THE VARIABILITY OF SAGITTARIUS A* AT 3 MILLIMETER

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ABSTRACT

We have performed monitoring observations of the 3 mm flux density toward the Galactic center compact radio source Sagittarius A* (Sgr A*) with the Australia Telescope Compact Array since 2005 October. Careful calibrations of both elevation-dependent and time-dependent gains have enabled us to establish the variability behavior of Sgr A*. Sgr A* appeared to undergo a high and stable state in the 2006 June session, and a low and variable state in the 2006 August session. We report the results, with emphasis on two detected intraday variation events during its low states. One is on 2006 August 12 when Sgr A* exhibited a 33% fractional variation in about 2.5 h. The other is on 2006 August 13 when two peaks separated by about 4 h, with a maximum variation of 21% within 2 h, were seen. The observed short timescale variations are discussed in light of two possible scenarios, i.e., the expanding plasmon model and the sub-Keplerian orbiting hot spot model. The fitting results indicate that for the adiabatically expanding plasmon model, the synchrotron cooling cannot be ignored, and a minimum mass-loss rate of $9.7 \times 10^{-10} M_\odot$ yr$^{-1}$ is obtained based on parameters derived for this modified expanding plasmon model. Simultaneous multiwavelength observation is crucial to our understanding of the physical origin of rapid radio variability in Sgr A*.

Key words: Galaxy: center – techniques: interferometric

Online-only material: color figure

1. INTRODUCTION

There is compelling evidence that Sagittarius A* (Sgr A*), the extremely compact radio source at the dynamical center of the Galaxy, is associated with a $4 \times 10^6 M_\odot$ black hole (Eckart & Genzel 1996; Ghez et al. 2000; Schödel et al. 2002; Eisenhauer et al. 2003). Since its discovery in 1974 (Balick & Brown 1974), Sgr A* has been observed extensively with radio telescopes in the northern hemisphere, and temporal flux variations at millimeter wavelengths were reported. With VLA8 observations, Yusef-Zadeh et al. (2006a) detected an increase of flux density at a fractional level of 7% and 4.5% at 7 and 13 mm, respectively, with a duration of about 2 hr. The peak flare emission at 7 mm led the 13 mm peak flare by 20–40 minutes. Mauerhan et al. (2005) detected intraday variations (IDVs) of about 20% and in some cases up to 40% at 3 mm using the Owens Valley Radio Observatory (OVRO). The rise and decay occurred on a timescale of 1–2 hr. At 2 mm, Miyazaki et al. (2004) reported a 30% flux increase in 30 minutes from the monitoring of the Nobeyama Millimeter Array (NMA). On the other hand, flares with violent intensity increases in very short timescales have also been detected at infrared (IR) and X-ray bands (Genzel et al. 2003; Baganoff et al. 2001; Eckart et al. 2006b), inferring that these emissions from Sgr A* originate within the very vicinity of the central massive black hole. This is further strengthened by the simultaneous detection of X-ray, IR, and submillimeter flares (Eckart et al. 2004, 2006a, 2008a, 2008b; Yusef-Zadeh et al. 2006b, 2008; Marrone et al. 2008).

Since Sgr A* is embedded in thick thermal material, it is particularly difficult to observe its intrinsic structure. But observations of IDVs can give indirect constraints on the source emission geometry and emission mechanisms. However, previous monitoring observations of Sgr A* from the northern hemisphere have been strictly limited to a short observing window (<7 hr day$^{-1}$) for the Galactic center region. We have performed monitoring observations of flux density toward Sgr A* at 3 mm since 2005 October when for the first time the Australia Telescope Compact Array (ATCA) of the Australia Telescope National Facility (ATNF) was available at 3 mm. The ATCA is an interferometer consisting of five 22 m radio telescopes at Narrabri, Australia, where Sgr A* passes almost overhead, allowing a much longer observing window (>8 hr at elevation angles above 40°). As such, the ATCA calibrations and flux density measurements of Sgr A* are expected to be more accurate.

In this paper, we report our effort to search for IDVs in Sgr A* with the ATCA. We first introduce the ATCA observations in Section 2. The data reduction and analysis with emphasis on the gain calibrations are described in detail in Section 3. In Section 4, we present the detection of IDV events in Sgr A*. To interpret the observations, we discuss two possible scenarios in Section 5, followed by a summary in Section 6. Throughout this paper, the fractional variation is defined as $\frac{S_{\text{max}} - S_{\text{min}}}{S_{\text{max}} + S_{\text{min}}}$; here $S_{\text{max}}$ and $S_{\text{min}}$ are the maximum and minimum flux densities, respectively.

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In 2005 and 2006, we performed 3 mm ATCA flux density monitoring of Sgr A* over 50 hr in the following three sessions: 2005 October 18, 2006 June 9, and August 9–13. Dual (linear) polarization double sideband (DSB) High Electron Mobility Transistor (HEMT) receivers were used. The first ever 3 mm ATCA monitoring of Sgr A* was performed on 2005 October 18 when data were simultaneously recorded in both the lower (93.504 GHz) and upper (95.552 GHz) sidebands, in 32 channels of total bandwidth of 128 MHz. For the observations in 2006, the data were recorded in two slightly different 3 mm bands: the lower sideband (86.243 GHz) was set to the transition frequency of the SiO J = 2 − 1 v = 1 line with 256 channels of total bandwidth of 16 MHz; the upper sideband (88.896 GHz) was a wideband with 32 channels of total bandwidth of 128 MHz. Since the continuum data of the lower sideband with narrow bandwidth have relatively low signal-to-noise ratio (S/N), only the upper sideband data were used for Sgr A* and other continuum sources.

