Flux monitoring of Sagittarius A\(^*\) at mm-wavelengths

Atsushi Miyazaki\(^1,4\), Zhi-Qiang Shen\(^1\), Makoto Miyoshi\(^2\), Masato Tsuboi\(^3\) and Takahiro Tsutsumi\(^2\)

\(^1\) Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, P.R.China
\(^2\) National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
\(^3\) Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Minamimaki, Minamisaku, Nagano 384-1305, Japan

E-mail: amiya@shao.ac.cn

Abstract.

We performed the monitoring observations of the flux density toward the Galactic center compact radio source, Sagittarius A\(^*\) (Sgr A\(^*\)), which is associated with a supermassive black hole, since 1996 using the Nobeyama Millimeter Array (NMA). The monitoring observations of Sgr A\(^*\) were carried out in the 3- and 2-mm (100 and 140 GHz) bands over one to several months on each NMA observable season. We have detected several flares of Sgr A\(^*\) with duration of, roughly, one month. The flux density at the flare peak increases 100\%–200\% at 100 GHz band and 200\%–400\% at 140 GHz band, respectively, while the averaged quiescent flux density was about 1 Jy. We also found some intraday variations (IDVs) of Sgr A\(^*\) at both 2- and 3-mm bands. The shortest twofold increase timescale of the IDV is estimated to be about 1.5 hr at 140 GHz. This short timescale variability suggests that the physical size of emitting region is compact on a scale at or below about 12 AU (\(\sim 150 R_S\)). The IDV at mm-wavelengths has a similar increase timescale as those in the X-ray and infrared flares but has a smaller amplitude.

1. Introduction

Sagittarius A\(^*\) (Sgr A\(^*\)) is a unique compact radio source located at the dynamical center of the Galaxy, and is widely believed to be associated with a supermassive black hole (SMBH) of mass \(\sim 4 \times 10^6 M_\odot\) (see, e.g., [1]). Since its discovery, Sgr A\(^*\) has been observed at many wavelengths, and temporal flux variations were reported, e.g. from cm- to sub-mm wavelengths in the radio, infrared, and X-rays. Thus, Sgr A\(^*\) is a source with time-varying luminosity. Because this source is embedded in thick thermal material, it is practically difficult to observe its detailed structure. Generally, the properties of temporal flux variations can give indirect constraints on the source emission geometry and the emission mechanisms.

At centimeter wavelengths, the time variability of Sgr A\(^*\) has been studied over the past decades (e.g., [2, 3, 4]). Very Large Array (VLA) cm-wavelength monitoring suggests a periodicity of about 110 days [3, 5]. However, at cm-wavelengths, Sgr A\(^*\) is dominated by effects of refractive interstellar scintillation, and it is difficult to measure all of its intrinsic properties. These effects are usually weaker at higher frequencies, so we can better ascertain the intrinsic nature of Sgr A\(^*\) at millimeter wavelengths. Earlier, in 1990, significant flux variations of Sgr A\(^*\) have
at 89 GHz were reported by [6]. Since 1996, we have been monitoring Sgr A* 3- & 2-mm flux densities using the Nobeyama Millimeter Array (NMA), the Nobeyama Radio Observatory\(^5\), Japan (see figure 1; [7, 8, 9, 10, 11]). We detected several Sgr A* flares with typical durations of a few weeks [7, 8]. Similar flares of Sgr A* were also detected at 1-mm wavelength using the Sub-Millimeter Array (SMA) [12]. Moreover, the intraday variations (IDVs) in the Sgr A* flux density at mm-wavelengths were detected [10]. In recent years, X-ray and infrared flares have also been detected, indicating very short timescales and violent intensity increases (X-rays: [13, 14]; IR: [15, 16]).

Sgr A* at mm-wavelengths is a relatively weak (∼1 Jy) compact component embedded in the extended and strong HII region of Sgr A West. The contribution of the free-free emission from the extended structure is significant even at mm-wavelengths. It is necessary to observe with higher angular resolution to discriminate the compact component from the extended components. Therefore, we conducted the flux monitoring experiments of Sgr A* at short mm-wavelengths using the NMA.

