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A decade of unchanged 1.3 cm VLBI structure of Sgr A*

J.M. Marcaide[1], A. Alberdi[2], L. Lara[2], M.A. Pérez-Torres[1], and P.J. Diamond[3]

[1] Departamento de Astronomía, Universitat de València, E-46100 Burjassot, Spain
[2] Instituto de Astrofísica de Andalucía, CSIC, Apdo. 3004, Granada, Spain
[3] National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801, USA

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Abstract. We observed Sgr A* at 1.3 cm on 1992 November 8 with a 14 station VLBI array and, using data from 10 of these stations, obtained a high-dynamic range image with a beam of 3.35×1.7 milliarcseconds in position angle 14°. The observed surface brightness distribution of Sgr A* is best modelled by an elliptically shaped gaussian component with parameter values: flux density 1.05 ± 0.10 Jy, major axis of FWHM 2.67 ± 0.15 milliarcseconds in position angle $79^\circ\pm10^\circ$, and axial ratio 0.61 ± 0.12, which are almost the same as the estimates of Alberdi et al. (1993). We found no evidence of changes in the source structure of Sgr A* among four sets of 1.3 cm VLBI observations spanning almost a decade. It seems reasonable to conclude that both the emission of Sgr A* itself and the surrounding medium acting as a refractive screen have reasonably constant relative orientation, emission rates and structures.

Key words: galaxies: jets – Galaxy: center – techniques: interferometric

1. Introduction

Sagittarius A* (Sgr A*) (Balick & Brown 1974) is presumed to be located at the dynamical center of the Galaxy and associated with a supermassive black hole. Sgr A* is brightest in the radio/mm band and its spectrum is unlike that of a blackbody (see Mezger et al. 1996, and references therein, and Narayan et al. 1998, for a compilation of previous results on the spectrum of Sgr A*). Recently, support for a supermassive black hole has come from IR studies of stellar proper motions in the innermost core of the Galaxy (Eckart & Genzel 1996, 1997), from successful modelling of the emission of Sgr A* with an advection-dominated accretion model (Narayan et al. 1998), from measurements of the simultaneous spectrum of Sgr A* over the cm and mm bands (Serabyn et al. 1997; Falcke et al. 1998), and from considerations of the lifetime of massive dark clusters (Maoz 1998).

Over the last 20 years great efforts have been made to determine the radio structure and the position of Sgr A*. However, it has only been recently that reliable VLBI images have been obtained at cm and 7 mm wavelengths (Lo et al. 1993; Alberdi et al. 1993; Backer et al. 1993; Krichbaum et al. 1993; Bower & Backer 1998) as well as estimates of source sizes at 3 mm (Rogers et al. 1994; Krichbaum et al. 1998), and reliable sky positions (Rogers et al. 1994; Menten et al. 1997). Krichbaum et al. (1998) have also obtained (marginal) detections at 1.3 mm wavelength.

Using a precise and novel method of registration of radio and infrared reference frames, Menten et al. (1997) have set a stringent upper limit on the 2.2 micron flux density of Sgr A* that is significantly lower than values predicted by earlier theoretical models. The model of Narayan et al. (1998) overcomes the difficulties of previous models, is compatible with the results by Menten et al. (1997), and as said above, provides further evidence for a massive black hole at the Galactic Center.

One of the reasons why it has been difficult to obtain radio images of Sgr A* in the past has been the λ^2 dependence of its size and the lack of suitable short length baselines for VLBI at cm wavelengths. This drawback has been overcome by the completion of the VLBA and by the development of mm-VLBI. Lo et al. (1993) and Alberdi et al. (1993) showed the first VLBA images at 3.6 and 1.3 cm, respectively. Those images were obtained with an incomplete VLBA. Their results, together with the maps and modelfitting results of Backer et al. (1993), Rogers et al. (1994), and Bower & Backer (1998) at mm-wavelengths indicate that the source morphology at cm and long-mm wavelengths corresponds to that of a diffractive-scattered source with a certain ellipticity and with the size scaling as λ^2, just as earlier longer wavelength observations indicated. The intrinsic size, less than 1 AU, remains to be determined and the intrinsic morphology of the source remains to be studied at wavelengths shorter than 3 mm. Yusef-Zadeh et al. (1994) have also found from VLA data at 20 cm that the scatter-broadened image is elongated with an axial ratio of 0.56 ± 0.22 in position angle $82^\circ \pm 1.8^\circ$, quite compatible with higher resolution VLBI observations.

