INTRADAY VARIATION OF SAGITTARIUS A* AT SHORT MILLIMETER WAVELENGTHS

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ABSTRACT

We have performed the monitoring observations of the flux density of Sagittarius A* at short millimeter wavelengths (100 and 140 GHz bands) for 7 years in the period from 1996 to 2003 using the Nobeyama Millimeter Array. We found intraday variation of Sgr A* in the 2000 March flare. The flux density at the peak of the flares increases 100%–200% at 100 GHz and 200%–400% at 140 GHz (ΔS/S), respectively. The twofold increase timescale of the flare is estimated to be about 1.5 hr at 140 GHz. The intraday variation at millimeter wavelengths has a similar increase timescale as those in the X-ray and infrared flares but has smaller amplitude. This short timescale variability suggests that the physical size of the emitting region is smaller than 12 AU (≈150R_S). The decay timescale of the flare was at most 24 hr. Such a light curve with rapid increase and slow decay is similar to that often observed in outburst phenomena with ejections.

Subject headings: galaxies: nuclei — Galaxy: center — radio continuum: galaxies

1. INTRODUCTION

Sagittarius A* (Sgr A*) is the compact radio source that is located at the dynamical center of our Galaxy and believed to be associated with the supermassive black hole of a mass of about 4 × 10^6 M☉ (e.g., Ghez et al. 2003; Schödel et al. 2002, 2003). Because this source is embedded in thick thermal material, it is practically difficult to observe its fine structures by the present very long baseline interferometry (VLBI; Doeleman et al. 2001; however, see also Bower et al. 2004, the recent detection of the intrinsic size of Sgr A* using the VLBI technique). Time variability observation is a powerful and alternate tool to probe the structure and the emission mechanism of Sgr A*. If the time variability is intrinsic in the source, it should be tightly related to the structure and the emission mechanism of the emitting region. If the origin is not intrinsic, the observation should at least provide information about thermal materials around Sgr A*.

The time variability of Sgr A* at centimeter wavelengths has been studied in the last two decades (Brown & Lo 1982; Zhao et al. 2001). The variability at short centimeter wavelengths seems to have a periodicity of about 106 days (Zhao et al. 2001). However, what causes the 106 day cycle is an open question. On the other hand, the variability at millimeter wavelengths has not been well observed, although it is believed to be caused by the activity of Sgr A* itself. Earlier, Wright & Backer (1993) reported that there were significant flux variations of Sgr A* at 86 GHz in several tens of days. The extractable information from such observations has been limited because of sparse observation intervals. Thus we performed the systematic flux monitor of Sgr A* at the 100 and 140 GHz bands in the winter seasons of 1996, 1997, and 1998 using the Nobeyama Millimeter Array (NMA), which is a six 10 m dish element interferometer at the Nobeyama Radio Observatory (Miyazaki et al. 1999; Tsuboi et al. 1999). The flux density of Sgr A* was measured every several days for 2 months. In these monitor observations we found a flare of Sgr A* and showed that the timescale of the flare is at most several days (Miyazaki et al. 1999; Tsuboi et al. 1999). The variability amplitudes at millimeter wavelengths are larger than those at centimeter wavelengths. Similar flares of Sgr A* have also been detected at 1 mm wavelength (Zhao et al. 2003). On the other hand, X-ray flares of Sgr A* were recently detected by Chandra (Baganoff et al. 2001) and XMM-Newton (Porquet et al. 2003; Goldwurm et al. 2003) observations. For example, the flare detected by Porquet et al. (2003) is rising in a few kiloseconds and with a peak luminosity ~160 times higher than the quiescent state. The short timescale of these flares shows that the emission arises from the region quite close to Sgr A*. Recently, infrared flares were also detected (Ghez et al. 2004; Genzel et al. 2003). The flare detected at the H, K_s, and L' bands has a factor of about 2–4 variability on a timescale of several tens of minutes (Genzel et al. 2003). The infrared flares are similar to the X-ray flares in the duration, rise/decay times, and band luminosities (Genzel et al. 2003). The apparent correlations between radio and X-ray flares (Zhao et al. 2004), between infrared and X-ray flares (Eckart et al. 2004), and among radio, infrared, and X-ray flares (Bagnonoff et al. 2002) were also reported. The relations among X-ray, infrared, and radio flares should be important for probing the emission mechanism of Sgr A*.

