Illinois 61801, USA
† Astronomy Department, University of California, Berkeley, California 94720, USA
‡ National Radio Astronomy Observatory, Edgemont Road, Charlottesville, Virginia 22903, USA
§ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Massachusetts 02138, USA
|| National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA

**THE compact non-thermal radio source at the Galactic Centre, known as Sgr A*, may mark the location of a massive black hole[1,2]. Here we present images of Sgr A* with milliarcsecond resolution obtained by using five telescopes of the partially completed Very Long Baseline Array (VLBA) in conjunction with a few additional telescopes. The image of Sgr A* at a wavelength of 3.6 cm confirms almost exactly the elliptical gaussian model that has been proposed on the basis of previous, more sparse data[3,4]. The source size at 1.35 cm wavelength is 2.4 ± 0.2 mas, similar to previous results[3,5]. At both wavelengths, the radio source is smooth, without detectable fine structure. These observations, along with other recent results[6], support the suggestion[7] that the radio emission from Sgr A* is strongly scattered by electron-density fluctuations along the line of sight. On the assumption[8] that the emission is due to a black hole accreting stellar winds from massive stars in the central 0.5 pc, the observations are consistent with a black-hole mass of $\lesssim 2\times 10^6\,M_\odot$.**

Since the compact radio source at the Galactic Centre, Sgr A*, was first unambiguously detected in 1974 (ref. 9), there have been many attempts to determine its structure[3-5,10], but the lack of radio telescopes with the appropriate combination of short and intermediate spacings meant that the source could not be imaged adequately. The partially completed VLBA now provides the necessary short spacings and has been used in conjunction with other telescopes to image Sgr A* at wavelengths 1.35 and 3.6 cm.

The 1.35-cm observations were made on 28 June 1991, using nine telescopes: five of the 25-m diameter VLBA telescopes (Pie Town, Kitt Peak, Los Alamos, Fort Davis and Owens Valley), the phased Very Large Array (VLA), the NASA Goldstone 70-m telescope, the Haystack 37-m telescope and the NRAO 43-m telescope in Green Bank. The Mk III very-long-baseline interferometry (VLBI) recording terminals were used in mode A (56-MHz recording bandwidth) at the telescopes, except for the VLBA telescopes where the VLBA recorders were used in a compatible mode (50-MHz recording bandwidth). Data recorded from the Owens Valley VLBA telescope and the Goldstone 70-m telescope could not be used, because of technical difficulties at the time of observations. At short wavelengths such as 1.35 cm, the antenna gain changes, and atmospheric attenuation becomes significant and difficult to calibrate at the low elevations at which Sgr A* is observed (from the Northern Hemisphere). To overcome these difficulties which limit the accuracy of the determination of the visibility amplitudes, we observed an $H_2O$ maser source in Sgr B2 at the end of each scan of Sgr A*. This maser source, being $\sim$0.7 degree away from Sgr A*, allows reliable calibration of the visibilities of Sgr A*. We also observed the unresolved source 1730 − 130 (NRAO 530) as a check on the calibration. Using the VLA data, we determined the total flux density of Sgr A* to be 0.98 ± 0.05 Jy during the observations.

The 3.6-cm observations were made on 25 November 1991 using seven telescopes: the same five VLBA telescopes, the phased VLA and the NASA Goldstone 70-m telescope. The VLBI recordings were made with a bandwidth of 28 MHz. Observations alternated between Sgr A* and the neighbouring calibrator source 1730 − 130 (NRAO 530). The measurements at the VLA during the observations of Sgr A* were used to determine the flux density of Sgr A* as 0.79 ± 0.05 Jy.

The data were correlated at the Haystack Observatory on the Mk IIIA correlator[11] and the correlation coefficients were then edited, calibrated and analysed using the Caltech VLBI package.

Sgr A* was detected on the short and intermediate baselines, whereas the calibrator source NRAO 530 was detected on all the baselines. The measured visibility amplitudes were well fitted by the amplitudes of an elliptical gaussian brightness distribution. The major axis angular diameter (FWHM) is 17.5 ± 0.5 mas, with an axial ratio of 0.49 ± 0.06, and the position angle (PA) of the major axis at 87° ± 5°.