To further check on the ellipticity of the source and to monitor possible structure changes with respect to previous epochs, we undertook new VLBI observations of Sgr A* at 1.3 cm with the complete VLBA and the most sensitive antennas existing in the world at this wavelength. In this paper we report our results which confirm the results of Alberdi et al. (1993) and set limits to any time changes in the structure of the source.

Send offprint requests to: J.M. Marcaide (jmm@vlbi.uv.es)

Table 1. Array antenna characteristics

Station	Code	D $[m]$	$T_{\rm sys}$ $[K]$	Gain $[K/Jy]$	Zenith Opacity
Hancock, NH	HN	25	107	0.087	0.067
Pie Town, NM	PT	25	106	0.135	0.045
Los Alamos, NM	LA	25	92	0.128	0.037
Fort Davis, TX	FD	25	77	0.095	0.044
Kitt Peak, AZ	KP	25	103	0.114	0.043
Brewster, OR	BR	25	106	0.087	0.030
Owens Valley, CA	OV	25	154	0.108	0.050
Phased-VLA, NM	Y	130	170	1.000	($\star$)
Green Bank, WV	G	43	160	0.060	0.044
Goldstone, CA	D	70	70	0.700	0.093

$\star$ For antenna Y the zenith opacity needs not to be estimated, since the ratio of system temperature to antenna temperature is available for each scan.

2. Observations and data reduction

VLBI observations of Sgr A*, at 1.3 cm, were made on 1992 November 8 (UT 10–17 in Europe; UT 17–02 in USA). The US array included eight telescopes of the Very Long Baseline Array (VLBA): Saint Croix (Virgin Islands, SC), Hancock (New Hampshire, HN), Pie Town (New Mexico, PT), Los Alamos (New Mexico, LA), Fort Davis (Texas, FD), Kitt Peak (Arizona, KP), Brewster (Oregon, BR), and Owens Valley (California, OV), along with individual antennas at Green Bank (West Virginia, G), Goldstone-DSS14 (California, D), and the phased VLA array (New Mexico, Y). In addition, the array comprised three European telescopes at Effelsberg (Germany, B), Madrid-DSS63 (Spain, M), and Medicina (Italy, L), although we did not use the European data in the analysis of the results presented in this paper. The European data were fully compatible with the rest but did not add to the analysis. Trans-Atlantic baselines did not show any fringes (sensitivity limit 20 mJy; no detection for baselines longer than 80 million wavelengths). Further, in our analysis we rejected data from station SC due to coherence problems. Thus, we finally analyzed the data with the antennas given in Table 1. Recording was done using the Mark III VLBI system (Rogers et al. 1983). The center frequency was 22236.99 MHz and the recorded bandwidth at the antennas used in the final analysis was 28 MHz. Each tape pass consisted of 12 minutes of data on Sgr A* followed by 1 minute of data on the water maser Sgr_B2N, the latter included for a better amplitude calibration. Several scans of compact calibration sources in the vicinity of the Galactic Center, NRAO 530, 1921-293, and 1958-179 were made during the experiment. Also a few scans of overall amplitude calibrators, 3C 84, 3C 273B, and DA 193 were made at the beginning and at the end of the observations. The data were correlated at the MkIIIA processor of the MPIfR at Bonn, Germany. The correlation was non-standard, requiring a first pass for auto-correlations of Sgr A* and Sgr_B2N, and a second pass for cross-correlations of Sgr A* and each of the calibration sources.

We encountered calibration problems from local interference at stations G and Y. The Sgr_B2N spectra were affected by an interference signal which remained constant in time. After spectral editing of the interference and Hanning smoothing of the edited spectra, we were able to use the Sgr_B2N autospectra for amplitude correction. The data were initially global fringe fitted and coherently averaged over 32 sec intervals (amplitude losses were never higher than 5%) and then transferred into the Caltech VLBI Software Package (Pearson 1991) and DIFMAP (Shepherd et al. 1995) where we performed data editing, calibration, imaging, and display operations.

For the calibration of Sgr A*, we followed two different approaches: (1) We improved the *a priori* radiometry by determining global correction factors for the nominal antenna gains (given in Table 1 together with nominal system temperatures) via an iterative procedure of modelfitting and self-calibration of DA 193, a well-known calibrator source. Further, the antenna gain curves were corrected for atmospheric opacity. Zenith opacities were determined from the dependence of the system temperatures on the air mass and are shown in Table 1 for each antenna; (2) We used the NRAO AIPS software package to calculate the antenna time-dependent relative gains as a function of elevation determined through a least-squares fit of the autospectra of the water maser Sgr_B2N at different elevations to a well calibrated total-power spectrum (see Diamond 1989 for further details). We chose as template the total-power spectrum of the LA antenna obtained at UT 20:07, which was calibrated with the *a priori* system temperature (117 K) and nominal gain (0.128 K/Jy) corresponding to this particular scan. With this method the global array was internally calibrated to better than 5%, the absolute calibration –a global scaling factor– may be in error by up to an additional 5%. Fig. 1 illustrates the relative amplitude corrections –which include antenna gain changes and atmospheric attenuation– obtained in this manner for all the antennas in Table 1.

