Rapid Intrinsic Variability of Sgr A* at Radio Wavelengths

F. Yusef-Zadeh1, M. Warde2, J. C. A. Miller-Jones3,4, D. A. Roberts5, N. Grosso6, and D. Porquet6

1 Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
2 Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia
3 NRAO, Charlottesville, 520 Edgemont Road, VA 22903, USA
4 International Center for Radio Astronomy Research - Curtin University, GPO Box U1987, Perth, WA 6845, Australia
5 Adler Planetarium & Astronomy Museum 1300 S. Lake Shore Drive, Chicago, IL 60605, USA
6 Observatoire astronomique de Strasbourg, Université de Strasbourg, CNRS, UMR 7550, 11 rue de l’Université, F-67000 Strasbourg, France

Received 2010 June 25; accepted 2010 December 31; published 2011 February 8

Abstract

Sgr A* exhibits flares in radio, millimeter, and submillimeter wavelengths with durations of ~1 hr. Using structure function, power spectrum, and autocorrelation function analysis, we investigate the variability of Sgr A* on timescales ranging from a few seconds to several hours and find evidence for subminute timescale variability at radio wavelengths. These measurements suggest a strong case for continuous variability from subminute to hourly timescales. This short timescale variability constrains the size of the emitting region to be less than 0.1 AU. Assuming that the minute timescale fluctuations of the emission at 7 mm arise through the expansion of regions of optically thick synchrotron-emitting plasma, this suggests the presence of explosive, energetic expansion events at speeds close to c. The required rates of mass processing and energy loss of this component are estimated to be \(\lesssim 6 \times 10^{-10}\) M\(_\odot\) yr\(^{-1}\) and 400 L\(_\odot\), respectively. The inferred scale length corresponding to 1 minute light travel time is comparable to the time-averaged spatially resolved 0.1 AU scale observed at 1.3 mm emission of Sgr A*. This steady component from Sgr A* is interpreted mainly as an ensemble average of numerous weak and overlapping flares that are detected on short timescales. The nature of such short timescale variable emission or quiescent variability is not understood but could result from fluctuations in the accretion flow of Sgr A* that feed the base of an outflow or jet.

Key words: accretion, accretion disks – black hole physics – Galaxy: center

Online-only material: color figures

1. Introduction

The compact radio source Sgr A* is located at the very dynamical center of our Galaxy (Reid & Brunthaler 2004) and is established to coincide with a 4 \(\times\) 10\(^8\) M\(_\odot\) black hole (Ghez et al. 2008; Gillessen et al. 2009). It is well known that the bolometric luminosity of Sgr A* (\(\sim 100\) L\(_\odot\)) is several orders of magnitude lower than expected for the estimated accretion rate. A number of theoretical models have been proposed to explain its very low radiative efficiency and to match the spectral energy distribution of its quiescent emission (Melia & Falcke 2001; Yuan et al. 2003; Liu et al. 2004). To address its underluminous nature, our approach has been to study the time variability of Sgr A*.

The bulk of the continuum flux of Sgr A* is believed to be generated in an accretion disk, where the source of variable continuum emission is also localized. Recent MHD simulations have also indicated that variability is a fundamental property of emission in the disk of Sgr A* (Hawley & Balbus 2002; Goldston et al. 2005; Chan et al. 2009; Moscibrodzka et al. 2009). The variable optical continuum flux of active galactic nuclei (AGNs) is also known to signal activities of the central engine and is detected throughout the entire electromagnetic spectrum with periods ranging from days to years (Arshakian et al. 2010). Sgr A*, being a hundred times closer than the next nearest example, provides us with the best view of the accretion disk surrounding a supermassive black hole. In addition, the relatively low mass of Sgr A* compared with those in AGNs presents an unparalleled opportunity for studying its temporal characteristics from minutes to years and investigate the process by which gas is captured, accreted, or ejected. As the dynamical time scales with the mass of a black hole, the timescale for variability can be argued to be proportional to the mass of the black hole. Here, we study light curves of Sgr A* based on several days of observations at 7 and 13 mm as well as radio, IR, and X-ray data taken simultaneously on 2007 April 4. These measurements will characterize the timescale of variability at multiple wavelengths.

