High Resolution Imaging of Sagittarius A*

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Abstract. High resolution radio imaging of Sgr A* provides an opportunity to study the accretion and outflow environment of a black hole that is not available for any other system. Strong interstellar scattering of radio waves, however, complicate the interpretation of radio images. High quality determination of the intrinsic size and shape require high quality images as well as accurate calibration of the scattering law. New results indicate that the intrinsic size is determined from 3.5 cm to 0.35 cm with a size at the shortest wavelength of $\sim 13R_s$ and a wavelength-size power law index of 1.5. Millimeter and submillimeter observations have the promise of constraining the mass density of the black hole on a smaller radius than any other technique.

1. Introduction
Imaging the radio emitting region surrounding the massive black hole in the Galactic Center, Sagittarius A*, has been a goal since its discovery [1]. Turbulent electrons along the line of sight to Sgr A*, however, scatter radio wavelength photons and produce an image that is an elliptical Gaussian with a major axis size of $\sim 0.5$ arcsec at 20 cm and a $\lambda^2$ dependence [2]. Separating the effects of the small intrinsic source from the effects of scattering has required observations at short wavelengths, careful calibration, and the use of closure amplitude techniques, which reduce sensitivity but remove uncertainty due to calibration error [3, 4]. These efforts have recently resulted in the first robust detections of intrinsic structure in Sgr A* at wavelengths of 1.3 cm, 0.7 cm and 0.35 cm. The intrinsic source has a size that scales with $\lambda^{1.1}$ or $\lambda^{1.6}$ to a minimum of $\sim 10$ Schwarzschild radii at 0.35 cm (assuming $M_{bh} = 4 \times 10^6 M_\odot$ and $d = 8$ kpc ; [5, 6]).

These detections of the intrinsic size of Sgr A* have a number of consequences. The brightness temperature of $10^{10}$ K strongly excludes advection dominated accretion flows [7] and Bondi-Hoyle accretion models [8]. These size measurements, however, cannot differentiate between jet models [9], generic radiatively inefficient accretion flows [10], and hybrids of these models [11]. This limitation is principally due to the limited sensitivity in the minor axis size of the scattering ellipse. Coupled with measurements of the proper motion of Sgr A* [12], the assumption that the black hole is smaller than the emission region implies a lower limit to the mass density of the black hole $\sim 10^5 M_\odot \text{AU}^{-3}$, which strongly excludes alternative models for dark mass objects.

The scattering medium itself is a system of intense interest [13, 14, 15]. The $\lambda^2$ size dependence of Sgr A* is a strict consequence of the strong scattering and the short projected baselines at the distances of the scattering medium [16].

We wish to clarify here the numerous axes and steps involved in translating observations of Sgr A* into a measurement of the intrinsic size. Very Large Array and Very Long Baseline
Array observations of Sgr A* are obtained with a synthesized beam that is extended North-South. Deconvolution of the observed image with the synthesized beam gives the apparent, scatter-broadened image of Sgr A*. This image is predominantly a two-dimensional Gaussian with the major axis oriented \( \sim 80 \) degrees East of North. Typically, when we refer to the major and minor axes, we refer to the orientation of the scattering ellipse. Finally, to obtain the intrinsic image, we deconvolve the apparent image with a model of the scatter-broadened image, which is determined from long wavelength apparent sizes.

2. New VLA Observations at Long Wavelengths

We recently used long wavelength measurements of Sgr A* to determine the scattering properties to unprecedented accuracy with detailed measurements of the source size at wavelengths that range from 17.4 to 23.8 cm using the Very Large Array and the Pie Town Very Long Baseline Array antenna [17]. The addition of the PT antenna to the VLA A configuration improves the East-West resolution by a factor of two.

Sgr A* is clearly resolved in both axes but with considerably more accuracy in the East-West axis than in the North-South axis. Fitting a point source to the data produced very poor quality fits, while fitting an elliptical Gaussian produced a residual image with no obvious systematic errors (Figure 1). The North-South resolution was considerably less accurate due to the presence of a transient due South of Sgr A*.

3. Theoretical Expectations for Scattering

The \( \lambda^2 \) dependence of the scattering law is strongly favored for theoretical reasons. The maximum baseline length projected to the scattering region is \( b_{\text{proj}} = D_{\text{scattering}}/D_{\text{SgrA}} \times b_{\text{max}} \sim 1 \text{km} \), where \( D_{\text{SgrA}} = 8 \) kpc is the distance to Sgr A*, \( D_{\text{scattering}} \approx 100 \) pc is the distance of the scattering region from Sgr A*, and \( b_{\text{max}} \approx 70 \) km is the maximum baseline between the VLA and PT. \( b_{\text{proj}} \) is substantially smaller than the expected and measured inner scales (\( b_{\text{inner}} \)) for the power spectrum of turbulent fluctuations (\( 10^2 \) to \( 10^{5.5} \) km; [18]). This result holds for the long VLBA baselines involved in imaging at shorter wavelengths, as well, where \( b_{\text{proj}} \sim 25 \) km at
0.7 cm wavelength. For the case of \( b_{\text{proj}} \ll b_{\text{inner}} \), the resulting image is very heavily averaged and must be Gaussian in shape with size \( \propto \lambda^2 \) [16].