On 2005 October 18, we observed Sgr A* in the H168C configuration of the ATCA, with a maximum baseline of 192 m, UV range of 13–61 kλ, and a synthesized beam of 2′9 × 1′7. On 2006 June 9, the observations were performed in the 1.5 D configuration with a maximum baseline of 1439 m, covering a UV range of 20–430 kλ, and yielding a synthesized beam of 2′1 × 0′3. In 2006 August, the observations were performed in SPLIT5 configuration with a maximum baseline of 1929 m, covering a UV range of 3–570 kλ, and yielding a synthesized beam of 1′3 × 0′2. In this array, the spacing between antennas 2 and 3 and antennas 3 and 4 is only 31 m, causing a severe shadow effect, especially for antenna 3.

Quasar 3C 279 was observed for 10 minutes at the beginning of the observation to calibrate bandpass. Either a planet or a bright radio source was observed for the flux density calibration. The first 3 mm ATCA observation of Sgr A* lasted for 10 hr on 2005 October 18. It alternated between Sgr A* and the only secondary calibrator PKS 1730–130, which was also used as the pointing calibrator. The primary calibrator Uranus was observed for 10 minutes at the end of the observation. In 2006 June and August, we observed Sgr A* in a total of 6 days with a thoughtful calibration strategy. Up to four secondary calibrators (control sources) including an SiO maser source (OH2.6-0.4) and three continuum sources (PKS 1921–293, PKS 1710–269, and PKS 1730–130) were observed to check the consistency of the gain calibrations. Limited by the weather, ATCA observed Sgr A* for only 1 hr on August 9, 4 hr on August 10, and 2 hr on August 11. Therefore, we will focus on the measurements on June 9, August 12 and 13. The pointing accuracy was checked every half hour by observing VX Sgr, a known strong SiO maser source. The instrumental gain and phase were calibrated by alternating observations of Sgr A* and all secondary calibrators. In 2006 June, the observations were performed using the following sequence: OH2.6-0.4 (2 minutes), Sgr A* (5 minutes), PKS 1730–130 (2 minutes), and PKS 1921–293 (1 minute). In 2006 August, the observing sequence was PKS 1710–269 (2 minutes), OH2.6-0.4 (1 minute), Sgr A* (10 minutes), PKS 1710–269 (2 minutes), OH2.6-0.4 (1 minute), PKS 1730–130 (1 minute), and PKS 1921–293 (1 minute). The observing details have been summarized in Table 1.

### Table 1: ATCA Observations of Sgr A* in 2006

| Date        | Length (hr) | IF1&IF2 (GHz) | BW1&BW2 (MHz) | UV Range | Beam |
|-------------|-------------|---------------|---------------|----------|------|
| 2005 Oct 18 | 10          | 93.504&95.552 | 128&128       | 13–61    | 2′9 × 1′7 |
| 2006 Jun 9  | 6           | 86.243&88.896 | 16&128        | 20–430   | 2′1 × 0′3 |
| 2006 Aug 9  | 1           |               |               |          |      |
| 2006 Aug 10 | 4           |               |               |          |      |
| 2006 Aug 11 | 2           | 86.243&88.896 | 16&128        | 3–570    | 1′3 × 0′2 |
| 2006 Aug 12 | 7           |               |               |          |      |
| 2006 Aug 13 | 9           |               |               |          |      |

Notes: Length is the duration of the observation. IF1&IF2 are intermediate frequencies for the lower and upper sidebands, respectively, with the corresponding bandwidths of BW1&BW2. Range of baselines are indicated by UV range. Beam is the ATCA synthesized beam.

3. DATA REDUCTION AND ANALYSIS

All the data processing was conducted using the ATNF MIRIAD package (Sault et al. 1995). At millimeter wavelengths, the atmosphere can no longer be approximately transparent. The opacity effect is included in an effective system temperature—the so-called “above atmosphere” system temperature (Ulrich 1980)—for the ATCA measurements at 3 mm. The bandpass corrections were made using the strong ATCA calibrator 3C279. For amplitude calibration, we first applied nominal elevation-dependent gains of the antennas and then used calibrators to further determine the additional corrections. On 2005 October 18, the flux scale was based on observation of Uranus. On 2006 June 9, the flux density scale was determined using PKS 1730–130, assuming its flux density of 2.27 Jy at 3 mm. In 2006 August, we derived the flux density scale with another brighter radio source, PKS 1921–293, which is reported to be 8.44 Jy during our observations from the ATCA calibrator list on the Web. From the ATCA calibrator flux density monitoring data during 2003 to 2006, we estimated its mean flux density of 8.66 Jy with a standard deviation of 1.04, implying a dispersion of about 12%. PKS 1921–293 is probably better than that of other calibrators simply because PKS 1921–293 data usually have very high S/N. So, we expect an accuracy ≤20% for the absolute amplitude calibration in these observations. After the phase self-calibration, the data were averaged in 5 minute bins to search for shorter timescale variability. The flux density of Sgr A* was estimated by fitting a point-source model to visibilities on projected baselines longer than 25 kλ. (about 85 m at 3 mm) to suppress the contamination from the surrounding extended components (Miyazaki et al. 2004; Mauerhan et al. 2005). Both the fitting error reported by MIRIAD and the rms of the residual visibilities were used to get the final error estimate.

In order to establish strong cases for variability of Sgr A* at millimeter wavelengths, reliable calibrations of both elevation- and time-dependent gains are crucial. We have carefully considered and corrected for the following factors that could affect the measurements during the calibration process.