2. Analysis

The structure function (SF) is defined as the mean difference of pairs of flux measurements separated by time lag \(t\), i.e., \(\langle |S(t) - S(t + \tau)| \rangle\) (e.g., Simonetti et al. 1985; Hughes et al. 1992). It has been argued that the slope of the SF (where SF \(\propto \tau^x\)) is related to the index of the power spectrum of fluctuations \(\alpha\), where power spectrum \(P \propto \tau^{-\alpha}\) (Do et al. 2009). Breaks in the power spectra are seen in both AGN and X-ray binaries, with the break timescale scaling with black hole mass and bolometric luminosity (i.e., mass accretion rate; McHardy et al. 2006). Using SF analysis, previous IR measurements have characterized the intrinsic variability timescale of Sgr A* (Do et al. 2009) and have determined the break frequency in the power spectral density (PSD) distribution or a turnover (rollover) timescale in the SF (Meyer et al. 2009). This technique is widely used in the study of AGN light curves in X-rays (Kataoka et al. 2001). However, a recent study by Emmanoulopoulos et al. (2010) concludes that any break timescales derived from SFs are doubtful as they depend significantly on the length and underlying PSD of the data sets used. Thus, this paper does not investigate the nature of breaks in the SF and uses different analysis techniques to confirm the behavior of the calculated SFs at short timescales.

To address the time variability of Sgr A*, we use three different methods of analysis, namely, SF, power spectra, and an autocorrelation function. Two different types of power
spectra are also calculated. One type of power spectrum is subjected to the CLEAN deconvolution algorithm and the power spectra are calculated using the procedure documented in Appendices B and C of Roberts et al. (1987). The CLEAN power spectrum is shown in equally spaced bins in log space, with 30 bins covering the range between \( v = 10^{-2} \) minutes\(^{-1}\) and 10 minutes\(^{-1}\). Another type of power spectrum follows the prescription given by Uttley et al. (2002). This derivation, which does not include any CLEAN deconvolution, computes the power spectrum from \( v_{\text{minute}} = 1/T \) (where \( T \) is the length of the light curve in the time domain) up to the Nyquist frequency and normalizes it such that the integration from \( v_1 \) to \( v_2 \) gives the contribution to the fractional rms squared variability on timescales from \( v_2^{-1} \) to \( v_1^{-1} \). Both power spectra are binned and power-law slopes are fitted into the entire spectrum. In addition, we present an autocorrelation function which can potentially provide information on the nature of the physical process causing any observed variability. The autocorrelation analysis uses the \( Z \)-transformed discrete correlation function (ZDCF) algorithm (1). A maximum in the likelihood value is identified at a zero time lag. The ZDCF is an improved solution to the problem of investigating correlation in unevenly sampled light curves. The standard solutions are interpolation of the existing light curve, which is considered to be unreliable when power exists on smaller timescales than the gaps, and binning the data using discrete correlation functions (e.g., Edelson & Krolik 1988). Here, we first investigate the nature of the time variability of Sgr A* in radio wavelengths using these three different statistical analyses. We then compare SF and CLEAN power spectrum of IR, X-ray, and radio data taken simultaneously on 2007 April 4.

3. RADIO VARIABILITY
3.1. Observations

Radio observations were taken with the Very Large Array (VLA)\(^5\) in its C configuration on 2008 May 5–6 and 10–11. We also analyzed archival data taken with the VLA in its A configuration on 2006 February 10 at 7 mm. Briefly, we used a fast-switching technique to observe Sgr A* simultaneously using three subarrays in the C configuration at 7, 13, and 35 mm. We cycled between the fast-switching calibrator 17443–31166 (2.3 away from Sgr A*) and 17456–29004 (Sgr A*) for 30 s and 90 s, respectively, throughout the observation. In addition, we observed the phase calibrators 1733–130 and 17458–28204 every 30 minutes for cross-calibration purposes. The calibration solution was derived from observing the secondary calibrator 1733–130 and then applied to both Sgr A* and 17443–31166. This experiment was designed to remove the amplitude errors resulting from the low elevation of Sgr A* and investigate the correlated flux variability. The 2006 observation was carried out in the A configuration using the fast-switching technique. In this experiment, 7 and 13 mm observations were alternated every few minutes using all the available antennas of the array. We focus mainly on high-frequency observations because extended free–free emission from the ionized gas in the vicinity of Sgr A* is suppressed at high spatial resolution.