The accuracy of the overall amplitude calibration, especially at low elevations, was judged by comparing the relative antenna gain corrections independently obtained by the two methods. Consequently, we can confidently assign an uncertainty in the amplitude calibration of 5–10%. Fig. 2 shows the visibility amplitude of Sgr A* versus resolution after the corresponding corrections have been applied to the data.

3. Modelling and imaging results

The essentially flat closure phases suggest from the start a symmetric structure for Sgr A*: the mean closure phases are $0^\circ \pm 10^\circ$ and $0^\circ \pm 30^\circ$ for the shortest and longest baselines, respectively. The Sgr A* data, thus calibrated with the help of DA 193, self-calibration and Sgr_B2N, were best fit by a single (elliptical) gaussian component model. The visibility amplitudes were fit well by an elliptical gaussian brightness distribution of flux density 1.05 ± 0.10 Jy, axial ratio 0.61 ± 0.12, and an angular size for the major axis of 2.67 ± 0.15 mas, in P.A. $79^\circ \pm 10^\circ$. The errors correspond to statistical standard errors, adjusted so that the resultant reduced χ^2 is unity. Using this elliptical gaussian as an

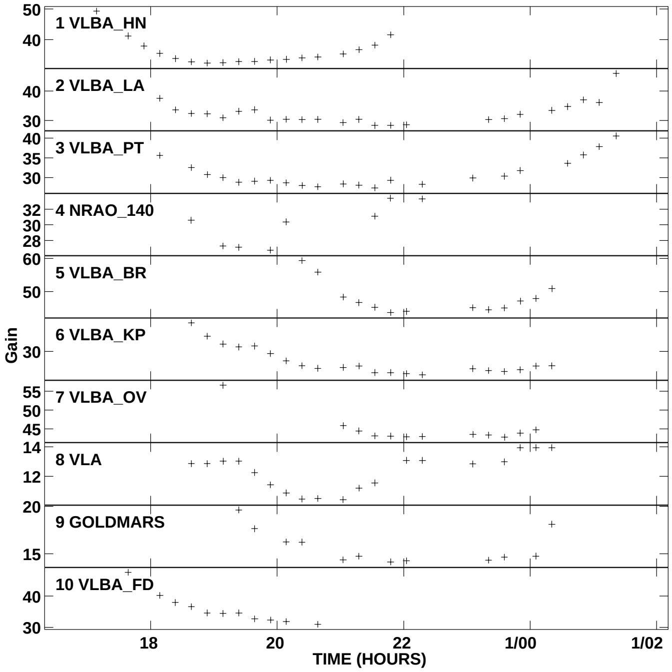

Fig. 1. Relative amplitude corrections versus UT of Sgr_B2N autospectra measured at every station.

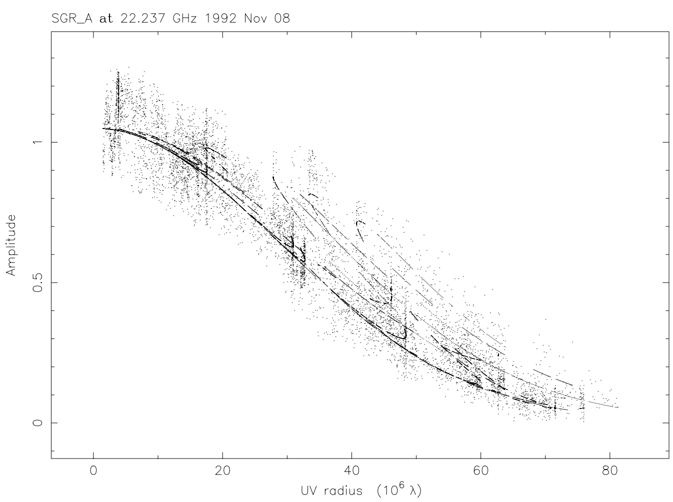

Fig. 2. Fringe amplitudes (Jy) of Sgr A* versus resolution after corrections shown in Fig. 1 have been applied to the data. Superimposed we show the predictions of the best elliptical gaussian model described in the text.

input model, we derived an image for Sgr A*, shown in Fig. 3, using the standard hybrid imaging procedure. We restored the image with a gaussian beam of 3.35×1.7 mas, P.A. $14°$, corresponding to uniform weighting.