Using the standard procedure of hybrid mapping[12], we have also derived the image shown in Fig. 1. The source is well

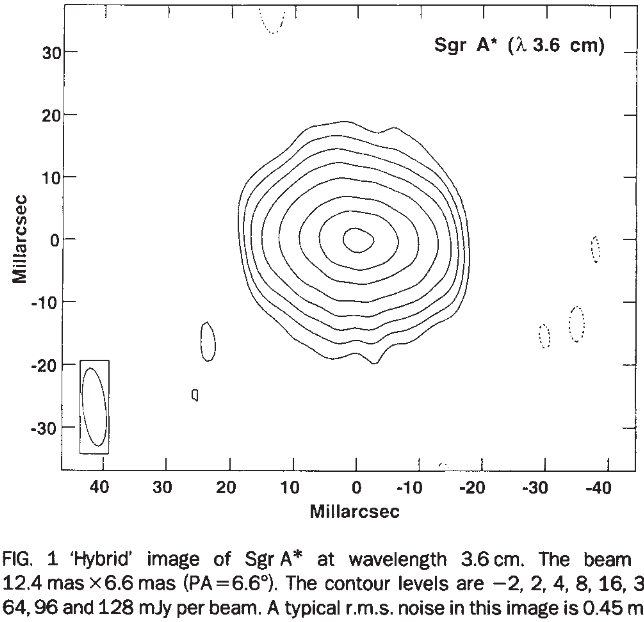

FIG. 1 'Hybrid' image of Sgr A* at wavelength 3.6 cm. The beam is 12.4 mas × 6.6 mas (PA = 6.6°). The contour levels are −2, 2, 4, 8, 16, 32, 64, 96 and 128 mJy per beam. A typical r.m.s. noise in this image is 0.45 mJy per beam. The origin of the image is at RA(1950) = 17 h 42 min 29.34 s, Dec(1950) = −28° 58′ 18.6″.

resolved by the synthesized beam of 12.4 mas × 3.6 mas (major axis PA = 6.6°). An elliptical gaussian model fitted to the deconvolved image has the following parameters: major axis (full width half maximum, FWHM) = 17.5 ± 0.5 mas, minor axis (FWHM) = 8.5 ± 1.0 mas, major axis PA = 87° ± 3°, essentially identical to a model fitting the visibility amplitudes.

There is no evidence of any fine structure at angular scales smaller than the gaussian source size in either the visibility amplitudes or the hybrid image. Further evidence that the source structure is smooth and symmetric can be seen in the closure phase data. Whenever the closure phase can be measured, it is consistent with zero, implying an absence of any asymmetric small-scale structure.

The 1.35-cm visibility amplitudes are well fitted by a circular gaussian model with a diameter of 2.4 ± 0.2 mas (Fig. 2). If we fix the axial ratio at 0.5 and the PA of the major axis at 87°, the same data can also be modelled by an elliptical gaussian brightness distribution, with a major axis diameter of 2.6 ± 0.2 mas. The currently limited north-south (*u*, *v*) coverage of the partial VLBA does not provide sufficient constraint on the ellipticity of Sgr A* at 1.35 cm. But an independent experiment at 1.35 cm (using the same telescopes but without the special calibration using the $H_2O$ maser source in Sgr B2) reported an elliptical gaussian model for Sgr A*: major axis (FWHM) = 2.6 ± 0.2 mas, PA = 75° ± 10° and an axial ratio = 0.5 ± 0.2 (ref. 13).

These results, based on the more extensive current data using the partially completed VLBA, confirm the apparent source structure of Sgr A* previously determined from much sparser data[6-8]. Given the definitive determination of the elliptical gaussian shape of Sgr A* at 3.6 cm, comparison to images at other wavelengths is now required to examine the wavelength ($\lambda$) dependence of the source size as well as source shape. The $\lambda^2$ dependence of size scale noted before may be too simplified a description. Comparison of the source sizes measured at $\lambda = 1.35$ cm over 8 years can, however, now be used to set an upper limit of 0.04 mas yr$^{-1}$ to any change in the source size (corresponding to a radial expansion velocity of ~0.8 km s$^{-1}$ at 8.5 kpc)[3]. If we assume that the observed size is dominated by interstellar scattering, then the upper limit can be two times larger.

It has been suggested[7] that the observed source size of Sgr A* is affected by scattering of interstellar electrons, but the large observed size of Sgr A* requires rather extreme conditions[14]. The wavelength dependence of the observed source size of Sgr A* could also be due to the synchrotron and free-free opacity of the source[15], but *ad hoc* assumptions are needed to reproduce the $\lambda^2$ dependence. Recent results from OH maser source-size measurements indicate a ~30′ region of pronounced scattering centred on Sgr A* (ref. 6), strengthening the interpretation of interstellar scattering.