Very Long Baseline Array (VLBA) observations were also carried at 7 and 3 mm simultaneous with VLA observations during 2008 May 5–6 and 10–11. A more detailed description of these observations will be given elsewhere. Briefly, these observations (BY122) used the inner eight of the 10 VLBA antennas excluding the Mauna Kea and St. Croix antennas which give the longest baselines that fully resolve Sgr A* due to scatter broadening. The observing sequence consisted of 3 minute observations of 1733–130 conducted every hour; these served as a fringe finder and to calibrate instrumental effects. Between these scans, we alternated 5 minute blocks of observations at 7 mm (43 GHz) and 3 mm (86 GHz). Each block consisted of a 30 s scan on J1745–2820 followed by a 270 s scan on Sgr A*.

The flux density scale was determined from standard VLBA antenna gain curves and system temperatures measured during the observations.

3.2. Results

Figure 1 shows four light curves of Sgr A* on 2008 May 5, 6, and 10, and 2006 February 10 using the VLA with a sampling time of 3.3 s at 7 mm. The light curves of the cross-calibrated calibrator are shown at the bottom of each panel in Figure 1. The flux variation is typically about 0.2–0.6 Jy with a fractional change of 20%–30% over ~6 hr of observations. The 2008 May 10 light curve shows an unusual variation during 8.456 hr and 8.522 hr UT. This sharp drop in the flux was also simultaneously detected at 13 mm with different set of VLA antennas. The drop in the flux at radio and submillimeter wavelengths was recently discussed in the context of adiabatically cooling plasma blobs that are partially eclipsing the background quiescent emission from Sgr A* (Yusef-Zadeh et al. 2010). However, we question the reality of this dramatic drop in the flux of Sgr A* by ~0.8 Jy. A more detailed account of these measurements will be given elsewhere. Excluding the sharp drop in the flux of Sgr A*, a high variation with a fractional change of ~40% is noted on 2010 May 10. The contamination of extended structures in the light curve can be significant for baselines less than 100k\(\lambda\), so we removed shorter baselines in construction of all the light curves presented in Figures 1(a)–(c) (Yusef-Zadeh et al. 2009). To further minimize any contribution of extended emission, we have selected data taken with the VLA in its A configuration. Figure 1(d) shows the light curve constructed from the A configuration observation on 2006 February 10. The light curves corresponding to 2008 May 10 (excluding the sharp absorption feature) and 2006 February 10 show flux variations of ~0.6 and 0.5 Jy with mean flux of 1.6 and 2.6 Jy, respectively.

Figure 2(a) presents a plot of the SF of Sgr A* on 2008 May 5 at 7 mm. To examine the frequency dependence of the variability, the binned CLEAN PSD and the power spectrum calculated by Uttley et al. (2002) are presented in Figures 2(b) and (c), respectively. To check the CLEAN power spectrum analysis, the power spectrum calculation using Uttley et al.’s technique shows that the binned data points in Figures 2(b) and (c) are consistent with each other but with different normalizations. These power spectra confirm that most of the power is at low frequencies. Power-law fits to the SF over a range between 1 and 10 minutes as well as to the PSD in Figure 2(c) over the entire frequencies are displayed in Figures 2(a) and (c). On short timescales, \( \tau < 1 \) minute, the SF and the PSDs at frequencies between 1 and 10 minutes\(^{-1}\) are constant within the error bars. However, the variability at values \( \tau > 2 \) minutes shows a steeper slope consistent with evidence for short timescale variability. For comparison, we constructed the SF of the calibrator 17443–31166 and found

\(^5\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Figure 1. (a) Top left: a light curve of Sgr A* at 7 mm for 2008 May 5 observations with a 3.3 s sampling time and the corresponding calibrator 17444–31166. (b) Top right: same as (a) except on 2008 May 10. (c) Bottom left: same as (a) except on 2008 May 6. (d) Bottom right: same as (a) except on 2006 February 10. (A color version of this figure is available in the online journal.)
that the slope of the SF remains flat over all timescales. The flat slopes in Figures 2(a)–(c) at $\tau < 1$ minute are consistent with measurement errors in amplitude or white noise (Hughes et al. 1992). For flux variability that is simply due to measurement errors with standard error $\sigma$, it is expected that SF amplitude is $2\sigma^2$.

To examine the reality of the short time variability at $\tau > 1$ minute, we have also constructed autocorrelation functions of the light curves taken on 2008 May 5. Figure 2(d) shows a plot of the autocorrelation function of the measurements showing a peak at zero time lag, followed by a sharp drop implying a lack of correlation on short timescales. The steep drop in the autocorrelation function is consistent with short timescale variability inferred from SF and PSDs.