1. Antenna gain varies with elevation angle mainly because of the gravitational distortion of the dish. The antenna efficiency of ATCA has its maximum value at an elevation angle of 60° and its minimum value at an elevation angle of 90°. A nominal gain–elevation correction in MIRIAD is applied at elevations greater than 40° for 3 mm observations; only those data observed at elevation angles above 40° were used. However, such nominal
observations in 2006 August, the 3 mm flux density of PKS 1710—269 was around 0.5 Jy, only one-fiftieth of that of OH2.6-0.4; therefore the modulation index of the flux density of Sgr A* is much larger than that of the antenna gain correction, the detected flux variation is most likely to be real. The modulation indices of Sgr A* and gain correction of five antennas derived from two nearby calibrators, OH2.6-0.4 and PKS 1710—269, on 2006 June 9, August 12 and 13 are plotted in Figure 1. The modulation indices of Sgr A* were quite large on 2006 August 12 and 13, indicating the real detection of IDV from Sgr A*. As mentioned in Section 2, many data obtained from antenna 3 in 2006 August were shadowed and thus not used in obtaining its gain correction, resulting in a large fluctuation in its gain correction and thus a bigger modulation index. During observations in 2006 August, the 3 mm flux density of PKS 1710—269 is around 0.5 Jy, only one-fiftieth of that of OH2.6-0.4; therefore the S/N of PKS 1710—269 data is much lower than that of OH2.6-0.4. This explains why the modulation indices of gain corrections derived from PKS 1710—269 are relatively high.

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

Figure 1. Modulation index of the flux density of Sgr A*, and gain corrections of five antennas (labeled 1, 2, 3, 4, and 5). They are derived from calibrators OH2.6-0.4 and PKS 1710—269 (from left to right) for three observations on 2006 June 9, August 12, and August 13 (from top to bottom). Many data obtained from antenna 3 in the August session were shadowed and have been flagged, so the uncertainty of this antenna is big compared with other antennas. During observations in 2006 August, the 3 mm flux density of PKS 1710—269 was around 0.5 Jy, only one-fiftieth of that of OH2.6-0.4; therefore the modulation indices of gain corrections derived from this source are particularly high.

Elevation-dependent gains built into MIRIAD do not seem to fully compensate the gain variation. We have plotted flux density as a function of elevation angle and found that a nearby calibrator was needed to make further correction, otherwise significant elevation effects (e.g., peaks at about 60°, or a minimum at 90° elevation angle) will show up in the light curve; this often indicates some calibration errors. PKS 1730—130, which is often used to calibrate phase and amplitude during observations from the northern hemisphere at millimeter wavelengths (e.g., Miyazaki et al. 2004; Yusef-Zadeh et al. 2008), proves to be unsuitable for the ATCA observations. It is 16.2 away from Sgr A*, and its elevation angle is only 72° when Sgr A* reaches the zenith. Thus, gain corrections derived from data on this source cannot fully compensate for the elevation effect in Sgr A*, especially for observations at high elevations. Similarly, PKS 1921—293, which reaches the zenith 2 hr later than Sgr A*, is not suitable either. So we only use two closer sources, PKS 1741—312 and OH2.6-0.4, for the gain calibration.

2. Calibrators are, in general, variable sources that will unavoidably introduce uncertainties into the nominal time-independent gains. For this reason, several secondary calibrators were actually scheduled to check the consistency. The complex gains derived from one control source were applied to both Sgr A* and other control sources. If such a control source is strongly variable, somewhat similar trends will appear in the light curves for all the other sources (including Sgr A*) after calibration.

To check the significance of any detected variability, we introduced the modulation index, which is defined as the rms of the gain correction of five antennas derived from calibrators and the flux density of Sgr A* divided by their mean, corresponding to the degree of variation for Sgr A*, and the fractional uncertainty in time-dependent gain correction, respectively. Obviously, if the modulation index of the flux density of Sgr A* is much larger than that of the antenna gain correction, the detected flux variation is most likely to be real. The modulation indices of Sgr A* and gain correction of five antennas derived from two nearby calibrators, OH2.6-0.4 and PKS 1710—269, on 2006 June 9, August 12 and 13 are plotted in Figure 1. The modulation indices of Sgr A* were quite large on 2006 August 12 and 13, indicating the real detection of IDV from Sgr A*. As mentioned in Section 2, many data obtained from antenna 3 in 2006 August were shadowed and thus not used in obtaining its gain correction, resulting in a large fluctuation in its gain correction and thus a bigger modulation index. During observations in 2006 August, the 3 mm flux density of PKS 1710—269 is around 0.5 Jy, only one-fiftieth of that of OH2.6-0.4; therefore the S/N of PKS 1710—269 data is much lower than that of OH2.6-0.4. This explains why the modulation indices of gain corrections derived from PKS 1710—269 are relatively high.

3. As mentioned in Section 2, we only used upper sideband (88.896 GHz) data with a bandwidth of 128 MHz for Sgr A* and other continuum control sources, and the lower sideband (86.243 GHz) data with a bandwidth of 32 MHz bandwidth only for the SiO maser source OH2.6-0.4. Will there be an additional uncertainty when applying to Sgr A* the gain solutions derived from OH2.6-0.4 data? We inspect this by comparing the results of the two sidebands on 2006 August 12 and 13. Similar to what we did for the upper sideband data, the flux density of Sgr A* was also estimated from the lower sideband using the same channels as OH2.6-0.4. The results from the lower sideband data show larger error bars mainly because of the relatively low S/N. The average deviations from the results of upper sideband data are 2.4% on August 12 and 3.6% on August 13, much smaller than the fractional variation of Sgr A* (see Section 4).