If the observed source structure of Sgr A* at 3.6 cm is due to interstellar scattering, the measured visibilities should pose some constraints on the parameters characterizing the structure of the interstellar electrons. The expected relation is $P_{\delta n_e}(q) = C_n^2 q^{-\alpha}$,

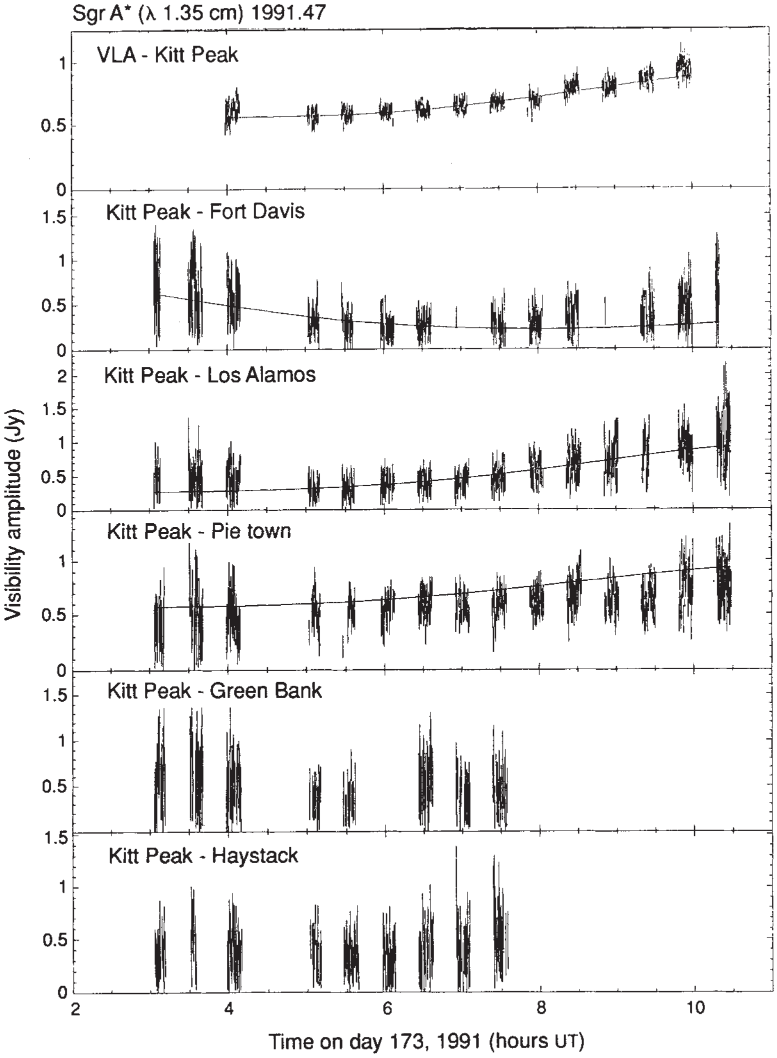

FIG. 2 Visibility amplitudes of Sgr A* at wavelength 1.35 cm plotted against time (UT) for six baselines all involving Kitt Peak. The solid curves are the predicted amplitudes for a circular gaussian model source with a FWHM diameter of 2.5 mas. There are no model curves plotted on the baselines from Kitt Peak to Green Bank and Haystack because the predicted amplitudes are vanishingly small. The amplitudes are consistent with pure noise, given the short integration time used to minimize decorrelation of the visibility due to the atmosphere.

where $P_{\delta n_e}$ is the power spectrum of the electron density fluctuations as a function of the wavenumber, $q = 2\pi/b$ ($b$ is the scale size of the fluctuations), in the range $2\pi/b_1$ to $2\pi/b_0$, where $b_0$ and $b_1$ are the inner and outer scales, respectively[6]. The VLBI image is derived from observations over about 7 hours, a timescale longer than that for diffractive scattering, $t_{\mathrm{diff}}$, but short compared with the timescale for refractive scattering, $t_{\mathrm{ref}}$. The image obtained by VLBI is thus an 'average' image, as defined by Goodman and Narayan[16] who analysed the dependence of the measured visibility on projected baseline length $b$ (and therefore scale size in the scattering medium) for various parameters of the power spectrum $P_{\delta n_e}$. The profile of $V(b)$, the normalized visibility $V$ against projected baseline length $b$, is sensitive to the index of the power spectrum under certain conditions[17,18].