To check the validity of the analysis of the data taken on 2008 May 5, we carried out simultaneous VLBA and VLA measurements at 7 mm. Due to the large interstellar scatter broadening of Sgr A*, only few short baselines of VLBA antennas could be used to investigate the nature of the variability of Sgr A* at 7 mm. The same plasma is responsible for daily time variability at centimeter wavelengths (Macquart & Bower 2006). Scintillation models predict variability at a level of 10% at 7 mm wavelengths on a timescale of few days (Macquart & Bower 2006). Thus, the variability measurements presented here show large flux variability on much shorter timescales, thus, should not be affected by interstellar scintillation. Figures 3(a)–(d) show the SF, two different PSDs, and the autocorrelation function of VLBA data at 7 mm, all of which are consistent with short-timescale variability, as measured by the VLA and shown in Figure 2. The measurement error bars in Figure 3 are high and the flat slope fitting the short timescale variation is consistent with high measurements errors. The consistent results from VLA and VLBA measurements on short timescales support the suggestion by earlier studies that the radio variability of Sgr A* arises from the inner AU of Sgr A* (Yusef-Zadeh et al. 2009) and that both show similar timescales for minute time variability.
Figures 4(a)–(d) show the SF, PSDs, and the autocorrelation function of VLA data taken on 2008 May 10 at 7 mm. The SF rises at short timescales, plateaus between 5 and 100 minutes, before rising again at longer time lags. The rapid steepening of the SF above 300 minutes reflects the decline of the light curve over the duration of the observations, and the sharp drop apparent on the very longest timescales is an artifact of the very limited sampling available at the longest lag times. It is clear that the slope of the SF changes between minute and hourly timescales. Similar behavior has been observed in the SF plots of X-ray data taken toward AGNs (Kataoka et al. 2001). The slopes to the CLEAN PSD and Uttley et al.’s (2002) PSD, as shown in Figures 4(b) and (c), range between $\alpha = -0.65$ and $-0.86$ and are consistent within $3\sigma$ errors of each other. Power-law fits to the SF at short timescales between 0.1 and 1 minutes and to the PSDs over their entire frequency spectra as well as the sharp drop in the autocorrelation function at zero time lag support evidence of short timescale variability.

The SF for the 2008 May 10 light curves, as shown in Figure 4(a), differs in two ways from that for 2008 May 5. First, a number of dips in the SF show what at face value might be considered as quasi-periodic oscillation (QPO) activity. A dip is produced when a pair of measurements separated by a time lag $\tau$ have similar flux density. The strongest dip is seen around 20 minutes followed by weaker dips at 50 and 100 minutes. Similar dips are also noted in the SF plot at 13 mm which were taken simultaneously with 7 mm. These dips which are not detected in other three days of observations in May 2008 are caused mainly by the sharp drop in the flux of Sgr A*, as shown in Figure 1(c). If we remove the sudden drop of flux, the dips in the SF disappear. Thus, we cannot confirm the reality of these dips.

The second feature apparent in Figure 4(a) is the steepening of the slope of the SF at $\tau < 3$ minutes down to timescales as short as 0.1 minutes, indicating that there is intrinsic variability on very short timescales. The reality of this short timescale variability is strengthened by the flat SF of the calibrator. In addition, we note that the expected value of the SF once it becomes dominated by the measurement error is $1.5 \times 10^{-3}$ Jy$^2$. The amplitude of the SF with lag time greater than 0.1 minutes.
Figure 4. (a) Top left: an SF plot for VLA observation of Sgr A* at 7 mm on 2008 May 10 with data sampling of 3.3 s. The mean error of individual data points is 0.027 Jy. The squares of the mean measurement errors are $7.3 \times 10^{-4}$ Jy$^2$ at 7 mm. (b) Top right: the corresponding CLEAN PSD of data shown in (a). The red dots represent smoothed bins. (c) Bottom left: the PSD using Uttley’s technique with red dots showing the binned data. The slope fitted through the entire spectrum is displayed. (d) Bottom right: a plot of the autocorrelation function. Power-law fits to the SF over a range between 0.1 and 1 minutes as well as to the corresponding power spectra over the entire frequencies are displayed on each figure.

is higher than this, supporting the reality of such short timescale variability. These measurements suggest continuous variability from subminute timescale to hour timescale variability, but with varying slopes. Figure 4(d) shows a dramatic drop in the amplitude of the autocorrelation during the initial 10 minutes, which is consistent with the PSD not flattening at higher frequencies. The steep drop in the autocorrelation function supports the intrinsic minute timescale variability.

