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Anisotropy in the Angular Broadening of Sgr A* at the Galactic Center

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ABSTRACT

We present the results of a $\lambda_{20}$ cm VLA$^2$ observation of the compact Galactic center radio source Sgr A$^*$. The scatter-broadened image is elongated in the East-West direction, with an axial ratio of $0.6\pm0.05$ and a position angle of $87^0\pm3^0$. A similar shape and orientation has been found previously at shorter wavelengths using VLBI and VLBA. Both the major and minor axes follow the $\lambda^2$ law appropriate for scattering by turbulence in the intervening medium.

Assuming that the anisotropy is caused by a magnetic field permeating the scattering medium, we argue that the scattering occurs within extended HII regions lying in the central 100 pc of the Galaxy. The magnetic field in this region must be poloidal, organized and is estimated to have a strength of at least 30 to 100 $\mu$Gauss.

Subject headings: galaxies: ISM— Galaxy: center —ISM: individual (Sgr A*, IRS 16)

1. Introduction

Sgr A*, the compact radio source at the Galactic center, shows nonthermal characteristics with a spectrum that rises as $\nu^{0.25}$ at radio wavelengths, and whose brightness temperature exceeds $10^{10}$K at $\lambda_{7}$mm (Backer 1993; Backer et al. 1993). With a radio luminosity of $\sim 2 \times 10^{34}$ erg/s ($\sim 1.1$ Jy at $\lambda_{2}$cm), Sgr A* is the brightest radio source within the inner several degrees of the Galactic center region. It lies close to the dynamical center of the Galaxy and the surface density distribution of the stellar cluster that engulfs the Galactic center is centered to within roughly 0.1" of Sgr A* (Eckart et al. 1993). Theoretical analysis of the radiation spectrum of this source is also consistent with it being a massive ($\approx 1-2$ $M_\odot$) black hole (Melia 1992). These properties as well as the intrinsic time variability (Brown and Lo 1982; Zhao et al. 1991; Backer 1993) suggest that Sgr A* resembles the cores of extragalactic radio sources, perhaps hinting at a common heritage.

The angular broadening of Sgr A* was first reported to scale quadratically with wavelength $\lambda$ (Davies et al. 1976) not long after the discovery of Sgr A* by Balick and Brown

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$^2$ VLA is a component of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract to the National Science Foundation
(1974). The broadening is caused by electron density fluctuations which change the refractive index of the interstellar medium along the line of sight. Anisotropies in the scatter-broadened image have been reported at relatively high frequencies for some time (Davies et al. 1976; Lo et al. 1985; Jauncey et al. 1989; Marcaide et al. 1992; Alberdi et al. 1993; Lo et al. 1993; Krichbaum et al. 1993; Backer et al. 1993). In one of the more recent measurements by Lo et al. (1993), the power law index of the major axis is estimated to scale as $\lambda^{1.94\pm0.03}$. Here we report VLA observations showing similar results to those of earlier VLBA and VLBI high-frequency measurements. The new observation indicates that the size of Sgr A* at $\lambda 20$ cm is asymmetric in the East-West direction. The measured size of Sgr A* scales as $\lambda^{2.01\pm0.02}$ and $\lambda^{2.13\pm0.04}$ for the semi-major and semi-minor axes, respectively. We argue that the turbulent medium responsible for scattering lies within the inner 100 pc of the Galaxy and that the asymmetry in the scatter-broadened size of Sgr A* is accounted for by an organized, large-scale poloidal magnetic field permeating the central region of the Galaxy. Estimates of the orientation and strength of the magnetic fields made here are quite consistent with an independent set of earlier magnetic field measurements carried out toward the nonthermal filamentary structures near the Galactic center (Yusef-Zadeh, Morris & Chance 1984; Sofue et al. 1987; Yusef-Zadeh & Morris 1987a).