We have fitted $\ln(1/V(b))$ to a power-law dependence on $b$ (corrected for ellipticity of the image) with data selected for sufficient signal to noise ratio, yielding a power law index of $2.05 \pm 0.15$, where the errors are the bounds of fits with different data selections[19]. This value can be taken to imply that the power-law index, $\alpha$, of $P_{\delta n_e}$ is 4.05, similar to that determined previously[20] but higher than that found for other objects[17,19] and higher than the value of a Kolmogorov power spectrum ($\alpha = 11/3$). On the other hand, it could be consistent with a Kolmogorov power spectrum with an inner scale of turbulence $b_0$ that is larger than the maximum baseline on which Sgr A* is detected, ~450 km (ref. 19). The $\lambda$-dependence of the measured major-axis sizes ($\lambda^{1.94 \pm 0.03}$) is consistent with either possibility.

One might expect some deviation of $V(b)$ from a smooth bivariate gaussian form with our integration time, but such effects should be small relative to both the gain errors in our data and the limits we can set on $V(b)$ on the longer baselines ($V < 0.05$). For example, deviations at the level of $V \sim 0.01$, presumably due to this effect, have been detected in another radio source[21]. On our most sensitive closure-phase triangle (Goldstone, VLA and Pie Town), there is no evidence for a detectable source on the long baseline Goldstone-VLA at the level of $V(b) = 0.01$.

The anisotropy of the image (in terms of both axial ratio and position angle) is unchanged over a timescale of ~7.5 years, the interval between the 3.6-cm observations reported here (November 1991) and the first detection of elongation of the source (May 1983)[10], which is longer than $t_{\mathrm{ref}}$. This 'permanent' anisotropy suggests an anisotropy in the spectrum of density fluctuations. In general, the image will be stretched out perpendicular to the direction along which the projected density blobs are elongated[16], which could be due to strong and smooth magnetic field threading the turbulent region or to anisotropic velocity fields arising from stellar winds or supernovae[17].

The unique properties of the radio source Sgr A* in the Galaxy cannot be explained by any known stellar radio source[2,3]. It may be best explained by a massive black-hole model[22], but its mass is not known. The absence of proper motion of Sgr A* is consistent with its being massive[23]. Direct determination of the mass distribution at the centre is clearly necessary. The best kinematic evidence for the presence of a large point mass at the Galactic Centre is from modelling the high-speed ionized gas within the central few parsecs[24]. Similar evidence from stellar velocity dispersion is also suggestive, although the current uncertainties of the core radius and the mass-to-light ratio of the central star cluster constrain the mass model[25-27]. The Sgr A* radio source has been modelled as a massive black hole accreting the fast wind generated by the sources in IRS16 (ref. 8). If one uses the predicted intrinsic source size of this model[28], the 1.35-cm measurement of the source size can be interpreted to exclude a black-hole mass of $> 2 \times 10^6$ solar masses ($M_\odot$). Given the many assumptions involved in the modelling, such limits on the mass are uncertain. The quest for the intrinsic source structure of Sgr A* requires further VLBA imaging at shorter wavelengths, where scattering by interstellar electrons (proportional to $\lambda^2$) decreases. Together with high-resolution infrared observations of the stars and gas in the central parsec, such observations will help to determine the true nature of the centre of the Galaxy. □

Received 19 November 1992; accepted 12 January 1993.