Figures 5(a)–(c) and 6(a)–(c) show the SF, CLEAN PSD, and the autocorrelation function of VLA data taken on 2008 May 6 at 7 and 13 mm, respectively. Figures 5(a) and 6(a) show the plots of the SF for the 2008 May 6 light curves at 7 and 13 mm, respectively. Overall, the SF is a shallow power law at short timescales before steepening at long timescales. Although the measurement errors of the 13 mm data are greater than at 7 mm, the SF at 13 mm has a similar trend to that seen at 7 mm. The power-law indices at 7 and 13 mm at short timescales are $(0.22 \pm 3) \times 10^{-4}$ and $(0.32 \pm 2.7) \times 10^{-4}$ and at long timescales are $(1.39 \pm 5.9) \times 10^{-5}$ and $(1.20 \pm 3.1) \times 10^{-4}$, respectively. The transitions from a shallow to a steep slope of the SF are at $\sim$30 and 60 minutes at 7 and 13 mm, respectively. The constructed CLEAN PSD and the autocorrelation of the 2008 May 6 data at 7 and 13 mm show that the slopes of the power spectra are not flat and that there is a steep drop in the amplitude of the autocorrelation function. These figures all show the evidence for short minute timescale variability at radio wavelengths.

Figures 7(a)–(c) and 8(a)–(c) show the SF, CLEAN PSD, and the autocorrelation function of VLA data taken on 2006 February 10 at 7 and 13 mm, respectively. As pointed out earlier, these measurements should have no contamination from the extended emission from the ionized gas surrounding Sgr A*. These figures show collectively the same pattern of continuous variability from 0.1 to 250 minutes. The subminute timescale variability and the deviation from a flat slope at short timescales in the SF and high frequencies are consistent with the short timescale variability of Sgr A*. The smoothly varying slope in these high-resolution observations is consistent with other low-resolution measurements taken in the C configuration of the VLA. Furthermore, the steep falloff of the correlation at...
short timescales implies rapid and continuous fluctuations over a wide range of timescales in the flux of Sgr A*.

4. IR AND X-RAY VARIABILITY

SFs have also been calculated for several nights of Keck observations of Sgr A* (Do et al. 2009). We have used data taken with VLT, XMM-Newton, and VLA observations on 2007 April 4 at IR, X-ray, and radio wavelengths (Porquet et al. 2008; Dodds-Eden et al. 2009; Yusef-Zadeh et al. 2009). Figures 9(a)–(f) show the SF and the corresponding CLEAN PSD plots of IR, X-ray, and radio observations, respectively, sensitive to time lags ranging from about 0.5 to a few hundred minutes. The X-ray and IR data on 2007 April 4 revealed simultaneous bright X-ray and IR flares at the beginning of observations.

The power-law fit to the IR data implies a slope of 0.9 in the SF. Different nights of Keck observations (Do et al. 2009) show a value of $\beta$ varying between 0.26 and 1.37 with lag times ranging between 1 and 40 minutes. The value of $\beta$ from VLT measurements is consistent with Keck measurements. We also note evidence of variability at about a one minute timescale at IR wavelengths (see also the analysis by Do et al. 2009 and Dodds-Eden et al. 2009). The slope of the CLEAN PSD at high frequencies is consistent with the short timescale variability inferred from SF analysis. There is no evidence for QPOs in the time domain that was searched. The reality of QPO activity of a hot spot orbiting Sgr A* is hotly debated mainly because of the low signal to noise and possible intermittent nature of such behavior (Eckart et al. 2006; Meyer et al. 2008; Do et al. 2009).

Unlike the IR SF, which is fit by a single power law, X-ray SF and CLEAN PSD give different characterization of the variability of Sgr A* in X-rays. We note a rise at short timescales, similar to that of IR, though somewhat shallower, followed by a plateau with time lags ranging between 30 and 300 minutes before a steepening of the SF again at longer timescales. Due to limited sensitivity and 100 s sampling of X-ray data, the flat part of the SF with time lags of few minutes indicates that there is no minute timescale variability and that the emission is dominated by white noise. The plateau time lags range between 30 and 300 minutes and are also consistent with white noise where there is no correlation of signals. At time lags greater than 300 minutes, the correlation begins again. The steepening
Figure 6. (a) Top left: an SF plot for VLA observation of Sgr A* at 13 mm on 2008 May 6 with data sampling of 3.3 s. The mean error is 0.03 Jy and the squares of the mean measurements errors are $9 \times 10^{-4}$ Jy$^2$ at 13 mm. (b) Top right: the CLEAN PSD of data shown in (a). The red dots represent smoothed bins. (c) Bottom: a plot of the autocorrelation function. Power-law fits to the SF over a range between 1 and 100 minutes as well as to the corresponding power spectra over the entire frequencies are displayed on each figure.

