REPORTS

Upper Limit of 3.3 Astronomical Units to the Diameter of the Galactic Center Radio Source Sgr A*

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Sagittarius (Sgr) A* is a unique radio source located at the center of our galaxy. The radiation from Sgr A* may be generated in matter accreting onto a massive black hole. In observations at long wavelengths, the apparent angular size of Sgr A* decreases in the manner expected for emission from a point source scattered by electron density fluctuations along the line of sight. Measurements at a wavelength of 7 millimeters with the nearly completed Very Long Baseline Array indicate a size of 0.7 milliarc seconds, which is consistent with an extrapolation from results at longer wavelengths. The true size of Sgr A* must be less than 0.4 milliarc seconds, or 3.3 astronomical units. The inferred black hole mass is less than 1.5 × 10^6 solar masses according to a recent model for the emission.

Sagittarius A* is an enigmatic object. Recent speckle imaging at a wavelength (λ) of 2 μm indicates that the centroid of the stellar sources at the galactic center is much closer to Sgr A* than to the IRS 16 stellar complex (*1*), suggesting that Sgr A* may be at the dynamical center of the galaxy. However, there is no firm estimate of the mass of the underlying body of Sgr A*, nor is there a generally accepted model for its emission mechanism. Many authors propose a black hole for the underlying body (*2–4*). Radiation arises in matter slowly accreted, or possibly expelled, by the black hole. Detections at infrared and x-ray wavelengths are possible additional clues to the nature of Sgr A*, but these lack the sensitivity or resolution needed to clearly identify these radiations with that of the extremely compact radio source (*5*).

High-resolution radio interferometer techniques are used to probe the intensity distribution of radiation from Sgr A* (*6*). These efforts are limited by blurring caused by diffractive scattering in the intervening turbulent plasma. The quadratic dependence of the scattering angle on wavelength allows higher resolution as we push to shorter wavelengths. A curious feature of these longer wavelength studies is an asymmetry of the blurred image, which may be interpreted as evidence of anisotropy in the turbulence caused by strong magnetic fields (*7*).

We report observations at λ 7 mm (43.1 GHz) that were made on 14 August 1992 with five antennas at the following Very Long Baseline Array (VLBA) sites: North Liberty, Iowa (NL); Los Alamos, New Mexico (LA); Pie Town, New Mexico (PT); Kitt Peak, Arizona (KP); and Owens Valley, California (OV). At millimeter wavelengths, the sensitivity of VLBA observations is limited by short coherence times attributable to path length fluctuations arising from tropospheric water vapor, by variable extinction in the troposphere, by the relatively poor sensitivity of some of the receivers, and by changes in the gain of individual antennas with elevation. Calibration of the antenna gains is also difficult at λ 7 mm because of the small number of strong, ultra-compact radio sources. In this experiment, calibration problems were exacerbated by poor weather at both New Mexico sites and by our incomplete knowledge of the VLBA antenna parameters at this early stage of the instrument. Several calibration steps were crucial to remove known effects.

The dominant term in the calibration of this data is the variable system temperature and extinction that are a consequence of the opacity of the troposphere. The elevation of Sgr A* is never greater than 29° at any of the telescopes. System temperature data were extracted from the VLBA calibration database and were plotted against air mass along the path, assuming a simple planar atmosphere. These plots indicated clearly that a steady value of each receiver's noise temperature could be estimated with an accuracy of about 10 K by extrapolation to zero air mass. The values ranged from 90 to 160 K. We then calculated the effects of extinction for each measurement using the measured system temperatures and the estimated receiver temperatures. Constant antenna gains based on previous VLBA calibration measurements were used in this first calibration step.

In a second calibration step, we analyzed observations, which were recorded twice per hour, of the SiO maser in the stellar source VX Sgr. The maser spectra provide sensitivity-limited measures of the ratio of the line intensity, which is proportional to the extinction, to the system temperature for each antenna. After application of the above extinction corrections, we could determine improved values for the relative antenna gains. In particular, the Owens Valley antenna gain required adjustment because its subreflector was fixed at an incorrect position during the observations. These data provided evidence for significant gain variations with elevation. The short integrations on VX Sgr, the weakness