This expectation of strong scattering is supported by previous measurements of the shape of the image of Sgr A*. Fitting the closure amplitudes of Sgr A* at 0.7 cm with a functional form for the visibilities of \( \propto e^{-b(\beta-2)} \), where \( b \) is the baseline length, revealed \( \beta = 4.00 \pm 0.03 \) [3]. That is, the best evidence indicates that the image of Sgr A* is a Gaussian. Following scattering theory, where the size is proportional to \( \lambda^{\alpha} \), then \( \alpha = \beta - 2 = 2.00 \pm 0.03 \) [16]. For the case of the VLA+PT data, we find \( \alpha = 1.98 \pm 0.11 \), which is consistent with the expectation of \( \alpha = 2 \).

A final caveat is required. The scattering medium is dynamic. The minimum time scale for a change in the medium is the refractive time scale, which is \( 0.5 \text{yr} \left( \frac{v}{100 \text{km/s}} \right) \left( \frac{\lambda}{1 \text{cm}} \right)^2 \) for Sgr A*, where \( v \) is the velocity of the scattering material relative to Sgr A* and the Sun [16]. The data presented here were obtained in a span of roughly a decade. The long-wavelength scattering properties are very unlikely to change on this time scale. However, at wavelengths as long as 4 cm, the refractive time scale is \(< 10 \text{ year} \). The many observations at 0.7 cm in this period, however, appear to produce a source of stable size, despite a refractive time scale less than one year. We conclude it is unlikely that the scattering size has changed significantly over this period.

4. High Resolution Observations at Short Wavelengths
Since the realization that the image of Sgr A* is dominated by scattering, there has been a strong motivation to observe Sgr A* at ever shorter wavelengths. The \( \lambda^2 \)-scaling for scattering size, the \(< \lambda^2 \)-scaling for intrinsic source, and the \( \lambda \)-scaling for telescope resolution combine to offer the promise of detection of the intrinsic size of Sgr A* at short wavelengths. Poor telescope performance, decreased interferometric coherence, and decreased gain stability conspire, however, to limit the accuracy of amplitude calibration and prevent high quality results at millimeter wavelengths.

To deal with these limitations, closure amplitudes and closure phases have been used to determine the size from VLBA measurements at wavelengths from 6 cm to 3.5 mm (Figure 2). The closure techniques trade reduced sensitivity for improved accuracy that is independent of amplitude and phase calibration. At short wavelengths, the major axis sizes are clearly larger than the expectation of the scattering law determined with longer wavelength observations and indicate sizes of \( \sim 25R_s \) at 7 mm and \( \sim 10R_s \) at 3.5 mm. The actual intrinsic sizes depend on the scattering law with increasing sensitivity at longer wavelengths.

5. The Intrinsic Size
Ideally, we would fit the intrinsic size and the scattering law simultaneously. A fit of the size proportional to \( \sqrt{a^2 \lambda^4 + b^2 \lambda^2} \) is not sufficiently constrained to set reasonable limits on the parameters \( a, b, \) and \( \gamma \). If we fix \( \gamma \) and search for \( a \) and \( b \), we find that \( \chi^2 \) for \( \gamma = 1 \) is four times the value for \( \gamma \) unconstrained, indicating that \( \gamma = 1 \) is strongly excluded. Without the assumption that the second term is negligible for wavelengths longer than 6 cm, therefore, we cannot determine the scattering law or the intrinsic size of Sgr A*.

With the assumption that the scattering law is determined accurately at wavelengths longer than 17 cm, we can determine the intrinsic size. We subtract in quadrature the scattering law size from the measured size (Figure 3). We compute the results for the best-fit major axis scattering law (\( b_{\text{sc}} = 1.32 \text{ mas/cm}^2 \)), and \( \pm 3\sigma \) of the best-fit value. For the best-fit case, the intrinsic size is accurately determined from 0.35 cm to 3.6 cm. Over this range, the intrinsic size is well-fit by a power-law \( \lambda^\gamma \), where \( \gamma = 1.6 \pm 0.1 \). For the smaller scattering size, we find a steeper power-law and measure the intrinsic size from 0.35 cm to 6 cm. For the larger scattering size, we cannot measure the intrinsic size at wavelengths longer than 1.3 cm and find a shallower power-law index of \( \gamma = 1.3 \pm 0.2 \).
Figure 2. Measured major axis size, minor axis size, and position angle as a function of wavelength. Triangles are VLBA measurements determined through closure amplitude analysis from [3] and [4]. Squares are the new VLA+PT measurements. The major and minor axis sizes have been normalized by $\lambda^2$. The solid red line in each curve is the best-fit scattering value determined from the VLA+PT data alone. Dotted red lines are $\pm 3\sigma$ of the best-fit scattering law.