2. Data Reductions and Results

Radio continuum observations of the Galactic center were carried out on January 10, 1985 using the A-array configuration of the VLA. We used the spectral line mode of the VLA correlator by choosing 16 channels of 1.5625 MHz bandwidth with only one sense of polarization. This observation was carried out with an antenna pointing centered at $\alpha(1950) = 17^{h}42^{m}25.0^{s}, \delta(1950) = -28^{0}57^{\prime}30^{\prime\prime}$. This is offset by about 108.6“ to the north and 4.3“ to the west of the position of Sgr A*. The bandwidth smearing of Sgr A* due to individual channels is roughly 140 mas at a PA$\approx -28^0$ which is smaller than the scatter-broadened size of Sgr A*. A correction for this effect was made as described below. The $\lambda 20$ cm observations consisted of two 25-minute scans separated in time by one hour.

The channel data were calibrated by using 1748-253 and 3C286 as the phase and flux
calibrators, respectively. In order to improve the dynamic range of the final images, we also used 3C286 and 1748-253 as bandpass calibrators before the first 14 channels of the data were averaged to form a continuum data set. The standard calibration procedures gave a flux density of 1.2075±0.02 Jy for 1748-253. We employed phase self-calibration of Sgr A* by restricting the $uv$ range to $>20$ kλ. A first order correction for the effects of bandwidth smearing were made using the AIPS program UVADC which corrects the amplitude loss in each visibility based on a model of the emission in the field. The final image was constructed after bandwidth smearing correction was applied using only baselines longer than 20 kλ. Due to the southerly declination of the source, the FWHM of the synthesized beam is $2400 \times 1000$ mas with PA=$-17^0$. There was 696 mJy of flux CLEANed from the image leaving the rms noise in a blank region of about 1 mJy. The region CLEANed was $250'' \times 250''$ centered on the position of Sgr A*. The CLEANing was done using task WFCLN.

An elliptical Gaussian fit to the final CLEAN image of Sgr A* yields a FWHM=$636 \pm 8 \times 382 \pm 32$ mas and a position angle $87^0 \pm 3^0$. In the uv domain, we also attempted an elliptical Gaussian fit at long, $>50$kλ, $uv$ spacings. In spite of the extended structure in the field, the Gaussian fits to the $uv$ data gave FWHM=$680 \pm 7 \times 459 \pm 3$ mas and a position angle $96^0 \pm 2^0$. The axial ratio in the $uv$ and in the image domain are 0.68±0.005 and 0.60±0.05, respectively. The $uv$ plane results do not appear to be terribly sensitive to the initial guess; however, using shorter baselines tends to make the source rounder. We believe that the result of Gaussian fitting in the image plane is more reliable than in the $uv$ plane since the λ20cm image of the field shows 100 mJy of flux outside of Sgr A* even excluding the shorter baselines. The parameters of the fit stated here are also more accurate than those given in recent preliminary presentation of the λ20cm data (Yusef-Zadeh 1993).

Jauncey et al. (1989) found an asymmetry at λ3.6cm and was recently confirmed by Lo et al. (1993). A similar asymmetry with an axial ratio close to 0.5±0.2 is also noted at 1.2cm (Marcaide et al. 1992; Lo et al. 1993), although recent MK II VLBA measurements at λ1.2cm gave a size of about 2.8 mas and were not able to constrain the axial ratio at this
critical wavelength (Walker, private communication). Backer et al. (1993) have recently reported the best elliptical Gaussian fit model to the closure amplitude data at $\lambda 7$mm, which gives a size $0.74 \pm 0.03 \times 0.04 \pm 0.20$ mas with the position angle $90^0 \pm 10^0$. The elongation of the source at this wavelength is consistent with the $\lambda 7$mm data presented by Krichbaum et al. (1993). Table 1 shows a list of position angle and axial ratio measurements of Sgr A* at a number of wavelengths. (Krichbaum et al. find Gaussian fits to two sources and the parameters of the fit to the strong source is shown in Table 1). Considering the uncertainties involved in measuring the minor axis of Sgr A* at high frequencies, the axial ratio of 0.6 at $\lambda 20$cm presented in this paper appears to be consistent with the previous VLB measurements at $\lambda 3.6$ and 1.35cm (Jauncey et al. 1989; Lo et al. 1993; Alberdi et al. 1993).