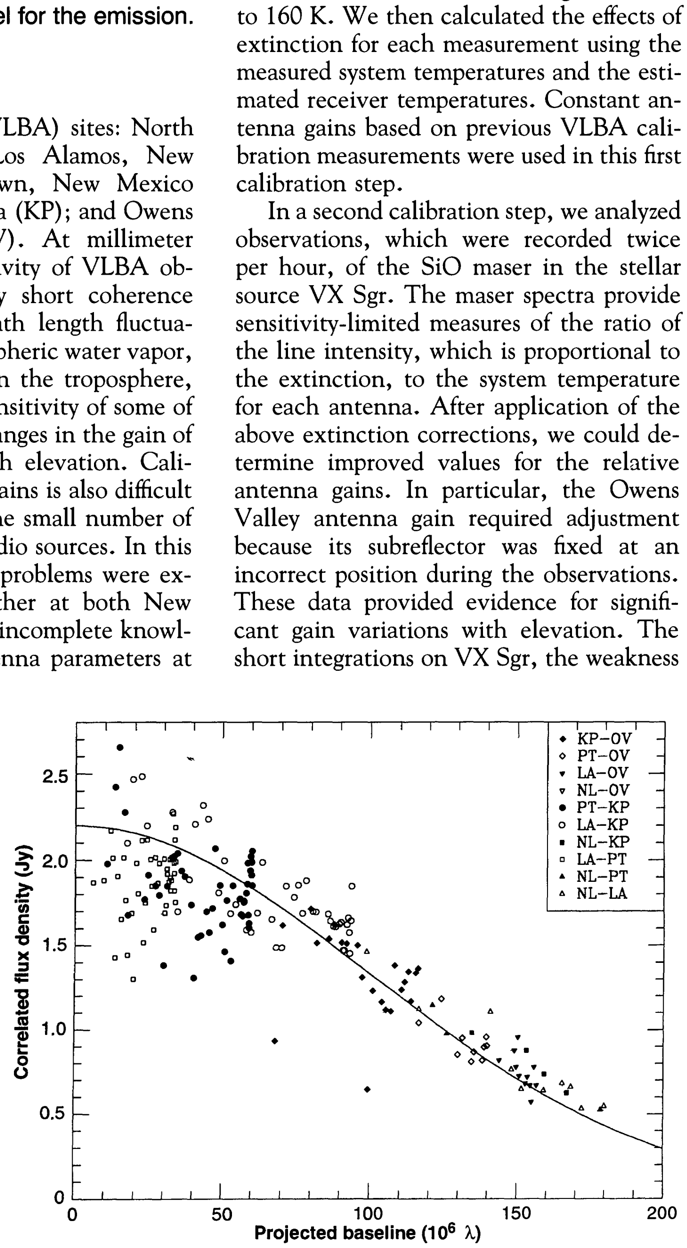

Fig. 1. Visibility data for λ 7 mm observations of Sgr A* with the VLBA are plotted as a function of projected baseline, given in units of millions of wavelengths. Data were recorded at five telescopes with a bandwidth of 56 MHz and were correlated using the Haystack Observatory MKIII VLBI correlator. Our analysis of this data is restricted to those observations above 10° elevation. The data for our amplitude analysis were coherently averaged for 10 s and then incoherently averaged in blocks of 1 to 5 min. Owing to the low sensitivity available with 10 s of integration, accurate removal of the noise bias in incoherent averages is required. The key to the telescope pairs uses the station codes given in the text. A circular Gaussian model with full width at half maximum of 0.74 mas is shown (solid line), along with models that differ in total flux density by 20% (dashed lines).

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of the SiO line, and the poor weather at some stations limited the usefulness of this calibration path.

In a third calibration step, we assumed that the source B1730-130 (NRAO 530), which was observed twice per hour, was unresolved with a flux density of 4.0 janskies (Jy), and solved for antenna gains whenever several baselines of data were available. These gains were then plotted against elevation to determine that a consistent relative gain curve of $0.26 + 0.014EL$, where EL is the elevation in degrees, applies to all telescopes over the range $10° < EL < 45°$. This gain curve was then added in our final calibration of the observations.

In Fig. 1, we show the calibrated fringe amplitudes as a function of projected baseline along with a circular Gaussian model that has a half-power apparent size of 0.74 milliarc seconds (mas). The flux-density scale was set by our assumed NRAO 530 core flux density. The results for different baselines are distinguished in Fig. 1, and the projected baselines are displayed in Fig. 2. The distribution of projections shows that these observations are most sensitive to the east-west structure of Sgr A*. The bunching of visibility measurements (Fig. 1) is the result of many measurements on the short baselines where the projected baselines change over a small range of angles but have nearly constant lengths (Fig. 2). The spread is then an indication of our short-term internal errors. The closure-phase measurements (Fig. 3) are consistent with zero, which indicates a structure with reflection symmetry.