4. We also consider the response of feeds to polarized emission. The feed of ATCA is linearly polarized, and its response to a signal is a combination of total and linear polarized intensity. Thus, two polarization products, XX and YY correlations, can be used as a direct measure of total intensity only when a calibrator is not linearly polarized. Unfortunately, polarizations of nearly 27% were observed in OH2.6-0.4 (Glenn et al. 2003). In addition, for ATCA antennas on altazimuth mounts, their feeds rotate with respect to the equatorial frame. This causes the actual response of ideal linearly polarized feeds to vary with the parallactic angle. To solve this problem, we used total intensity by summing the two polarization products (XX and YY) to remove the effect of linear polarization of the SiO maser OH2.6-0.4, and then derived the gain correction. In other words, a single joint solution was determined. This is generally a reasonable approximation given that antenna gains are dominated by changes common to both polarizations and the difference between them is only a few percent, and can be safely ignored (M. Voronkov 2008, private communication).

Overall, OH2.6-0.4, which is relatively stable and close to Sgr A* (about 2:7 away), proved to be the best control source. As such, it was used as the main secondary calibrator to determine the antenna gain corrections for all the results presented in this paper.
4. RESULTS

During the first 3 mm ATCA observation of Sgr A* on 2005 October 18, the flux density of Sgr A* ran up to 3.5 Jy, much brighter than the normally expected 1.5 Jy in the quiescent phase, and thus Sgr A* was very likely to be in an active phase during our observation. Although Sgr A* seems to vary in its total flux density as a function of time, we cannot rule out the possibility of the elevation-dependent gain effect as the use of the only secondary calibrator PKS 1730−130 (16.2° from Sgr A*) severely limited the amplitude calibration. Because of this, starting from observations in 2006 June and August (see Section 2), we paid particular attention to the strategy of calibration. As a result, the light curves of Sgr A* at 3 mm in 2006 are reliably obtained (Figure 2). All the data were calibrated using OH2.6-0.4. The flux densities were estimated by fitting a point-source model to visibility data on projected baselines longer than 25 kλ. The following is a detailed description of the results from each observation.

The flux density of Sgr A* was relatively high (around 3 Jy) but stable on 2006 June 9. As shown in Figure 1, the modulation index of Sgr A* is small and comparable to that of antenna gains. Therefore, no IDV was detected.

During the first three days in the 2006 August session (August 9, 10, and 11), very limited data were available. The flux density of Sgr A* decreased from 2.52 to 2.25 Jy in 1 hr on August 9, stayed around 1.9 Jy quite stably during the 4 hr run on August 10, and around 2.0 Jy over the 2 hr observation on August 11. So, we conclude that no ascertained IDV was detected.

Two clear IDV events were seen in the last two days of the 2006 August session. As shown in the light curves of Sgr A* and other sources on 2006 August 12 (Figure 3, left), the flux density of Sgr A* first decreased from 1.65 to 1.50 Jy, then increased to 2.11 Jy in 2.5 hr before decreasing again to 1.90 Jy. The fractional flux density variation is estimated to be 33%. On 2006 August 13 (Figure 3, right), the flux density of Sgr A* first increased from 1.95 to 2.14 Jy, reached its first peak before decreasing to 1.80 Jy in 1.7 hr, reached the second peak 2.22 Jy in 1.9 hr, and then declined to 1.98 Jy in 1.2 hr. The maximum fractional flux density variation is 21% with a timescale of about 2 hr. As shown in Figure 1, the modulation indices of Sgr A* on both August 12 and 13 are much greater than that of gain corrections, supporting our conclusion that the observed flux density variations are most likely to be real.

The NMA observations of Sgr A* from 1996 to 2003 indicate that Sgr A* has quiescent and active phases: the peaks of flares were 2–3 Jy at 3 mm, while the mean flux density in a quiescent phase was 1.1 ± 0.2 Jy at 90 GHz (Tsutsu et al. 2002; Miyazaki et al. 2004), which are in accord with our ATCA observations. As shown in Figure 2, the mean flux density of Sgr A* dropped from 2.97 to 2.16 Jy from the 2006 June to August session. The day-to-day fractional variation of Sgr A* appeared to be low from 2006 August 10 to 13. Comparison of flux densities in two observing sessions in 2006 indicates that Sgr A* appeared to undergo a high state in the 2006 June session, and a low state in the 2006 August session. Such different states were also noted by Herrnstein et al. (2004). They found a bimodal distribution of flux densities at centimeter wavelength and thought that it might indicate the existence of two distinct states of accretion onto the supermassive black hole. Different radiation states are usually associated with certain physical parameters or radiation models. For example, a unified inner advection dominated accretion flow (ADAF) model with different accretion rates and consequently different geometries of accretion flow has been proposed to explain five distinct spectral states that have been identified in black hole X-ray binaries (BHXBs), namely the quiescent, low, intermediate, high, and very high states (Esin et al. 1997). Supposing that the accretion model of Sgr A* has something in common with that of BHXBs, the accretion rate in the 2006 August session...
should be smaller than that in the June session, but the accretion rate may not change much over days in August.

5. DISCUSSION

Several models have been invoked to explain the flaring activity of Sgr A*, such as the expanding plasmon model and orbiting hot spot model. We will discuss them separately.

5.1. The Plasmon Model

The expanding plasmon model of van der Laan (1966) was invoked to explain the observed time delay in variation of Sgr A* at 7 and 13 mm (Yusef-Zadeh et al. 2006a, 2006b, 2008). In this model, rather than the synchrotron cooling, the adiabatic cooling associated with expansion of the emitting plasma is responsible for the decline of the flare. Flaring at a given frequency is produced through the adiabatic expansion of an initially optically thick blob of synchrotron-emitting relativistic electrons. The initial rise of the flux density is produced by the increase in the surface area of the blob, while it still remains optically thick; the curve turns over once the blob becomes optically thin because of the reduction in the magnetic field, the adiabatic cooling of electrons, and the reduced column density as the blob expands. This kind of blob ejected from an ADAF is also thought to be a possible explanation for nonthermal flares and recombination X-ray lines in low-luminosity active galactic nuclei and radio-loud quasars (Wang et al. 2000).