We have conducted intensity monitoring observations toward Sgr A* at short millimeter wavelengths using NMA. In this Letter, we concentrate on intraday variation of Sgr A*. The long time variability will be presented in another paper. In § 2, we present the details of observations and calibrations. In § 3, we present the results of monitoring observations and discuss the properties of flares. In this Letter, we assume that the Galactic center distance is 8.0 kpc (Reid 1993).

2. OBSERVATIONS AND CALIBRATIONS

We have performed intensity monitoring observations toward Sgr A* at the 100 and 140 GHz band (λ = 3 and 2 mm)
using the NMA since 1996 (also see Tsuboi et al. 1999; Miyazaki et al. 2003). The observations were carried out over winter to spring. Each epoch consists of a set of sequent observations of 2–3 days. The epochs of the observations in 2000 were separated by about 5 days. The observational dates in 2000 March are summarized in Table 1. The observing time for each day was 2–3 hr. The maximum observable time of Sgr A* with NMA is 4 hr.

Sgr A* was simultaneously observed in two frequencies, either at 90 and 102 GHz or at 134 and 146 GHz using both lower and upper sidebands, each with a bandwidth of 1 GHz (Okumura et al. 2000). We observed NRAO 530 and 1830 every 20 minutes as phase calibrators. The flux densities of these calibrators are determined from Uranus or Neptune, which were used as the primary flux calibrators. The absolute uncertainties of the flux scaling, which are caused mainly by phase instability and the signal-to-noise ratio of phase calibrators, are about 15% and 20% at the 100 and 140 GHz bands, respectively. The flux densities of NRAO 530 and 1830—210 were separated by about 5 days. The observational dates in winter to spring. Each epoch consists of a set of sequent observations.

The absolute flux density of Sgr B2(M) in 2000 March (Okumura et al. 2000). We observed NRAO 530 and 1830 using both sidebands for each day was 2–3 hr. The maximum observable time of Sgr A* with NMA is 4 hr.

Almost all observations including the detections of flares of Sgr A* were performed by the array configuration with intermediate baselines of the NMA. The projected baselines range from 7 to 55 kλ at the 100 GHz band and from 70 to 77 kλ at the 140 GHz band. The visibilities with projected baselines over 25 kλ \((U^2 + V^2)^{1/2} \geq 25\) kλ are used in order to suppress the contamination from the extended components surrounding Sgr A*. We CLEANed the maps with the restricted visibilities using the AIPS package. Typical synthesized beam sizes (half-power beamwidth) were about 3′′ × 6′′ and 2′′ × 4′′ at the 100 and 140 GHz bands, respectively. The observed flux density is reduced by the phase error because of atmospheric phase fluctuation of timescales less than the scan interval of the phase calibrators. From the flux densities of the calibrator measured on the maps, the fractions of the decorrelation are 10%–20% for the 100 GHz band and 20%–40% for the 140 GHz band. In order to correct the decorrelation, the observed flux densities of Sgr A* were divided by the correction factors, 0.8–0.9 for the 100 GHz band and 0.6–0.8 for the 140 GHz band, respectively. We averaged two measured flux densities of Sgr A* that were individually calibrated by the two phase calibrators. After this calibration process, the residual contribution from the extended components in the flux measurements is smaller than 0.2 and 0.1 Jy at the 100 and 140 GHz bands, respectively.

### 3. Results

The total number of observations of Sgr A* at the 100 GHz band from 1996 to 2003 is about 60 days. The light curve shows that Sgr A* has quiescent and active phases (Miyazaki et al. 2003). Mean flux densities in a quiescent phase are 1.1 ± 0.2 and 1.2 ± 0.2 Jy at 90 and 102 GHz, respectively.