2. Observations
We have performed the flux monitoring observations toward Sgr A* in the 100 and 140 GHz bands (λ=3 and 2-mm) since 1996 using the NMA, a six element 10-m dish interferometer, at the NRO. The observations were carried out using multiple array configurations of the NMA over a period of a few months to half a year for each observable season (winter to spring). Each epoch consists of a set of sequential observations over about 2 days. The epochs were separated by several days to 2 weeks. For each observing day, the observing time was 2–4 hrs within the maximum observable time of about 4 hrs.

We used double sideband (DSB) SIS receivers in the 3- and 2-mm bands as the front-ends. Almost all the data were obtained using the Ultra Wide Band Correlator (UWBC) with 1 GHz bandwidth. With this UWBC system, simultaneous observations of both the lower and upper sidebands, separated by 12 GHz, are allowed. Thus, these observed frequencies were 90 and 102 GHz for the 3-mm band, and 134 and 146 GHz for the 2-mm band. The instrumental gain and phase were calibrated by alternating observations of Sgr A* and NRAO530 at about 20 min intervals. We also used an additional phase calibrator, 1830-210, a known QSO, after 2000. The flux densities of the calibrators are determined from Uranus or Neptune, which were used as the primary flux calibrator. The absolute uncertainties of the flux scaling are about 15% and 20% in the 100 and 140 GHz bands, respectively. Because the observations for Sgr A* in the 2-mm band requires the best weather conditions and phase stability, these observations were made less frequently.

Most of the observations, including the detections of the flares of Sgr A*, were performed by the array configuration with intermediate baselines, C-configuration, of the NMA. The projected baselines in this array range over ∼7 – 55 kλ in the 100 GHz band and ∼10 – 77 kλ in the 140 GHz band. We made spatially filtered maps from the visibilities with projected baselines exceeding 25 kilo-wavelengths (\((U^2 + V^2)^{1/2} \geq 25kλ\)) to suppress the contamination from the extended components surrounding Sgr A* (17 kλ for the data taken with the compact array configuration, D-configuration, in the 100 GHz band). Typical synthesized beam sizes (HPBW) for the C-configuration were about 3″ × 6″ and 2″ × 4″ at 100 and 140 GHz, respectively. From the flux densities of the calibrators measured on the maps, the fractions of the decorrelation due to atmospheric phase fluctuation are 10–20% at 100 GHz and 20–40% at 140 GHz. We corrected the measured flux densities of Sgr A* for the decorrelation, and averaged two measured flux densities of Sgr A* which were individually calibrated by each of the two phase calibrators.

\(^5\) Nobeyama Radio Observatory (NRO) is a branch of the National Astronomical Observatory, National Institutes of Natural Sciences, Japan.
more detailed description of the observations and the data calibrations have also been presented in our other papers [9, 10, 11].

3. Results & Discussion

3.1. Flare of Sgr A*

Figure 1 shows the light curves of Sgr A* in the 100 and 140 GHz bands constructed from all monitoring data from 1996 to 2005. Red circles and blue squares indicate the flux densities in the 100 and 140 GHz bands, respectively. The total number of observations is about 102 days. Mean flux densities of Sgr A* in quiescent phase are $1.1 \pm 0.2$ Jy and $1.2 \pm 0.2$ Jy at 90 and 102 GHz, respectively. These light curves show that Sgr A* may distinguish between the active phase and the quiescent phases [9]. There are at least four flares in March 1998, March 2000, April 2002, and March 2004 (Flare I, Flare II, Flare III, and Flare IV, respectively, indicated in figure 1) with duration of, roughly, one month during the whole observing period [11]. The peak flux density in these flares increases by 100%-200% at 100 GHz, and by 200%-400% at 140 GHz ($\Delta S/S$), respectively, while the averaged quiescent flux density was about 1–1.5 Jy. For near-simultaneous millimeter spectra made from our observations, it appears that the variability of the flux density in the flare increases with frequency [8, 9, 11].