Our observed IDVs with different amplitudes and timescales seem consistent with the expanding plasmon model in the context of a jet or outflow. The amplitudes and timescales vary with the relativistic particle energy distribution, expanding velocity, and size of the blob. To apply the model to the light curves on 2006 August 12 and 13, we first assumed a power-law spectrum of the relativistic particle energy (\( n(E) \propto E^{-\gamma} \)). Hornstein et al. (2007) reported a constant spectral index of 0.6 using multiband IR observations of several flares. Here we adopt a spectral index of 0.6, corresponding to the particle spectral index of 2.2; the energy of the particles was assumed to range from 10 MeV to 3 GeV. The expanding velocity was supposed to be constant. As stated by Yusef-Zadeh et al. (2008), the relationship between the quiescent and flaring states of Sgr A* is not fully understood. Their results indicate that the quiescent emission at 7 and 13 mm varies on different days. The minimum flux density was 1.5 Jy during our 2006 August observing session: the quiescent flux density, if it exists, should not be more than this value. We then assume a quiescent flux density of 1.4 Jy, while the flare is produced by the blob. Other parameters were derived by means of the weighted least-squares method. We adopt an exponentially increasing step length for number density during the fitting in order to improve efficiency. The uncertainties of the parameters were assessed by scaling up the 68.3% confidence region of parameter space, as an increase of \( \chi^2 \) from \( \chi^2_{\text{min}} \) to \( \chi^2_{\text{min}} + \chi^2_{\omega} \) with the reduced \( \chi^2 = \chi^2_{\text{min}} / N_{\text{dof}} \), where \( N_{\text{dof}} \) is the difference between the number of data and the number of fitting parameters (see Shen et al. 2003).

We used two blobs to fit the flare observed on 2006 August 12 and three blobs for those observed on 2006 August 13. Initial magnetic fields of 20–50 G were derived from the fit. The electron cooling timescale due to synchrotron loss is (e.g., Marrone et al. 2008)

\[
t_{\text{syn}} = 38 \left( \frac{\nu}{90} \right)^{-1/2} \left( \frac{B}{10} \right)^{-3/2} \text{[hr]},
\]

where the frequency (\( \nu \)) is in GHz and magnetic field (\( B \)) in Gauss. Its value is about 3.4 hr for a magnetic field of 50 G at 90 GHz, which is comparable to the observed decreasing timescale of 2 hr. Thus, the synchrotron cooling of the electrons should not be ignored. We took this into account and redid the whole fit. The energy-loss rate is given by You (1998)

\[
\left( \frac{\text{d} \gamma}{\text{d}t} \right)_{\text{syn}} = -3 \times 10^{-8} \nu^2 U_{\text{mag}},
\]

where \( U_{\text{mag}} = \frac{B^2}{8\pi} \). With a constant expanding velocity \( v \), the radius of the blob \( R \) can be expressed as \( R = R_0 + vt \), where \( R_0 \) is the initial radius of the blob at a specific instant \( t_0 = 0 \). Substituting \( B \) and \( t \) with \( v, R, R_0 \), and the initial magnetic field \( B_0 \), Equation (2) can be written as

\[
\left( \frac{\text{d} \gamma}{\text{d}R} \right)_{\text{syn}} = \frac{1}{v} \left( \frac{\text{d} \gamma}{\text{d}t} \right)_{\text{syn}} = -\frac{3 \times 10^{-8} B_0^2 R_0^3}{8\pi v^2} \nu^2 R^{-4} = -c_1 \nu^2 R^{-4},
\]

where \( c_1 = \frac{3 \times 10^{-8} B_0^2 R_0^3}{8\pi v} \). The energy-loss rate due to the adiabatic expansion is

\[
\left( \frac{\text{d} \gamma}{\text{d}R} \right)_{\text{exp}} = -\frac{\gamma^2}{R}.
\]

Thus, the total energy-loss rate due to both synchrotron cooling and expanding is

\[
\frac{\text{d} \gamma}{\text{d}R} = -\frac{\gamma^2}{R} - c_1 \nu^2 R^{-4}.
\]

Equation (5) is a Bernoulli equation with a solution

\[
\gamma = \gamma_0 \left( \frac{R}{R_0} \right)^{-1} \left\{ 1 - \frac{3\gamma_0 c_1 R_0^3}{4} \left[ 1 - \left( \frac{R}{R_0} \right)^{-4} \right] + \frac{1}{4} \right\}^{-1}.
\]