The results at longer wavelengths indicate an apparent east-west diameter of $(1.40 \pm 0.05)\ \lambda^{2.0}$ mas (λ is in centimeters), and the λ 3.6 cm visibility data fit a profile that is very closely Gaussian along both major and minor axes of the apparent source brightness distribution (6, 8). The simplest explanation for these effects is interstellar diffractive scattering in a region near the galactic center where the plasma turbulence is dominated by a nearly uniform magnetic field. The interpretation of these effects in terms of scattering in the vicinity of the galactic center has received strong confirmation from OH maser observations (9). The measured visibilities sample the structure function of electron density fluctuations along converging lines of sight to Sgr A* (8). If the scattering occurs within 10^2 to 10^3 pc of Sgr A*, then we sample scales of 10^6 to 10^7 cm that are likely to be much less than the inner scale of the turbulence spectrum (*10*). The measured quadratic frequency dependence of the apparent diameter and the Gaussian form of the measured brightness distribution are consistent with expected scattering effects for sampling on baselines less than the inner scale. The scattering model predicts an identical form of the apparent brightness distribution at higher frequencies with simple scaling by $\lambda^{2.0}$ until the intrinsic size adds significantly in quadrature or the scattering becomes weak. Refraction and insufficient averaging can modify these results (*11*), but large differences from the diffractive model are not expected.

In our data, there are systematic deviations at the 10% level that can be attributed to residual calibration errors. A closure amplitude analysis can remove residual effects (*12*) that are station dependent. Errors in atmospheric opacity, system temperature, and antenna gain, but not effects of oscillator coherence, can be removed. The closure variable is formed from data on four closed baselines, which requires simultaneous data from four antennas. A circular Gaussian fit to the 19 closure amplitude data points provides a formal estimate of 0.03 mas for the error in the 0.74-mas diameter. The measured size is then very close to that expected on the basis of an extrapolation of the $\lambda^{2.0}$ dependence reported at longer wavelengths, 0.67 ± 0.03 mas. From the close agreement, we conclude that the intrinsic source diameter at λ 7 mm adds no more than 0.13 mas to the apparent east-west diameter when added in quadrature, and the intrinsic east-west diameter is no more than 0.4 mas, or 3.3 astronomical units (AU) (R_0 = 8.5 kpc).

The strong azimuthal asymmetry seen at longer wavelengths (2:1) is also consistent with our data. The best fit of an elliptical Gaussian source model to the closure amplitude data has diameters of 0.74 ± 0.03 mas by 0.40 ± 0.20 mas with the major axis in position angle $90 \pm 10°$. These diameters and the position angle are fully consistent with the extrapolation from long wavelengths. The corresponding limit on the intrinsic north-south diameter is about 0.5 mas, or 4 AU. The inferred limits on the intrinsic angular size give a corresponding limit to the Sgr A* brightness temperature: 1.4×10^{10} K. Observations at increasingly shorter wavelengths may one day reveal the intrinsic structure in this enigmatic radio source.

Krichbaum *et al.* (*13*) have presented λ 7

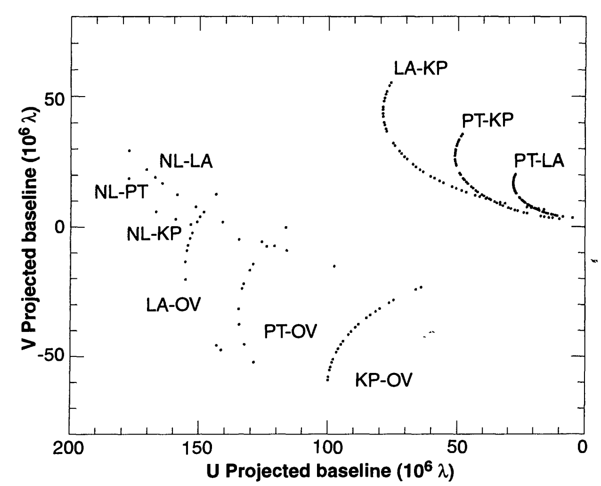
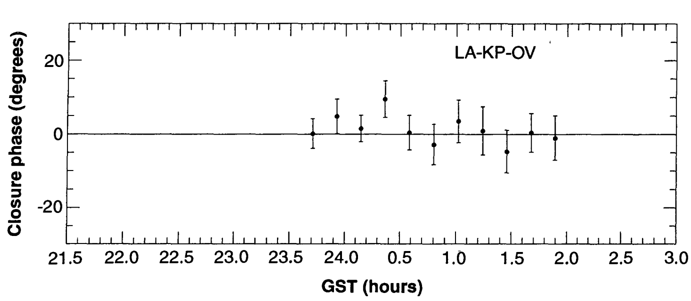


Fig. 2. Projected lengths of baselines (U, east-west; V, north-south) corresponding to data plotted in Fig. 1. The baselines are identified by a pair of antenna codes that are identified in the text. The maximum east-west baseline is 180 × 10^6 λ and the maximum north-south baseline is 60 × 10^6 λ, which correspond to angular resolutions of 0.78 and 2.3 mas, respectively.