![Figure 1](image-url)

Figure 1. 1996-2005 light curve (center) of Sgr A* in the 100 & 140GHz bands. Open circles - 90GHz, filled circles - 102GHz, open squares - 134GHz, filled squares - 146GHz. Top and bottom panels show light curves in 1998, 2000, 2004, 2000-2001, and 2004-2005 in detail. The dotted lines indicate the averaged quiescent flux level.

3.2. Intraday Variation

We detected the intraday variation (IDV) of Sgr A* on the 7th March, 2000 [10]. As shown in the upper panel of figure 1, the light curves of Sgr A* in March 2000 indicate particularly strong variability in the 100 and 140 GHz bands in the active phase of Flare II. The most prominent flare was observed on March 7, 2000 in the 140 GHz band, and the peak flux density at 146 GHz
was 3.9 ± 0.8 Jy. On the 7th March, 2000, the Sgr A* flux density have strongly increased during observing session, thus it indicates obviously the IDV [10]. The flux density increases about 30% during 30 minutes, and the twofold timescale of the IDV is estimated to be about 1.5 hours assuming that the increase has a constant gradient [10].

**Figure 2.** Light-curves of Sgr A* and the calibrators during each observation at 102 or 146 GHz. The light-curves in each panel indicate Sgr A* (red circles with the straight-line), and the calibrators, NRAO 530 (blue squares with the broken-line) and/or 1830-210 (black squares with the dashed-line). The arrows indicate significant flux variations.

Then, we have performed to search for the intraday variability (IDV) based on our NMA monitoring data of Sgr A* flux density. In the analysis, we adopted the monitoring data in good condition from November in 2001 to December in 2005 to exclude the data taken with the compact array configuration. Date of the analyzed data are summarized in Table 1, and total number of the usable data is ~22 days. We measured the flux densities averaged every 4–5 minutes bin on visibility data self-calibrated for phase to search for shorter timescale variability. The flux measurements of Sgr A* were estimated to fit a point source model in visibility plane with longer $uv$ distance of $\geq 25$ k$\lambda$ in order to suppress the contamination from the surrounding extended components around Sgr A*.

In Figure 2, each panel shows some light-curves of Sgr A* at 102 or 146 GHz during each observing session from 2 to 4 hours. Red circles with the straight-line indicate the light-curve of Sgr A*, and blue squares with the broken-line and black squares with the dashed-line indicate the light-curve of the calibrators, NRAO 530 and/or 1830-210, respectively. Some light-curves look like to indicate significant flux variation (see the arrows in figure 2). The most prominent
flux variation in the analysis was shown in the light-curves in the 100 GHz band on the 6th April, 2005. The peak-to-peak amplitude (difference between maximum and minimum flux) in the IDV on April 6, 2005 was $\sim 1.1$ Jy at 102 GHz.

Table 1. Log of IDV searching with the NMA

| Frequency | Observing Date |
|-----------|----------------|
| 100 GHz   | 2002.4.6, 2003.1.9, 2003.3.2, 2003.3.13, 2005.2.19, 2005.2.21, 2005.4.6, 2005.12.2, 2005.12.3, 2005.12.5, 2005.12.10, 2005.12.26 |
| 140 GHz   | 2001.11.18, 2002.4.6, 2003.3.12, 2004.3.6, 2004.3.8, 2004.3.14, 2004.3.24, 2004.3.31, 2005.2.20, 2005.3.7 |

Figure 3 shows the light-curve (bottom panel) at 90 and 102 GHz on April 6, 2005. Red circles and blue squares indicate the light-curve of Sgr A* and NRAO530 as the calibrator, respectively. The variation of the flux densities of Sgr A* was much larger than the flux scatters of the calibrator, NRAO530, and thus it indicates obviously the IDV. The peak flux densities were 2.5 Jy at 90 GHz, and 2.7 Jy at 102 GHz. The typical relative uncertainties were at or below about 0.1 Jy. The flux density of Sgr A* at 102 GHz increased from $\sim 1.6$ to $\sim 2.7$ Jy between 18:15 to 19:45 UT on April 6, 2005. The flux density increases about 70% during 1.5 hours, and the two-fold timescale of the increase is estimated to be about 2 hours assuming that the increase has a constant gradient. Top panel of Figure 3 shows the variability of the spectral indices estimated between the flux at 90 and 102 GHz.