| $\lambda$ (cm) | Major axis (mas) | Axial ratio | PA (°) | Reference |
|-------------|-----------------|-------------|--------|-----------|
| 0.7         | 0.74 ± 0.03     | 0.54 ± 0.2  | 90 ± 10| Backer et al. 1993 |
| 0.7         | 0.70 ± 0.1      | 0.6         | −65 ± 20| Krichbaum et al. 1993 |
| 1.35        | 2.6 ± 0.2       | 0.5 ± 0.2   | 75 ± 10| Lo et al. 1993 |
| 1.35        | 2.58 ± 0.08     | 0.5 ± 0.2   | 79 ± 6 | Alberdi et al. 1992 |
| 3.6         | 17.4 ± 0.5      | 0.53 ± 0.1  | 82 ± 6 | Jauncey et al. 1989 |
| 3.6         | 17.5 ± 0.5      | 0.49 ± 0.06 | 87 ± 5 | Lo et al. 1993 |
| 20.7        | 636 ± 8         | 0.60 ± 0.05 | 87 ± 3 | this paper |

Table 1

The position angle of the asymmetry in the scattered-broadened image of Sgr A*, as seen in Table 1, is consistent with the East-West elongation as noted at $\lambda 3.6$, 1.2cm and 0.7cm. An axial ratio of 0.6 at $\lambda 20$cm confirms that the intervening scattering medium is anisotropic. There is a hint that the shape of Sgr A* becomes more anisotropic at shorter wavelengths, though this needs be confirmed in future observations. Figure 1 shows the relationship between the size of Sgr A* vs. $\lambda$ for the semi-major and semi-minor axes as a function of wavelength. Also shown is a least-square fit to the data, where the mean of the logarithmic upper and lower error bars has been used to determine the weighting for each data point. The major axis follows a slope $-2.01 \pm 0.02$ whereas the fit to the size of the
minor axis is steeper, -2.13±0.04 as it passes through the recent λ7mm data point (Backer et al. 1993). The slope of the size of the minor axis is dictated by two data points at λ20 and 3.6cm, though consistent with high-frequency points with large error bars. Obviously, future VLBA observations at a number of frequencies, should be able to determine if the size of Sgr A* become somewhat more asymmetrical at very high frequencies.

3. Discussion

It has been suggested (Jauncey et al. 1989; Lo et al. 1993; Backer et al. 1993) that the elongation of Sgr A* is caused by anisotropy of the turbulence in the scattering medium imposed by a strong magnetic field, which permits small-scale density and velocity fluctuations perpendicular to the direction of the field (Cordes et al. 1984; Higdon 1984, 1986). The scattered image is stretched in a direction perpendicular to the average projection of the field in the plane of the sky, so the inferred average field direction is oriented North-South.

Van Langevelde et al. (1992) found that OH/IR stars within 15 arcminutes of the Galactic Center suffer a large angular broadening. They suggested that the scattering medium could either lie close to the Galactic center or could be relatively local. The observed anisotropy favours the former model because the inferred magnetic field direction is consistent with the large scale poloidal field that exists in the central 100 to 200 parsecs of the Galaxy (Yusef-Zadeh, Morris and Chance 1984; Tsuboi et al. 1986) rather than with the field direction of the Galactic disk. Assuming that the position angle of the scatter-broadened shape of Sgr A* is 80° ± 10°, the predominant component of the magnetic field is inferred to be oriented 70° ± 10° away from the Galactic plane.

A survey by Mezger and Pauls (1979) shows that the inner 150 pc × 50 pc (l×b) of the Galaxy is enveloped in strong radio continuum emission. Half this emission is now known to be thermal, arising from extended HII regions (Schmidt 1978; Handa et al. 1987). These HII regions are good candidates for the source of scattering since they can support anisotropic turbulence on small length scales (Higdon 1984). As a simple model for the scattering medium we assume that HII regions are uniformly distributed within the inner
100 pc of the Galaxy. The HII regions have characteristic electron density $n_e$, with rms fluctuation $\delta n_e$, and the total path length that intercepts the HII regions is $L$. From Mezger and Pauls (1979), the emission measure due to thermal ionized gas is $n_e^2L \approx 2 \times 10^4 \text{cm}^{-6} \text{pc}$, whereas the observed angular size of Sgr A* requires that $\delta n_e^2L \approx 200 \text{cm}^{-6} \text{pc}$ (Backer 1978). This implies that $\delta n_e/n_e \approx 0.1$, independent of the degree of clumping of the ionized gas.