Figure 4. Two kinds of theoretical model light curves as a function of expanding blob radius at 90 GHz with different \( B_0 \). Results from the expanding plasmon model of van der Laan (1966) are shown as dotted lines, and results from the expanding plasmon model with synchrotron cooling are shown as solid lines.
Then the optical depth scales as
\[ \tau(v, R) = \tau(v_0, R_0) \left( \frac{v}{v_0} \right)^{-\frac{4}{2}} \left( \frac{R}{R_0} \right)^{-2} \]
\times \left\{ \frac{1}{4} c_1 \gamma_0 R_0^3 \left[ 1 - \left( \frac{R}{R_0} \right)^{-4} \right] + 1 \right\}^{1-p}, \tag{7} \]
and the flux density scales as
\[ S(v, R) = S(v_0, R_0) \left( \frac{v}{v_0} \right)^{-\frac{2}{4}} \left( \frac{R}{R_0} \right)^{3} \frac{1 - \exp(-\tau(v, R))}{1 - \exp(-\tau(v_0, R))}, \tag{8} \]
where \( \tau(v_0, R_0) \) and \( S(v_0, R_0) \) are optical depth and flux density for frequency \( v_0 \) at the specific instant \( t_0 \). The critical optical depth \( \tau_{\text{crit}}(R) \), at which the flux density for any particular frequency peaks for radius \( R \), satisfies
\[ e^{\tau_{\text{crit}}(R)} = \frac{1}{2}(2p + 3)\tau_{\text{crit}}(R) - C_2(R)\tau_{\text{crit}}(R) - 1 = 0, \tag{9} \]
where \( C_2(R) = \frac{1}{3} c_1 \gamma_0 R_0^{-3} (p - 1) \left( \frac{R}{R_0} \right)^{-4} \left[ \frac{1}{2} c_1 \gamma_0 R_0^{-3} [1 - \left( \frac{R}{R_0} \right)^{-4}] + 1 \right]^{-1}. \]
In the expanding plasmon model of van der Laan (1966), optical depth scales as
\[ \tau(v, R) = \tau(v_0, R_0) \left( \frac{v}{v_0} \right)^{-\frac{4}{2}} \left( \frac{R}{R_0} \right)^{-2} \], \tag{10} \]
and \( \tau_{\text{crit}}(R) \), the critical optical depth at the maximum of the light curve at any frequency, depends only on \( p \) through the equation (Yusef-Zadeh et al. 2006a, 2008)
\[ e^{\tau_{\text{crit}}(R)} - (2p/3 + 1)\tau_{\text{crit}}(R) - 1 = 0. \tag{11} \]
Comparison of Equations (7) and (10) indicates that the only difference between these two equations is the factor \( \left\{ \frac{1}{2} c_1 \gamma_0 R_0^{-3} [1 - \left( \frac{R}{R_0} \right)^{-4}] + 1 \right\}^{1-p} \) in the former, which is the result of synchrotron cooling. Similarly, the only difference between Equations (9) and (11) is the factor \( C_2(R) \) of \( \tau_{\text{crit}}(R) \) in the former, which decreases as \( R^{-4} \). The optical depth at which the flux density peaks at \( t_0 \) satisfies
\[ e^{\tau_{\text{crit}}(R_0)} - \frac{1}{3}(2p + 3)\tau_{\text{crit}}(R_0) - C_2(R_0)\tau_{\text{crit}}(R_0) - 1 = 0. \tag{12} \]
For typical values of \( p = 2.2, B_0 = 20 \, G, \gamma_0 = 20, R_0 = 4r_g, \) and \( v = 0.004c, \)
\[ C_2(R_0) = \frac{1}{3} c_1 \gamma_0 R_0^{-3} (p - 1) = \frac{1 \times 10^{-8} B_0^2 \gamma_0 R_0 (p - 1)}{8 \pi v} \]
\[ = 0.08 \ll \frac{1}{3} (2p + 3) = 2.5, \tag{13} \]
which implies that \( \tau_{\text{crit}}(R_0) \) mainly depends on \( p \). Since \( c_1 \gamma_0 R_0^{-3} (p - 1) \propto B_0^2 \), \( B_0 \) is the most sensitive parameter for the evolution of flux \( S(v, R) \). To illustrate this, we choose typical values of \( p = 2.2, \gamma_0 = 20, R_0 = 4r_g, \) and \( v = 0.004c \) and show the resulting model light curves at 90 GHz with \( B_0 = 10, 20, 30, 40, \) and 50 G in Figure 4. Results from the expanding plasmon model of van der Laan (1966) are shown as dotted lines, and results from the expanding plasmon model with synchrotron cooling are shown as solid lines. The differences between the two results are significant above 30 G, implying that the synchrotron cooling of electrons should not be ignored for strong magnetic fields.

The best-fit model for the light curve of 2006 August 12 is plotted as a solid line in Figure 5 (left). Two blobs were required to fit the data, which were assumed to appear at 7.0 and 10.3 UT. We attribute the turnover in the light curve to the birth of a new blob, so the second blob was assumed to appear before the flux increases. The corresponding initial blob radii \( 1.8_{-0.6}^{+0.8} r_g \) and \( 2.6_{-0.5}^{+0.4} r_g \), expanding velocities \( 4_{-2.5}^{+4.3} \times 10^{-3} c \) and \( 2_{-1.2}^{+1} \times 10^{-3} c \), electron number densities of \( 2.56_{-1.0}^{+2.4} \times 10^{17} \, \text{cm}^{-3} \) and \( 5.12_{-1.4}^{+1.2} \times 10^{17} \, \text{cm}^{-3} \), and magnetic fields of \( 19_{-0}^{+3} \) and \( 7_{-0}^{+4} \) G were derived from the fit. The uncertainty that we were unable to be assess is left blank as it is not such a sensitive parameter. The peak flux densities of the two blobs are estimated to be 0.26 and 0.59 Jy, respectively. The half-power durations are 1.7 and 5.2 hr, respectively. Blob masses of \( 2.3 \times 10^{20} \, \text{g} \) and \( 1.4 \times 10^{21} \, \text{g} \) were estimated.