Figure 3. Light-curves (bottom panel) of Sgr A* (red circles) and the calibrator (blue squares), NRAO530, at 90 and 102 GHz on April 6, 2005. In this plot, the data were divided into 5 mins bin. The flux variation of Sgr A* was significantly larger than the scatters of the flux densities of the calibrator. Moreover, top panel shows the spectral indices between the flux at 90 and 102 GHz.

Recently, the other radio IDVs of Sgr A* were reported by some investigators (e.g., VLA at cm-wavelengths [17]; OVRO mm-interferometer at 3-mm [18]; VLA & ATCA at 7- & 12-mm [19]; SMA at 880$\mu$m (340 GHz) [20]). The variation of Sgr A* has probably the period of a few hours according to periodicity analyses in these reports [18], and our NMA results are consistent with
the results of those. However, as for its amplitude, the IDV at mm- or submm-wavelengths is much larger than that at lower frequency, and these variability of the flux density increases with frequency. Considering these results, it seems that radio IDV in Sgr A* are not rare, especially at shorter wavelengths. The intraday flare at mm-wavelengths has a similar increase timescale as those known in the X-ray and infrared flares, but has a smaller amplitude ([13, 14, 15, 16]). The shortest increase timescale, 1.5 hr, suggests that the physical size of the emitting region in the accretion disk is compact on a scale at or below about 12 AU (∼150 R_S; the Schwarzschild radius R_S = 2GM/c^2, assuming a black hole mass of 4×10^6 M_☉) [10].

As shown in the top panel of Figure 3, we estimated the spectral indices, \( \alpha (S_\nu \propto \nu^\alpha) \), between 90 and 102 GHz of each measured bin on the 6th April, 2005. Figure 4 shows the relations between the flux density and the spectral index estimated between 90 and 102 GHz (left panel), or 134 and 146 GHz (right panel) in each measured bin on each observing session. The typical uncertainties of these spectral indices are ∼0.8 in the 100 GHz band and ∼1.4 in the 140 GHz band, which is slightly large because of a small frequency span (12 GHz). The straight lines in each panel indicate a best fit for the linear function, and these relations have probably the positive correlation though the uncertainties in the index are large. Each best fit for the linear function are \( \alpha_{100GHz} = (0.81 \pm 0.11) \cdot S_{102GHz} - (1.11 \pm 0.24) \) in the 100 GHz band, \( \alpha_{140GHz} = (0.15 \pm 0.17) \cdot S_{146GHz} + (0.67 \pm 0.46) \) in the 140 GHz band. It appears that the scatter of the index in lower flux density is large. As mentioned in the previous subsection, the flux increase during the flare in the 140 GHz band is larger than that in the 100 GHz band [8, 9, 10]. From these results, these demonstrate that the spectral index of Sgr A* was large during the flux increase in the IDV. The spectral variation suggests that the energy injection to photons was occurred in the higher frequency regime and the emitting frequency was shifted to millimeter wave regime with time.

![Figure 4. Correlation plots between the flux density and the spectral index estimated between upper- and lower-sidebands (90 and 102 GHz, or 134 and 146 GHz) of each measured bin on each observation. Left-panel and right-panel are in the 100 GHz and 140 GHz bands, respectively. The straight lines each panel indicate a best fit for the linear function.](image-url)

On the other hand, we have also performed the 3-mm observations of Sgr A* on October 18, 2005 and June 9, 2006 using the the Australia Telescope Compact Array (ATCA), the Australia Telescope National Facility (ATNF) [21]. The ATCA in southern hemisphere has a longer observing window of the Galactic center region for about 10 hrs in a day, and so it is very useful instrument to search for a IDV of Sgr A*. For the preliminary result of our observations with the ATCA, we detected a significant flux variation of Sgr A*, which seem to be the IDV, on the 18th October, 2005 [21]. The Sgr A* flux density first decreased from about 3 Jy to 2 Jy, and then increased to 3.5 Jy on October 18. It appear that the light curve on the 9th June, 2006 don’t have significant flux variation.
4. Conclusions
We have performed the monitoring observations of the flux density of Sgr A* in the 3-mm (100 GHz) and 2-mm (140 GHz) bands using the NMA at the NRO since 1996.