A lower limit can be placed on the magnetic field in this region because it has to be strong enough to resist being bent by turbulence, that is, the field pressure should be at least as large as the thermal pressure. Adopting a temperature of $10^4 \text{K}$, this yields $B/(n_e)^{1/2} > 8 \text{cm}^{3/2} \mu \text{G}$. Thus for $L = 100 \text{pc}$, there is one extended HII region with $n_e = 17 \text{cm}^{-3}$ and $B > 30 \mu \text{G}$ whereas for $L = 1 \text{pc}$, we obtain $n_e = 170 \text{cm}^{-3}$, and $B > 100 \mu \text{G}$. Such a high value of the magnetic field is not unexpected since a number of large-scale magnetized filaments in the Galactic center region are thought to have milliGauss field strengths in the direction perpendicular to the Galactic plane (Yusef-Zadeh & Morris 1987b; Serabyn & Güsten 1991).

The field strength can be independently estimated from Faraday rotation measurements. The observed rotation measure ranges between 1000 and 5500 rad. m$^{-2}$ (Inoue et al. 1984; Sofue et al. 1987, Yusef-Zadeh & Morris 1987a). Adopting the middle of this range, $n_eB_\parallel L \approx 3000 \text{cm}^{-3} \mu \text{G} \text{pc}$, we find $B_\parallel$ of 2 or 18 $\mu \text{G}$ for L=100 or 1 pc respectively, significantly less than the limit on the total field strength. This is consistent with the idea that the large-scale field runs vertically through the plane near the Galactic center. The projection of the field on the plane of the sky must be fairly uniform so that the image of Sgr A* is not circularized by the cancellation of different contributions along the line of sight. Future observations of the scatter-broadened shape of of OH/IR stars lying in the inner 15’ of the Galactic center are crucial in testing this picture.

It has been suggested that the wind from the IRS 16 cluster which lies within the inner pc of the Galaxy may in fact be responsible for the scattering medium. However the required size of the density fluctuations is larger for screens closer to Sgr A*, both
because they are thinner and because the scattering angles become larger. At one pc from Sgr A*, electron density fluctuations of 2000 cm$^{-3}$ are needed, whereas the mean density of the IRS 16 wind at 1 pc is only 10 cm$^{-3}$. Further, an entrained magnetic field will be stretched parallel to the East-West line joining IRS 16 and Sgr A*, scatter-broadening Sgr A* orthogonal to the observed direction.

Although the deviation in the scaling of the size of the minor axis from a $\lambda^2$ law may not be significant it is worth noting that a deviation would raise an interesting problem because anisotropic turbulence should produce a shape that is frequency-independent. That is, both major and minor axes should depend quadratically on wavelength. One possibility is that the intrinsic emission from Sgr A* is contributing to the change in its apparent shape. This is intriguing given the recent prediction that a one to two million solar mass black hole accreting at the location of Sgr A* should have an intrinsic size of several mas at cm wavelengths (Melia, Jokipii and Narayanan 1992). The apparent flux distribution is a convolution of the emission intrinsic to Sgr A* and the angular broadening associated with scintillation. Recent 3D hydrodynamical simulations (Ruffert and Melia 1993), suggest that at longer wavelengths, we are sampling the larger sized structure which follows the general bow-shock pattern, whereas as the frequency increases, smaller scale lengths corresponding to the more compact region of the infalling plasma are sampled. Since the flow becomes more radial as it falls in toward the blackhole, then one should expect to see a decrease in the axial ratio as a function of increasing frequency. The slope of the minor axis in Figure 1 may give a hint in support of the above suggestion. However, it is clear that an improved measurement of the minor axis at $\lambda$0.7, 1.35, 20 and 90cm are crucial to confirm the change in shape with wavelength as well as to give better estimates of the intrinsic source size and the shape of the anisotropy.

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Figure 1. A logarithmic plot showing the size of the semi-major (top) and semi-minor (bottom) axes of Sgr A* at a number of frequencies (Backer et al. 1993; Alberdi et al. 1993; Lo et al. 1993; this paper). The fit to each axis is also shown.
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