At short wavelengths, the result is consistent with the conclusions of recent efforts by [3] and [4]. The size of Sgr A* at 0.35 cm is $13.3^{+6.7}_{-3.1} R_s$, where $R_s = 1.2 \times 10^{12}$ cm is the Schwarzschild radius for $M_{bh} = 4 \times 10^6 M_\odot$ and the Galactic Center distance $d = 8$ kpc. This compact size confirms tight restrictions on accretion models and black hole alternatives previously claimed and stated in §1.

The wavelength dependence of the source size agrees with that found by [3] and is steeper than that found by [4], who found $\gamma \approx 1.1$. The steeper dependence indicates that the brightness temperature decreases as $\lambda^{-1}$, assuming that the size in the second dimension is proportional to the major axis size. The peak brightness temperature at 0.35 cm is $\sim 10^{10}$ K for a flux density of 1 Jy. The power-law dependence of the size as a function of wavelength indicates a stratified, smoothly varying emission region.
Figure 3. Intrinsic size in Schwarzschild radii for the East-West dimension using three different estimates of the major axis scattering law. We assume a $4 \times 10^6 M_\odot$ black hole at a distance of 8 kpc. In the central panel, we show results for the best-fit scattering law. In the left and right panels, we show the results for the $-3\sigma$ and $+3\sigma$, respectively. The solid red lines are the best fit curves for size $\propto \lambda^{\gamma}$.

6. Source Modeling
Detailed jet models for Sgr A* predict $\gamma \approx 1$ [19]. Generalized jet models, however, allow a range of $\gamma$, depending on the details of the magnetic field and particle energy density distributions [20]. A jet with $B \propto r^{-1}$, electron density decreasing as $r^{-1}$, and optically thin power-law index of 1 will show a size $\propto \lambda^{1.4}$.

[21] model the size of Sgr A* for a radiatively inefficient accretion flow. They fit sizes at 0.35 cm and 0.7 cm that are fit with a power law of index $\gamma = 1.1$. Variations in the nonthermal electron distribution or deviations from equipartition, however, could alter $\gamma$ in their model.

The future of modeling the size of Sgr A* lies in direct comparison between observed and modeled closure quantities. Deconvolution of the size of Sgr A* into a two-dimensional Gaussian component becomes a poor approximation as the size measurements become more accurate. In Figure 4 and 5, we show preliminary results from direct comparison of jet models with 7mm closure amplitudes and closure phases (Markoff & Bower, in preparation).

7. Future Goals for Imaging of Sgr A*
The critical remaining observational goals for understanding the image of the radio emission of Sgr A* are a measurement of the two-dimensional size and detection of structural variability. The simple one-dimensional deconvolution that we have performed here only gives schematic information on the size of Sgr A*. With a more accurate two-dimensional scattering model, future analysis will directly compare the observed image with non-Gaussian source models convolved with the imaging and scattering constraints. Astrometric observations may indicate a shift in the centroid of the image with frequency. A heterogeneous jet will exhibit such a shift due to changing location of the optically thick surface of the source [20].

8. Approaching the Event Horizon
At mm and submm wavelengths, the gravity of the black hole will distort the image of Sgr A* [22, 23]. These effects are apparent on a scale of $\sim 5R_\bullet$. The actual images that will be seen at these short wavelengths depend on the nature of the emission region. Detailed characterization of the shape of the longer wavelength image will provide the background emission region that will be transformed by the black hole’s gravity. For the simple case of a homogeneous spherical
Figure 4. Jet models for comparison with 7mm VLBA observations of Sgr A*. The logarithm of the intensity is shown. The models are required to reproduce the spectrum of Sgr A* using the constraint of polarization on the accretion rate.

emission region, the apparent image will be a ring of radius $5R_s$. Detection of this ring, or of the “shadow” that the black hole casts on the emission region, will constrain the mass of the black hole to the smallest radius yet, providing one of the strongest tests of the existence of black holes.

The observations to achieve this result are technically demanding. They will rely on an ad hoc array of telescopes including CARMA, SMA, and ALMA, make use of high bandwidth data recorders, and require high fidelity in time standards and frequency systems. Additionally, the image of Sgr A* may change on a timescale of an orbital period, which is 10s of minutes, preventing traditional synthesis imaging. Phase-referenced imaging may be required to track these changes. This requires rapid switching between Sgr A* and a background source and/or tropospheric phase-correction hardware. Phase-referencing between polarized and total intensity images is a potentially simpler technique, although there have not been theoretical predictions of the relationship between polarized and total intensity images in these regions.

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Figure 5. Reduced $\chi^2$ as a function of jet position angle for the models shown in Figure 5. Where no curve is present, the reduced $\chi^2$ is off the scale. Some models and position angles are clearly favored. Detailed characterization of the sensitivity of the technique is necessary to determine which models and position angles are excluded.

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