(A color version of this figure is available in the online journal.)

The SF at 300 minutes is due to the large count rate difference between the beginning of the light curve when there was a bright X-ray flare and the end of the observation when the emission was at its quiescent level. The X-ray shape of the SF plot of Sgr A* is remarkably similar to that of Mrk 421 with time lags that are an order of magnitude larger (see Figure 4(c) of Kataoka et al. 2001). Similarly, the mass of the black hole in Mrk 421 is estimated to be 50 times higher than the mass of Sgr A* (Barth et al. 2003). The characteristic timescale of X-rays from Mrk 421 is considered to place a constraint on the size of the variable X-ray emission from the base of the jet (Kataoka et al. 2001).

Figures 9(e) and (f) represent the SF and PSD at 7 mm taken simultaneously with IR and X-ray data, as part of an observing campaign that took place on 2007 April 4 (Yusef-Zadeh et al. 2009). We note a rise of the amplitude of the SF similar to that seen in the IR SF plot. The power-law fit to the radio data shows a slope of 0.78 in the SF which is close to that of IR data, as seen in Figure 9(a). A correlation between the optically thin IR, X-ray flare, and optically thick 7 mm radio flare has been suggested for the strong flare that occurred on this day (Yusef-Zadeh et al. 2009; Dodds-Eden et al. 2009). The radio flare emission at 7 mm was argued to be delayed with respect to the near-IR and X-ray flare emission, consistent with the plasmon picture. The similar behavior of the SF of IR and radio data is not inconsistent with a picture that flaring activity in radio and IR wavelengths is correlated.

5. DISCUSSION

5.1. Long Timescale Variability

Our multi-wavelength monitoring of Sgr A* characterizes the intrinsic time variability of Sgr A* by studying the SF of the observed light curves. SF analysis of the IR, X-ray, and radio data suggests that most of the power falls in the long timescale fluctuation of the emission from Sgr A* and that the variation is generally aperiodic with no obvious QPO activity, confirming earlier analysis of IR data (Do et al. 2009; Meyer et al. 2008). The SF analysis of radio data shows a number of new features, the most interesting of which is a statistically significant time variability on subminute to hourly timescales. Unlike the IR SF, which can be well represented by a single power law, at radio
wavelengths the SFs are more complex and could only be fit by multiple power-law components.

Using the long timescale lags, we fit a power law to the PSD and SF of radio data and find the power indices of radio variability. The long timescale variability of Sgr A* at radio wavelengths characterized in the SF plots is similar to the duration of typical flares as detected in both radio and submillimeter wavelengths (e.g., Yusef-Zadeh et al. 2006; Marrone et al. 2006). These measurements at 7 and 13 mm are consistent with the power spectrum analysis of the time variability of Sgr A*, suggesting intraday variability at 3 mm (Mauerhan et al. 2005). The rapid decay of the SF plots at large lag times appears to reflect a turnover in the PSD of the variability. However, this turnover is probably due to an artifact of limited sampling of radio data at large time lags (see Emmanoulopoulos et al. 2010).

The ∼ hour-long flaring in radio and submillimeter has been argued to be due to adiabatic cooling of synchrotron-emitting electrons in an expanding plasma blob (Yusef-Zadeh et al. 2009). These measurements support this picture and show that the light curves peak at successively lower frequencies (submillimeter, millimeter, and then radio) as a self-absorbed synchrotron source region expands after the initial event that energizes the electrons. The emission at a particular frequency peaks as the blob becomes optically thin at that frequency; so the blob size determines the peak flux of the flare and the expansion speed determines the flare duration. The estimated expansion speed of the plasma is a few percent of c; the plasma itself may be bound to Sgr A* or be embedded in the base of a jet (Maitra et al. 2009; Yusef-Zadeh et al. 2009). In this scenario, the contributions of the flares to the SFs at 7 and 13 mm should be related to one another. To examine this, first consider the frequency dependence of the properties of individual flares. For an $E^{-p}$ electron energy spectrum, the light curve of each flare follows the characteristic frequency dependence of the plasmon model (van der Laan 1966; Yusef-Zadeh et al. 2006):

$$S_\nu = S_0 \left( \frac{R}{R_0} \right)^3 \left( \frac{v}{v_0} \right)^{5/2} \frac{1 - e^{-\tau_v}}{1 - e^{-\tau_0}},$$