Figure 5 (right) shows the best-fit model for the light curve of 2006 August 13. Similarly, three blobs appearing at 6.6, 10.0, and 13.0 UT are required to fit the flare. Initial blob radii \( 4.2_{-0.2}^{+0.4} r_g, 2.8_{-0.4}^{+0.8} r_g, \) and \( 2.3_{-0.4}^{+0.8} r_g \), expanding velocities \( 5_{-1.2}^{+1.4} \times 10^{-3} c, 5_{-1}^{+3} \times 10^{-3} c, \) and \( 5_{-2}^{+1} \times 10^{-3} c \), electron number densities of \( 1.6_{-0.1}^{+0.1} \times 10^{18} \, \text{cm}^{-3}, 2.56_{-2.2}^{+2.6} \times 10^{17} \, \text{cm}^{-3}, \) and \( 5_{-1.2}^{+1.4} \times 10^{17} \, \text{cm}^{-3} \), and magnetic fields of \( 23_{-1}^{+4} \), \( 15_{-0}^{+5} \), and \( 13_{-0}^{+6} \) G were
derived from the fit. The peak flux densities of the three blobs are 0.67, 0.66, and 0.48 Jy, respectively. The half-power durations are 3.2, 2.8, and 2.4 hr, respectively. Blob masses of $1.8 \times 10^{20}$ g, $8.5 \times 10^{20}$ g, and $9.4 \times 10^{20}$ g were estimated based on derived parameters. The mass-loss rate contributed by the blob was then calculated to be $9.7 \times 10^{-10} M_\odot$ yr$^{-1}$. This value is lower than the accretion rate range $2 \times 10^{-7} M_\odot$ yr$^{-1}$ to $2 \times 10^{-9} M_\odot$ yr$^{-1}$ estimated by the rotation measurement (Marrone et al. 2007). The derived parameters are summarized in Table 2.

In principle, the expanding plasmon model can also be used to interpret the 2000 March 7 NMA short-millimeter flare reported by Miyazaki et al. (2004). In their observation, the peak flux density at the 140 GHz band is apparently larger than that at the 100 GHz band. The spectral variation suggests that the energy injection to photons occurred in the higher frequency regime first and the emitting frequency was shifted to the millimeter-wavelength regime with time, which is well consistent with the scenario predicted by the expanding plasmon model. A time delay of 1.5 hr was observed for near-IR (NIR) and submillimeter flare on 2008 June 3 (Eckart et al. 2008b), which has been explained with a similar model with adiabatically expanding source components. There, the spectral index (0.9–1.8), expansion velocity (0.005$c$), and source size ($\sim 2r_g$) are fairly consistent with the parameters derived here. In order to compare with their modeling results, we calculate the optical depth at submillimeter wavelengths based on parameters derived here. Taking the first blob of 2006 August 13 as an example, according to Pachołczyk (1970), the optical depth at 90 GHz is calculated to be 8.23 at $t_0$. The critical optical depth at which the flux density for any particular frequency peaks at $t_0$ is calculated to be 1.82 based on Equation (12). According to Equation (7), the optical depth at 345 GHz is 0.14, which is smaller than the critical value. Therefore, at both NIR and submillimeter wavelengths, the emission is optically thin at the beginning. Since we attribute the turnover in the light curve to the emergence of a new blob, the new blob is assumed to appear right before the observed flux density increases. Extending the model in time might help give the time delay between NIR and submillimeter; however, the birth time of the blob is difficult to determine. Future simultaneous multiwavelength observations, especially the correlation between optically thin (such as NIR/ X-ray) and 3 mm flaring emission, are expected to help improve the model fitting.

5.2. The Hot Spot Model

An orbiting hot spot model has been frequently used to mainly explain the observations of short-term NIR and X-ray variability (Broderick & Loeb 2005, 2006; Meyer et al. 2006a, 2006b; Trippe et al. 2007; Eckart et al. 2006b, 2008a). The hot spot is modeled by an overdensity of nonthermal electrons centered at a certain point of its Keplerian orbit. This situation may arise in the case of a magnetic reconnection event similar to the solar flare. Due to the Doppler shift and relativistic beaming the approaching portion of the hot spot orbit appears considerably brighter than the receding portion. This model is successful in explaining the NIR 17 minute quasi-periodic oscillation (Genzel et al. 2003). The hot spot model is applied to the radio band by including the effects of disk opacity for a typical RIAF model (Broderick & Loeb 2006). In these studies, the hot spot is always close to the innermost stable circular orbit (ISCO); thus the NIR 17 minute quasi-periodic oscillation can be produced. Since the creation of such a hot spot is still under discussion, it is also possible that this kind of spot may appear somewhere away from the ISCO and thus produce quasi-periodic oscillation with a longer timescale.

In the accretion disk, neighboring annuli of differentially rotating matter experience a viscous shear that transports angular momentum outward and allows matter to slowly spiral in toward the center of the potential (Merloni 2002). As a result, the gas rotates with a sub-Keplerian angular velocity (Narayan et al. 1997). In the following, we assume that the rotation of the hot spot is also sub-Keplerian and fit our detected IDV events using a sub-Keplerian rotating hot spot model. To simplify the calculation, the angular velocity is assumed to be 0.4 times the Keplerian angular velocity of a Schwarzschild black hole.

We assumed that the values of most physical parameters of the hot spot model are the same as those in the expanding plasmon model when starting to fit the hot spot model to light curves. These include the energy range of relativistic particles, the particle spectral index, and the quiescent flux density. Then we estimated other parameters by means of the weighted least-squares method. The magnetic field was assumed to range from 1 to 100 G. In the RIAF model, the electron number density of the accretion disk is about $2 \times 10^6$ cm$^{-3}$ at a distance $20r_g$ from the central black hole (Yuan et al. 2003). Since the hot spot is modeled by an overdensity of nonthermal electrons, it is safe to assume the electron number density ranges from $4 \times 10^6$ to $1 \times 10^7$ cm$^{-3}$. In addition, the accretion disk is assumed to be edge-on to maximize the boosting effect (Huang et al. 2007, 2008). The final result is the combination of the quiescent flux density and the flux density of the hot spot. The derived parameters are summarized in Table 3.