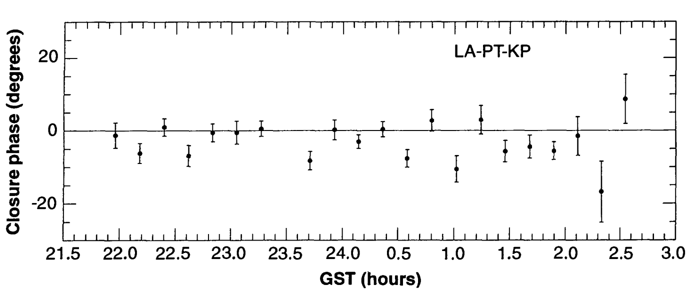


Fig. 3. Closure-phase results for two baseline triangles with codes explained in the text. Data has been averaged coherently over 1000 s. Time is Greenwich Sidereal Time (GST) on days 227 to 228 of 1992.

mm data obtained in May 1992 with use of four VLBA antennas. Their data are in general agreement with our results. Their best fit to a circular Gaussian model has a diameter of 0.75 mas, which is identical to our result, and their B1 component is consistent with our closure-amplitude fit. Both observations are dominated by the east-west structure owing to the limited range of baseline projections. Krichbaum *et al.* suggest the presence of one or more additional faint components with 0.2 to 0.4 Jy for which we have no evidence. The total flux density of the source at the epoch of their observations was 0.8 Jy less than that found during ours, and this could result in some differences owing to limited dynamic range. New observations with the full VLBA made under good weather conditions over multiple epochs are needed.

A long-standing alternative to the scattering interpretation for the observed wavelength-dependent brightness distribution is a nonuniform thermal or synchrotron source (*14*). Although such models could match the observations, extreme parameters are required, and, most importantly, the observed scattering of the OH masers within 15 arc min of Sgr A* would need to be coincidental. Melia (*3*) has explored further a nonuniform source model using the context of accretion onto a massive black hole from the winds blown out of the IRS 16 complex. He assumed that current size estimates are dominated by scattering and makes predictions about the contribution of the intrinsic source distribution to the apparent size as a function of wavelength. This work makes a number of critical assumptions to allow estimation of the spectrum from radio waves to x-rays for a range of central masses. On the basis of calculations that have been used to develop this black hole model (*15*), our upper limit to the intrinsic size of 3.3 AU corresponds to an upper limit to the mass of the black hole at the galactic center of 1.5×10^6 solar masses. This is comparable to estimates based on other lines of evidence (*16*). The radio source luminosity of Sgr A* is about 10^{34} erg s^{-1} for an isotropic spectrum of radiation extending to 100 GHz (*17*). The small size and large radio luminosity of Sgr A* in combination with its low peculiar velocity (*18*) and its central location in the 3.8–arc sec (0.15-pc), dense stellar cluster (*1*) are all strong indicators that the underlying body of Sgr A* is a massive black hole.

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Photoactivated Conformational Changes in Rhodopsin: A Time-Resolved Spin Label Study

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Rhodopsin has been selectively spin-labeled near the cytoplasmic termini of helices C and G. Photoactivation with a light flash induces an electron paramagnetic resonance spectral change in the millisecond time domain, coincident with the appearance of the active metarhodopsin II intermediate. The spectral change is consistent with a small movement near the cytoplasmic termination of the C helix and reverses upon formation of the MIII state. These results provide an important link between the optical changes associated with the retinal chromophore and protein conformational states.

Rhodopsin is a member of the receptor family linked to G proteins (heterotrimeric guanosine triphosphate–binding proteins) and is one of the most extensively studied because of its natural abundance in the retina. The activation of receptors in this family presumably leads to a conformational change that presents new topological features recognized by a G protein. In rhodopsin, light absorption initiates a cascade of events involving discrete intermediates, each defined by an optical absorption maximum arising from the retinal chromophore (*1*). The relation of the optical changes to structural changes in the protein remains uncertain, but it appears that receptor activation is closely associated with the appearance of a species that absorbs at 380 nm that is referred to as metarhodopsin II (MII) (*2*).

The nature of the protein conformational change associated with receptor activation lies at the heart of the signal transduction mechanism and has been the subject of active investigation. Proteolysis (*3*), Fourier transform infrared difference spectroscopy (FTIR) (*4*), linear and circular dichroism (*5*), and cyanogen bromide reactivity (*6*) all reveal differences between native rhodopsin and the MII state as defined by the 380-nm absorbance. However, this absorbance may not uniquely define a protein conformation, and it is important to obtain direct time-resolved data on the protein conformation to draw unambiguous correlations with receptor activation and the optical transitions. In addition, it is necessary to localize the changes within the protein structure for a meaningful interpretation. To date, FTIR spectroscopy has provided the most detailed information on the conformational transitions but has not been time-resolved in the appropriate range, and the changes have only been generally localized within the structure (*4*).

In this report, we show that the time-resolved electron paramagnetic resonance (EPR) signal from spin-labeled rhodopsin in the native disc membrane directly reveals a light-triggered conformation transition in the region of the second cytoplasmic loop with an appearance rate constant and acti-

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