Figure 7. (a) Top left: an SF plot for VLA observation of Sgr A* at 7 mm on 2006 February 10 with data sampling of 3.3 s. The power-law fit is shown in dashed red lines. The amplitudes are in Jy$^2$. The mean error is 0.009 Jy. The squares of the mean measurement errors are $9 \times 10^{-4}$ Jy$^2$ at 7 mm. (b) Top right: the CLEAN PSD of data shown in (a). The red dots represent smoothed bins. (c) Bottom: a plot of the autocorrelation function. Power-law fits to the SF over a range between 0.1 and 1 minutes as well as to the corresponding power spectra over the entire frequencies are displayed on each figure.

(A color version of this figure is available in the online journal.)
Figure 8. (a) Top left: an SF plot for VLA observation of Sgr A* at 13 mm on 2006 February 10 with data sampling of 3.3 s. The power-law fit is shown in dashed red lines. The amplitudes are in Jy^2. The mean error is 0.003 Jy. The squares of the mean measurement errors are 9 \times 10^{-6} Jy^2 at 13 mm. (b) Top right: the CLEAN PSD of data shown in (a). The red dots represent smoothed bins. (c) Bottom: a plot of the autocorrelation function. Power-law fits to the SF over a range between 0.1 and 1 minutes as well as to the corresponding power spectra over the entire frequencies are displayed on each figure.

(A color version of this figure is available in the online journal.)

where the optical depth of the blob

\[ \tau_\nu = \tau_0 \left( \frac{R}{R_0} \right)^{-2(p+3)} \left( \frac{\nu}{\nu_0} \right)^{-2(p+4)/2}, \]

and the reference optical depth \( \tau_0 \) is chosen so that the peak flux at frequency \( \nu_0 \) is \( S_0 \), and this occurs when the blob radius is \( R_0 \). This means that \( \tau_0 \) is determined by \( dS_\nu/dR = 0 \); it turns out that \( \tau_0 \sim 1 \) and is a weak function of \( p \) (Yusef-Zadeh et al. 2006). At frequency \( \nu \), the peak flux

\[ S_p = S_0 \left( \frac{\nu}{\nu_0} \right)^{(7p+3)/(4p+6)} \]

occurs when the blob radius is

\[ R_p = R_0 \left( \frac{\nu}{\nu_0} \right)^{-(p+4)/(4p+6)}. \]

Then, we may rewrite the flux and optical depth at \( \nu \) as

\[ S_\nu = S_0 \left( \frac{R}{R_p} \right)^{(7p+3)/(4p+6)} \frac{1 - e^{-\tau_\nu}}{1 - e^{-\tau_0}}, \]

and

\[ \tau_\nu = \tau_0 \left( \frac{R}{R_p} \right)^{-2(p+3)} \]

respectively. These expressions show that the flux as a function of blob radius at \( \nu \) can be found from the light curve at \( \nu_0 \) through a simple linear stretch of the \( R \)-axis by a factor of \( R_p/R_0 \) and a compression of the flux axis by a factor of \( S_p/S_0 \). Under the assumption that the blob has constant expansion speed, the mapping between \( R \) and time is linear and the light curves behave in the same way. To summarize, the adiabatic expansion scenario implies that the amplitude and timescales of a single flare scale as \( \nu^a \) and \( \nu^{-b} \), respectively, where

\[ a = \frac{7p+3}{4p+6} \]

and

\[ b = \frac{p+4}{4p+6}. \]

Suppose now that the variations in the light curves of Sgr A* at 7 mm arise through a superposition of flares, each with the
same $E^{-p}$ electron energy spectrum but with a distribution of amplitudes and timescales. Because the amplitude and timescales of the contribution of each flare scale with frequency as $\nu^a$ and $\nu^{-b}$, respectively, the SFs of the light curve at $\nu$ and $\nu_0$ are related by

$$SF_\nu(t) = \left( \frac{\nu}{\nu_0} \right)^{2a} SF_{\nu_0}((\nu/\nu_0)^b t) ,$$

(9)
where \( a \) and \( b \) are given by Equations (7) and (8). In particular, note that if the SF at \( \nu_0 \) is a power law, the SF at \( \nu \) will also be a power law with the same index but different normalization.