Figure 1 shows the light curve of Sgr A* at 100 GHz and 140 GHz (right) bands during 2000 March–April. Open and filled circles indicate the observed frequencies. 90 and 102 GHz for the 100 GHz band and 134 and 146 GHz for the 140 GHz band, respectively. The flux density at 100 GHz was violently changing. There is a steep peak at the 140 GHz band on March 7. The flux densities of Sgr A* at the peak were 3.5 ± 0.7 Jy at 134 GHz and 3.9 ± 0.8 Jy at 146 GHz, respectively. The horizontal dotted line indicates the mean flux density in a quiescent phase. Moreover, squares indicate the measured peak flux density of Sgr B2(M) (see § 2). The horizontal dashed line indicates the mean flux density of Sgr B2(M), 6.6 Jy at the 100 GHz band and 7.0 Jy at the 140 GHz band, respectively. The scatter of the flux densities is less than the absolute uncertainties.

### Table 1

| Date       | Time (UT)     | Frequency (GHz) |
|------------|---------------|-----------------|
| Feb 27     | 21:10–23:00   | 90 and 102      |
| Feb 28     | 20:50–22:50   | 134 and 146     |
| Mar 6      | 20:50–23:00   | 90 and 102      |
| Mar 7      | 21:10–22:40   | 134 and 146     |
| Mar 8      | 21:00–23:00   | 134 and 146     |
| Mar 13     | 20:10–23:00   | 90 and 102      |
| Mar 14     | 20:20–23:00   | 134 and 146     |
| Mar 20     | 19:40–21:30   | 90 and 102      |
| Mar 22     | 19:40–21:30   | 90 and 102      |
| Mar 27     | 19:10–21:00   | 90 and 102      |
| Mar 29     | 19:10–21:00   | 90 and 102      |

Figure 1.—Light curve of Sgr A* (circles) at 100 (left) and 140 GHz (right) bands during 2000 March–April. Open and filled circles indicate the observed frequencies. 90 and 102 GHz for the 100 GHz band and 134 and 146 GHz for the 140 GHz band, respectively. The flux density at 100 GHz was violently changing. There is a steep peak at the 140 GHz band on March 7. The flux densities of Sgr A* at the peak were 3.5 ± 0.7 Jy at 134 GHz and 3.9 ± 0.8 Jy at 146 GHz, respectively. The horizontal dotted line indicates the mean flux density in a quiescent phase. Moreover, squares indicate the measured peak flux density of Sgr B2(M) (see § 2). The horizontal dashed line indicates the mean flux density of Sgr B2(M), 6.6 Jy at the 100 GHz band and 7.0 Jy at the 140 GHz band, respectively. The scatter of the flux densities is less than the absolute uncertainties.

3. RESULTS

The total number of observations of Sgr A* at the 100 GHz band from 1996 to 2003 is about 60 days. The light curve shows that Sgr A* has quiescent and active phases (Miyazaki et al. 2003). Mean flux densities in a quiescent phase are 1.1 ± 0.2 and 1.2 ± 0.2 Jy at 90 and 102 GHz, respectively.

Figure 1 shows the light curves of Sgr A* at the 100 and 140 GHz bands in 2000. This is representative of the active phase. Figure 2 shows the light curves of Sgr A*, which is probably the quiescent phase, at the 100 GHz band in 2000–2001. The flux densities in the figure were averaged for 1 observation day. There was violent variability in the active phase in 2000. Several flares with durations of days to a few weeks were identified. A most prominent flare was observed on 2000 March 7 at the 140 GHz band. The peak flux densities of Sgr A* at 134 and 146 GHz were 3.5 ± 0.7 and 3.9 ± 0.8 Jy, respectively. The flux density then decreased to 2.2 ± 0.4 Jy at 146 GHz on the subsequent day, 2000 March 8. Weather conditions on March 7 and 8 were fine. The water
vapor pressure was less than 2 hPa, which is translated to opacity less than 0.1 at zenith, during the observations on both March 7 and 8.

The half-decay timescale of the flare at 146 GHz was at most 24 hr. The averaged quiescent flux was about 1 Jy at the 140 GHz band. The flare amplitude was about 300% ($\Delta S/S$) of the mean flux density level at 146 GHz, which is larger than that at the 100 GHz band (200%). This probably indicates that the variability increases with frequency.