Our new results essentially confirm those of Alberdi et al. (1993). Our better uv-coverage, more sensitive array, and added care in the calibration of the amplitudes with DA 193 and Sgr_B2N have indeed led to a higher dynamic range map of higher resolution than that obtained previously by Alberdi et al. (1993), but not to a different result. Since recently an error was discovered in the software program ERRFIT of the Caltech Standard VLBI Package, we have reanalyzed earlier data which we present in Table 2. In this table we have also collected the earliest estimate of the elliptical component of Sgr A* by Lo et al. (1985). In this case, we could not reanalyze the data. The time span of the results shown in Table 2 is almost a decade. Our results from 9 February 1985 (Marcaide et al. 1992), being compatible with those in Table 2, do not "per se" require an elliptical shape for Sgr A* and hence have not been included in Table 2.

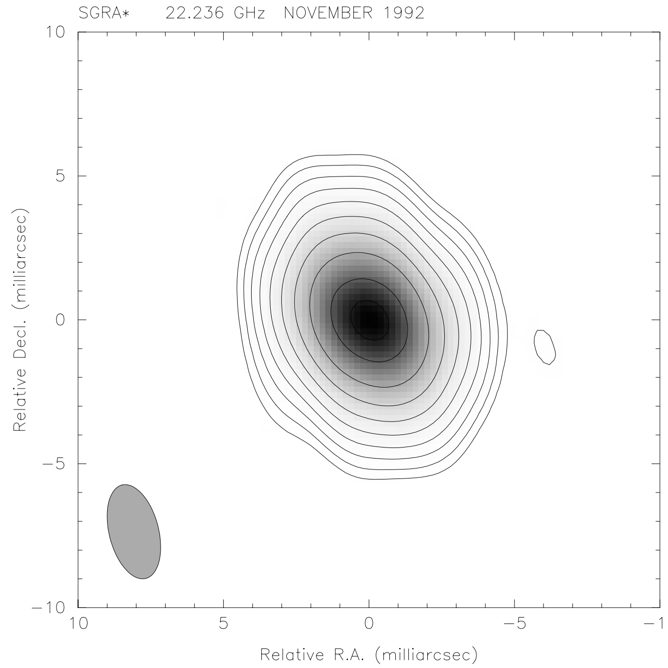

Fig. 3. VLBA image of Sgr A* at 1.3 cm. The map has been convolved with a gaussian beam of FWHM 3.35×1.7 mas, P.A. $14°$. Contour levels are -0.25, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, and 90% of the peak flux density of 0.52 Jy/beam.

4. Discussion

We have made a special effort in obtaining high-dynamic range maps to set stringent limits to any emission larger than the scatter-broadened component detected at all wavelengths longer than 3 mm. Our map noise limit of 0.53 mJy/mas^2 permits us to confidently ignore components other than the gaussian component. Also the shape of the visibility versus resolution plot in Fig. 2 indicates that all considerations should be restricted to an elliptically scatter-broadened component of 2.67 ± 0.15 mas major axis in P.A. $79° \pm 10°$ and axial ratio 0.61 ± 0.12. It is worth noticing that a similar axial ratio (0.56 ± 0.22) has been estimated by Yusef-Zadeh et al. (1994) at a much longer wavelength with the VLA. These authors argue that the scattering must occur in thin ionized surface layers of molecular clouds lying in the central 100 pc of the Galaxy, that the source elongation could be caused by anisotropy of the turbulence in the scattering medium imposed by a sufficiently strong magnetic field, and estimate electron densities of $10^4\,cm^{-3}$ and milligauss magnetic field strengths for such ionized regions. Van

Table 2. Summary of Sgr A* structure determinations

Observing epoch	Major axis (mas)	Axial ratio	Position angle (degrees)	Reference
23 Jun 1983	2.2 ± 0.2	0.55± 0.5	87±30	Lo et al. (1985)†
22 Jun 1991	2.60 ± 0.20	0.5 ± 0.3	80±15	Alberdi et al. (1993)‡
8 Nov 1992	2.67 ± 0.15	0.61± 0.12	79±10	This paper

† Errors as given by authors.
‡ Errors re-estimated with corrected program ERRFIT. See text.

Langevelde et al. (1992) and Frail et al. (1994) report that OH/IR stars appear similarly elongated by interstellar scattering in the vicinity of Sgr A*.