To test this hypothesis, we take the power-law fits to the SFs at 7 mm for 2008 May 6 and 2006 February 10 and compute the 13 mm SF predicted by Equation (9), setting \( \nu_0 \) and \( \nu \) to 43 and 22 GHz, respectively. The amplitude of the predicted 13 mm SF using our model and extrapolated from the 2008 May 6 data at 7 mm is lower by 30% than that observed at 13 mm. The only adjustable parameter available is \( p \), the power-law index of the electron energy spectrum. We overplot the result on the measured 13 mm SFs in Figure 10. We conclude that SFs at 13 mm for 2008 May 6 and 2006 February 10 are quantitatively reproduced from their 7 mm counterparts for \( p \approx 0.5-1 \). This is consistent with earlier fits to individual large flares in other radio and submillimeter data sets (Yusef-Zadeh et al. 2006, 2009).

### 5.2. Short Timescale Variability

The most interesting feature of the analysis presented here is that the SF at radio wavelengths shows short timescale variability of Sgr A* \( \approx 0.3 \) minutes with a shallower slope than seen at longer time lags. This is the shortest timescale variability that has been detected toward Sgr A* and suggests that radio emission may arise from the innermost region of the accretion flow. The best case for minute timescale variability is seen in Figures 3(a) and 5 where the SF rises for lag times greater than 0.3 minutes. In both cases, the amplitude of the SF at timescales greater than 0.3 minutes for data taken on 2008 May 10 and 2006 February 10 is greater than twice the mean square of the measurement errors, providing the evidence for subminute timescale variability. The transition timescales where the slope of the SF changes was estimated between 30 and 60 minutes at 7 and 13 mm. These transitions suggest that the physical mechanism for the production of the variability may be different.

As noted before, the component of the variability shows a different slope at short timescales than that at hourly timescales which dominate the power spectrum of the variable emission. The steepening of the slope at longer time lags reflects the systematic increase of the flux from Sgr A* over the course of the observations, and is removed if a linear increase in flux is subtracted from the light curve. After subtracting off the secular change over several hours of observations, the SF shows that there is continuous variability at 7 mm on minute to hourly timescales and that there is variability on a longer timescale than several hours. Given that hourly timescale variability is interpreted in the context of an adiabatically expanding hot plasma blob with sub-relativistic expansion, it is natural to consider that the short timescale variability is also optically thick.
near-light speeds suggests that they might feed into an outflow or jet. We note that the inferred scale length corresponding to 1 minute light travel time is comparable to the time-averaged spatially resolved 0.1 AU scale observed at 1.3 mm by Doeleman et al. (2008). The quiescent variable emission from Sgr A* could then be interpreted mainly as an ensemble average of numerous flares that are detected on minute timescale. This short timescale emission or quiescent variability could be due to fluctuations in the accretion flow of Sgr A* due to magnetic field fluctuations resulting from magneto-rotational instability, as recent MHD simulations in a number of studies indicate.

6. CONCLUSIONS

In conclusion, the rapid fluctuation of emission from Sgr A* allows us to probe the spectacular activities of the central engine at remarkably small spatial scales. We have constructed SFs, power spectra, and autocorrelation functions using radio, IR, and X-ray data in order to characterize the time variability of Sgr A*. These plots indicate that most of the power in the time variability is on hourly timescales. However, the shapes of the SF in X-rays and radio wavelengths are different than that of IR data. Radio continuum variability is detected to be continuous from short, subminute timescales to long, hourly timescales. We argue that rapid fluctuations of the radio emission imply rapid expansion that could feed the base of an outflow or jet in Sgr A*. The bulk of the continuum flux from Sgr A* at radio and submillimeter wavelengths is believed to be generated in its accretion disk. The localization and characterization of the source of variable continuum emission from Sgr A* give us opportunities to further our understanding of the launching and transport of energy in the nuclei of galaxies.

This work is partially supported by grants AST-0807400 from the National Science Foundation and DP0986386 from the Australian Research Council. We thank Mark Reid for his help in reducing VLBA data, and the referee for useful comments.