1. Lynden-Bell, D. & Rees, M. J. *Mon. Not. R. astr. Soc.* **152,** 461–475 (1971).
2. Lo, K. Y. in *The Galactic Center* (ed. Morris, M.) 527–534 (Kluwer, Dordrecht, 1989).
3. Lo, K. Y. *et al. Nature* **315,** 124–125 (1985).
4. Jauncey, D. *et al. Astr. J.* **98,** 44–48 (1989).
5. Marcaide, J. *et al. Astr. Astrophys.* **258,** 295–301 (1992).
6. van Langevelde, H., Frail, D., Cordes, J. & Diamond, P. *Astrophys. J.* **396,** 686–695 (1992).
7. Davies, R., Walsh, D. & Booth, R. *Mon. Not. R. astr. Soc.* **177,** 319–333 (1976).
8. Melia, F. *Astrophy. J.* **387,** L25–L28 (1992).
9. Balick, B. & Brown, R. L. *Astrophys. J.* **194,** 265–270 (1974).
10. Lo, K. Y., Cohen, M. H., Readhead, A. & Backer, D. C. *Astrophys. J.* **249,** 504–512 (1981).
11. Rogers, A. E. E. *et al. Science* **219,** 51–54 (1983).
12. Cornwell, T. & Wilkinson, P. *Mon. Not. R. astr. Soc.* **196,** 1067–1087 (1981).
13. Marcaide, J. *et al.* in *Sub Arc Second Radio Astronomy* (ed. Davies, R. J.) (Cambridge Univ. Press, in the press).
14. Blandford, R. in *The Galactic Center* (ed. Morris, M.) 649–654 (Kluwer, Dordrecht, 1989).
15. de Bruyn, G. *Astr. Astrophys.* **52,** 439–447 (1976).
16. Goodman, L. & Narayan, R. *Mon. Not. R. astr. Soc.* **238,** 995–1028 (1989).
17. Spangler, S. & Cordes, J. *Astrophys. J.* **332,** 346–353 (1988).
18. Moran, J. M. in *Very Long Baseline Interferometry: Techniques and Applications* (eds Felli, M. & Spencer, R. E.) 47–59 (Kluwer, Dordrecht, 1989).
19. Spangler, S. R. & Gwinn, C. R. *Astrophys. J.* **353,** L29–L32 (1990).
20. Backer, D. C. in *AIP Proc. 174: Radio Wave Scattering in the Interstellar Medium* (eds Cordes, J., Rickett, B. & Backer, D.) 111–116 (AIP, New York, 1988).
21. Mutel, R. L. & Lestrade, J.-F. *Astrophys. J.* **349,** L47–L49 (1990).
22. Rees, M. in *AIP Proc. 83: The Galactic Center* (eds Riegler, G. & Blandford, R.) 166–176 (AIP, New York, 1982).
23. Backer, D. & Sramek, R. in *AIP Proc. 155: Symp. honoring C. H.Townes,* (ed. Backer, D.) 163–165 (AIP, New York, 1987).
24. Serabyn, E., Lacy, J. H., Townes, C. H. & Bharat, R. *Astrophys. J.* **326,** 171–185 (1988).
25. Rieke, G. H. & Rieke, M. *Astrophys. J.* **330,** L33–L37 (1988).
26. McGinn, M. T., Sellgren, K., Becklin, E. E. & Hall, D. N. B. *Astrophys. J.* **338,** 824–840 (1989).
27. Sellgren, K., McGinn, M. T., Becklin, E. E. & Hall, D. N. B. *Astrophys. J.* **359,** 112–120 (1990).
28. Melia, F., Jokipii, J. & Narayanan, A. *Astrophys. J.* **395,** L87–L90 (1992).

ACKNOWLEDGEMENTS. We thank M. Titus and A. Rogers for help with the correlation of data and J. Shen and T. Pearson for help in the data analysis. The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the NSF. Research at the Universities of Illinois and California at Berkeley is partially supported by the NSF. Radio Astronomy at the Deep Space Network is supported by the Jet Propulsion Laboratory.

---

# Microsecond-resolved XAFS of the triplet excited state of $Pt_2(P_2O_5H_2)_4^{4-}$

**Daniel J. Thiel*, Pēteris Liviņš†, Edward A. Stern† & Aaron Lewis*‡**

* Department of Applied Physics, Cornell University, Ithaca,
New York 14853, USA
† Department of Physics, FM-15, University of Washington, Seattle,
Washington 98195, USA
‡ Division of Applied Physics, The Hebrew University of Jerusalem,
Jerusalem, Israel

**LITTLE is known about the excited-state structures of most inorganic compounds. Time-resolved resonance Raman and time-resolved infrared spectroscopies can provide only indirect structural information for short-lived excited species in solution at room temperature. Time-resolved X-ray diffraction[1] has the potential to give more direct information, but no excited-state structures have yet been reported; picosecond gas-phase electron diffraction has been proposed recently[2], but not yet demonstrated. Here we report a technique that combines the X-ray absorption fine-structure (XAFS) method[3] with rapid-flow laser spectroscopy[4] to measure structural changes in a solution-phase excited-state transition-metal complex with microsecond resolution. We find that the triplet excited state of $Pt_2(P_2O_5H_2)_4^{4-}$, with a lifetime of about 4 μs, undergoes a contraction in the Pt–Pt distance of 0.52 ± 0.13 Å relative to the ground state. We anticipate that time-resolved XAFS will have broad applications in chemistry and biology.**