We divided the data set at the 140 GHz band observed on 2000 March 7 and 8 into about a 5 minute bin around the peak and 7–14 minute bins for others and measured the flux density of Sgr A* at each bin in order to search for shorter timescale variability. Figure 3 shows the light curve of Sgr A* at 140 GHz in the 2 days. On March 7, the flux density around the peaks changed rapidly. This is summarized in Table 2. The peaks of the flares at 134 and 146 GHz occurred at 22:14 UT. The flux density of Sgr A* at 146 GHz increased from 3.5 to 4.7 Jy between 21:45 and 22:15 UT on March 7. The peak flux densities were 4.2 ± 0.8 Jy at 134 GHz and 4.7 ± 0.9 Jy at 146 GHz. We used the same flux scales, which were determined from the flux calibration in 2000 March, for both data on March 7 and 8. The relative uncertainty in the 2 days depends only on the accuracy of the gain calibration and the estimation of decorrelation. The relative uncertainty is smaller than the absolute one. The typical relative uncertainties of the 100 and 140 GHz bands were estimated to be a few % and 6%, respectively. The top panel in Figure 3 shows the light curves of the calibrators (NRAO 530, 1830–210). The scatters of the measured flux density are much smaller than the variation in the flare of Sgr A*. The projected baselines change with earth rotation. This change in sampling of the source structure might cause artificial variation in flux density. However, such an effect is not significant because no variation in flux density was observed within the relative uncertainty on March 8. Thus the observed 30% increase in 30 minutes must be real. The timescale that the flux density increased by 100% (twofold increase timescale) is estimated to be about 1.5 hr assuming that the increase has a constant gradient. On the other hand, the intraday variation was not found in the 100 GHz band data taken during the active phase in 2000 March. The intraday variation of Sgr A* at centimeter wavelengths reported by Bower et al. (2002) indicates that the 15 GHz flux density increased by about 10% in 2 hr. The amplitude of the variation in our millimeter-wavelength observations is much larger than the value of the centimeter-wavelength observations. The intraday variation at millimeter wavelength has also been reported for the galactic nucleus of M81 (Sakamoto et al. 2001).

4. DISCUSSION

The peak flux at 146 GHz corresponds to a factor of 4.5 increases from the mean value in the quiescent phase. The radio luminosity of the flare at the peak is $L_R \approx 3 \times 10^{34}$ erg s$^{-1}$ assuming that the frequency width of the flare is 150 GHz. The X-ray flare is rising at about 1 hr and with the peak luminosity observed by XMM-Newton of $3.6^{+3.3}_{-1.4} \times 10^{35}$ ergs s$^{-1}$ (Porquet et al. 2003). On the other hand, the peak luminosity of infrared flares observed by the Very Large Telescope at the $H$ band is about $9 \times 10^{35}$ ergs s$^{-1}$ (Genzel et al. 2003). The observed
infrared flares are similar to the X-ray flares in the duration, rise/decay times, and luminosities (Genzel et al. 2003). The flare at millimeter wavelengths has a similar increasing timescale as the X-ray and infrared flares, although it has a smaller amplitude.

During the flare peak, flux densities at 146 GHz became larger than those at 134 GHz. The last column in Table 2 shows spectral indices, $\alpha$, estimated between 134 and 146 GHz. The typical errors of indices are about ±1.4.

The spectral indices, $\alpha$, estimated between 134 and 146 GHz ($S \propto \nu^{-\alpha}$). The positive spectral index during the flare peak is clear, although an uncertainty in the index is large because of a small frequency span. The decay rate decreased significantly between March and 8 and 14 as the flux density on March 14 was 2 Jy, which is still twice as large as the mean value in a quiescent phase. Then, the total energy of the flare is as large as $10^{39}$ ergs. However, apparent flattening of the decay rate may be due to another unseen flare.

5. SUMMARY

We have performed the monitoring observations of the flux density of Sgr A* at 3 mm (100 GHz) and 2 mm (140 GHz) bands using the NMA from 1996 to 2003. We detected several active phases. In the 2000 March flare, the flux densities of Sgr A* at the 140 GHz band had reached a peak, ~4.5 Jy, on March 7 and increased $\Delta S/S \approx 400\%$. Then the flux was decreased to a half in a day. Moreover, we detected the 30% flux increase in 30 minutes on 2000 March 7. The timescale that the flux density increased by 100% is estimated to be about 1.5 hr assuming that the increase has a constant gradient. The upper limit for a size of the variable component estimated from the timescale of this intraday variability is a few tens of AU. Such a light curve with rapid increase and slow decay is similar to that often observed in outburst phenomena with ejections.

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