The hot spot model for the 2006 August 12 flaring is plotted as a solid line in Figure 6 (left). The quiescent flux density was assumed to be 1.4 Jy. Two hot spots are needed to fit the data. Radii of $(6.5 \pm 0.5)r_g$ and $(8.0 \pm 0.5)r_g$, magnetic intensities of
Figure 6. Light curves produced by the sub-Keplerian orbiting hot spot model on 2006 August 12 (left) and 13 (right). An assumed quiescent flux density of 1.4 Jy is indicated by the straight dotted line. Two hot spots used to fit the data on August 12 (left) are indicated by dashed curves.

Table 3
Parameters of the Sub-Keplerian Orbiting Hot Spot Model

| Date       | $R (r_g)$ | $N_e (cm^{-3})$ | $B (G)$ | $D (r_g)$ | $\chi^2_{r_g}$ |
|------------|-----------|-----------------|---------|-----------|----------------|
| 2006 Aug 12| 6.5 ± 0.5 | $4^{+26}_{-26} \times 10^6$ | 3$^{+2}_{-2}$ | 10 ± 1 | 1.04          |
|            | 8.0 ± 0.5 | $4^{+26}_{-26} \times 10^6$ | 1$^{+2}_{-2}$ | 12$^{+5}_{-5}$ |              |
| 2006 Aug 13| 4.1 ± 0.3 | $6^{+44}_{-44} \times 10^6$ | 6$^{+2}_{-2}$ | 11.4$^{40.4}_{-36.2}$ | 12.32         |

Notes. $R$ is the radius of the hot spot, $N_e$ is the electron number density, $B$ is the magnetic field strength, $D$ is the distance between the hot spot and the central black hole, and $\chi^2_{r_g}$ is the reduced chi-square.

3$^{+2}_{-2}$ and 1$^{+2}_{-2}$ G, and electron number densities of $4^{+26}_{-26} \times 10^6$ cm$^{-3}$ and $4^{+26}_{-26} \times 10^6$ cm$^{-3}$ were derived from the weighted least-squares fitting. The separations to the central black hole are $(10 \pm 1)r_g$ and $12^{+5}_{-5}r_g$.

The hot spot model for the light curve of 2006 August 13 is plotted as a solid line in Figure 6 (right). The quiescent flux density was 1.4 Jy too. One hot spot is required to fit the data. A radius of $(4.1 \pm 0.3)r_g$, magnetic intensity of $6^{+2}_{-2}$ G, and electron number density of $6^{+44}_{-44} \times 10^6$ cm$^{-3}$ were derived. The hot spot is at $11.4^{40.4}_{-36.2}r_g$ from the central black hole.

The electron cooling timescales due to synchrotron losses are calculated to be greater than 2 days at 90 GHz, much longer than the observed variation timescale; thus the synchrotron energy loss can be ignored in the fitting. Since the synchrotron cooling time is long, the lifetime of the hot spot should mainly depend on the dynamical timescale. Reid et al. (2008) analyzed the limits on the position wander of Sgr A* by ruling out the possibility of hot spots with orbital radius above $15r_g$ that contribute more than 30% of the total 7 mm flux. All the orbital radii listed in Table 3 are smaller than $15r_g$. Hence, the presented hot spot model is not in contradiction with their result.

The discussion above shows that both the expanding plasmon model and the orbiting hot spot model can be used to interpret the two IDV events detected. Given that the former model predicts a time delay in flare emission while the latter does not, the time delay between different frequencies in flare emission is believed to be critical to distinguish between them (Yusef-Zadeh et al. 2006a). Recently, Yusef-Zadeh et al. (2008) detected time lags of 20.4 ± 6.8, 30 ± 12, and 20 ± 6 minutes between the flare peaks observed at 13 mm and 7 mm. At shorter wavelength, a possible time delay of $110 \pm 17$ minutes between X-rays and 850 $\mu$m was observed (Marrone et al. 2008). Though these observations seem to support the expanding plasmon model, the hot spot model is still a possible explanation, especially for the nearly symmetrical light curves observed.

6. SUMMARY

We presented the results of the ATCA flux density monitoring of Sgr A* at 3 mm, with emphasis on the two IDV events detected. Comparison of flux densities in two observing sessions in 2006 indicates that Sgr A* appeared to undergo a high state in the June session and a low state in the August session. On 2006 August 12, Sgr A* exhibits a 33% fractional variation in about 2.5 hr. Two peaks with a separation of 4 hr are seen on the 2006 August 13 flare, which exhibits a maximum variation of 21% within 2 hr.

The short timescales inspire us to consider mechanisms other than synchrotron cooling that may be responsible for the variation. Both the expanding plasmon model and the sub-Keplerian rotating hot spot model were discussed and applied to interpret the observed light curves. Because of a relatively large derived magnetic intensity (and thus a short synchrotron cooling timescale), we incorporated the synchrotron cooling into the original adiabatically expanding plasmon model to model the observed IDV data. The radius of the blob was estimated to range from $1r_g$ to $5r_g$, the expanding velocity range from 0.001$c$ to 0.007$c$, the electron number density larger than $1 \times 10^6$ cm$^{-3}$, and the magnetic field range from 7 to 30 G. A minimum mass-loss rate of $9.7 \times 10^{-10} M_\odot yr^{-1}$ was deduced based on these derived parameters. We assume that the rotation of the hot spot is sub-Keplerian while applying the hot spot model. It seems that both models can reasonably fit the IDV events detected. Future simultaneous multiwavelength monitoring is expected to discriminate between them and tell us where such IDV events come from.

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