At the 1.3 cm wavelength of our observations the linear size of the elliptical scatter-broadened component major axis (distance of 8 Kpc to the Galactic Center, Reid (1993), Metzger et al. (1998)) is 23 AU (14 AU on the minor axis). At 3 mm, the linear size of the major axis of the expected λ^2 down scaled size of the scatter-broadened component is 1.5 AU (0.9 AU the minor axis). Both axis sizes are compatible with the upper and lower limits obtained from 3 mm VLBI observations by Rogers et al. (1994) and Krichbaum et al. (1998). Narayan et al. (1998) have presented an elaborate advection-dominated accretion flow (ADAF) model which matches the flux density measured at 3 mm and is compatible with the measured size limits at this wavelength. Narayan et al. (1998) predict however a lower than measured flux density at 1.3 cm. They have suggested several ways out of the discrepancy and argued in favor of a slightly modified electron temperature profile in their model which could be obtained including radial transport processes without altering the overall flow dynamics and energetics. They also mention, but downplay, the possibility that the missing emission might be due to a jet of size less than the size of the 1.3 cm scatter dominated component, namely less than 23 AU along P.A. 80° or less than 14 AU along P.A. 350° using our angular size estimates.

From uncertainties in the flux density measurement at 3 mm and the discrepancy between the ADAF model of Narayan et al. (1998) and the observed flux densities at 1.3 cm a rough global spectral index for a putative jet would be -1, which is not an unreasonable value, and hence the possibility of the jet cannot be completly ruled out. Furthermore, since one would expect such a jet in a direction roughly perpendicular to the galactic plane its size would be limited to 16 AU. Krichbaum et al. (1993) suggest a possible jet in P.A. 335° from 7 mm observations but Backer et al. (1993) do not confirm it. The possible jet suggested by Krichbaum et al. would be 30° off the expected direction (assuming a jet perpendicular to the galactic plane; of course, there are AGNs where the jets are not perpendicular to the corresponding galactic planes) and unfortunately almost coaligned with the beam major axis, which makes it suspect. More recent observations at 7 mm by Bower & Backer (1998) have not confirmed the jet existence either, although as they mention, they cannot rule out such component in the past. Future observations at 7 mm might further clarify the situation.

Nearly- and quasi-simultaneous flux density observations encompassing two decades of wavelength made by Serabyn et al. (1997) and Falcke et al. (1998), respectively, show that the millimeter spectrum is more inverted than the centimeter one and provide evidence, not contaminated by variability, of an excess of emission at millimeter wavelengths which can be interpreted as due to self-absorbed emission by an extremely compact object. Additionally, submillimeter observations by Gwinn et al. (1991) show no variability due to refractive scintillation and hence these authors argue in favor of a source size larger than 0.1 AU at 0.8 mm wavelength. Narayan et al. (1998) can naturally account for these two observational results with a different model, namely that of an optically thin emission due to an ADAF, which also calls for a compact object. The source emission variability seems to only manifest itself at wavelengths where the source intrinsic size is smaller than a scattering disk, namely at wavelengths longer than 3 mm. Only observations by Wright & Backer (1993) seem to contradict the previous statement with flux density variations of $\sim$300 % in time scales of $\sim$10 days, with an instrument of a $3'' \times 7''$ resolution. Zhao et al. (1992) suggest that some of the longer wavelength variability may be also intrinsic.

Thus, taking the paradigm that at 1.3 cm the flux density changes are not due to an intrinsic compact source, but to changes in a hypothetical jet or to refractive scintillation, we have tried to detect possible structure changes. We find no evidence of such changes. Our sampling of the structure of Sgr A* spans 8 years of our own data and almost a decade if we include the observations of Lo et al. (1985). The results obtained can be summarized as a constant 23 AU×14 AU elliptical gaussian source with major axis along P.A. 80°. Thus, it seems reasonable to conclude that both the region around the massive black hole (2.5×10^6 $M_\odot$, Eckart & Genzel 1996,1997) responsible for the compact low emission efficiency source Sgr A* via an ADAF mechanism and the surrounding medium acting as a refractive screen have reasonably constant relative orientation, emission rates, and structures.

Our result also argues against changes in a putative jet although it says nothing about its reality which is in accord with the interpretation of Sgr A* as a low luminosity AGN with an accretion rate well below the Eddington limit (Melia et al. 1992, Falcke et al. 1993, Narayan et al. 1998). Recently, Mahadevan

(1998) has considered the consequences of charged pion production from a two-temperature ADAF. Energetic proton collisions create charged pions which subsequently decay into high energy electrons and positrons. These particles interact with the local magnetic fields to produce synchrotron radiation which increases the predicted radio flux. This mechanism provides an elegant and likely definitive solution to the discrepancy between the measured flux densities and ADAF predictions, which possibly renders unnecessary other considerations based on putative jets.

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