(i) We detected several flares of Sgr A* with duration from a few weeks to a month. The flux density at the flare peak increases 100%–200% at 100 GHz band and 200%–400% at 140 GHz band ($\Delta S/S$), respectively, while the averaged quiescent flux density was about 1-1.5 Jy.

(ii) We have searched for the intraday variations (IDV) on the NMA monitoring data of Sgr A* flux density, and detected some IDVs of Sgr A* at both 100 and 140 GHz bands. The amplitude of variation is over 1 Jy during a few hours.

(iii) The twofold increase timescale in these IDVs is estimated to be a few hours. The shortest increase timescale, 1.5 hrs, suggests that the physical size of the emitting region (light crossing time) in the IDV is a scale at or below $\sim 12$ AU ($\sim 150 R_S$).

Acknowledgments
We thank the staff of NMA group of the NRO for support in the observation.

References
[1] Ghez, A.M., Salim, S., Hornstein, S.D, et al. 2005 ApJ 620 744
[2] Brown, R.L., & Lo, K.Y. 1982 ApJ 253 108
[3] Zhao, J.-H., Bower, G.C., & Goss, W.M. 2001 ApJL 547 L29
[4] Herrnstein, R.M., Zhao, J.-H., Bower, G.C., & Goss, W.M. 2004 AJ 127 3399
[5] Zhao, J.-H. 2003a, Astron. Nachr. 324 S1 355
[6] Wright, M.C.H., & Backer, D.C. 1993 ApJ 417 560
[7] Miyazaki, A., Tsutsu, T., & Tsuboi, M. 1999 Advances in Space Research 23 5/6 977
[8] Tsuboi, M., Miyazaki, A., & Tsutsu, T. 1999, in The Central Parsecs of the Galaxy, ASP Conf. Ser. 186 (San Francisco: ASP) 105
[9] Miyazaki, A., Tsutsu, T., & Tsuboi, M. 2003 Astron. Nachr. 324 S1 363
[10] Miyazaki, A., Tsutsu, T., & Tsuboi, M. 2004 ApJL 611 L97
[11] Tsutsu, T., Miyazaki, A., & Tsuboi, M. 2006 AJ, submitted
[12] Zhao, J.-H., Young, K.H., Herrnstein, R.M. et al. 2003b ApJL 586 L29
[13] Baganoff, F.K., Bautz, M.W., Brandt, W.N., et al. 2001 Nature 413 45
[14] Porquet, D., Predehl, P., Aschenbach, B. et al. 2003 A&A 407 L17
[15] Genzel, R., Schödel, R., Ott, T., et al. 2003 Nature 425 934
[16] Ghez, A.M., Wright, S.A., Matthews, K., et al. 2004 ApJL 601 L159
[17] Bower, G.C., Falcke, H., Sault, R.J., & Backer, D.C. 2002 ApJ 571 843
[18] Mauerhan, J.C., Morris, M., Walter, F., & Baganoff, F.K. 2005, ApJL 623 L25
[19] Yusef-Zadeh, F., Bushouse, H., Dowell, C.D., et al. 2006 ApJ 644 198
[20] Marrone, D.P., Moran, J.M., Zhao, J.-H., & Rao, R. 2006, ApJ 640 308
[21] Miyazaki, A., Shen, Z.-Q., Fletcher, A.B., Sault, R.J., Miyoshi, M., Tsutsu, T., & Tsuboi, M. 2006, in preparation