Sub-Millimeter Array Observations of Sagittarius A*: Flares at 1 Millimeter Wavelength

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Abstract

We summarize the results from recent observations of Sgr A* at short-/sub-millimeter wavelengths made with the partially finished Sub-Millimeter Array (SMA) on Mauna Kea. A total of 25 epochs of observations were carried out over the past 15 months. Noticeable variations in flux density at λ1.3 mm were observed showing three "flares". The SMA observations suggest that Sgr A* is highly pulsed towards the submillimeter wavelengths during a flare suggesting the presence of a break wavelength around λ3 mm. Cross-correlations of the SMA data at λ1 mm with the λ1 cm data obtained with the VLA show negative lags, suggesting that sub-millimeter wavelengths tend to peak first. The SMA observations indicate that Sgr A* is constantly powered by the central engine but the flaring plasma might well be confined within the characteristic radius ($\sim$40 R_{sc}) at λ3 mm. The SMA data appears to provide unique, important information for understanding the puzzling phenomenon of Sgr A*. The trial observations of Sgr A* have demonstrated that the SMA is a powerful telescope for studying the nature of accretion flows, possible outflows and their immediate environments surrounding a supermassive black hole.

1. Introduction

Sgr A*, a compact radio source, is believed to be associated with the supermassive black hole at the Galactic center (Eckart & Genzel 1997; Ghez *et al.*, 1998). The inferred bolometric luminosity (L$\sim 10^{-8.5}$ L_{Edd}) is far below the Eddington luminosity assuming that the mass of the black hole is M=2.6×10^6 $M_\odot$ hereafter. Sgr A* represents an extremely dim AGN. Because of its compactness, we have known little about its intrinsic structure. The apparent structure at radio wavelengths up to λ3 mm appears to be mainly dominated by the scattering structure due to the ISM. Its intrinsic size measured at λ3 mm is less than 0.27 mas (Doeleman *et al.* 2001) suggesting that a characteristic source size at λ3 mm is $\sim$ 40 Schwarzchild radii (R_{sc} hereafter). The compactness of the source appears to be just beyond our current capability to image its detailed structure using the available telescopes. Alternatively, a promising way to explore this extremely compact source is to monitor the variations of the emitting flux density at multi-wavelengths from radio to X-ray.

The variations in radio flux density of Sgr A* have been known for two decades (Brown & Lo 1982). The nature of the radio variability has not been well understood. At the long wavelengths, the flux density of Sgr A* might be modulated by the scintillation due to the turbulence in the ISM (Zhao *et al.* 1989).

The radio light curves observed with the VLA at wavelengths from λ20 to 1.3 cm during the period of 1990-1993 suggests that the amplitude variations increased towards short wavelengths and that the rate of radio flares appeared to be about three per year (Zhao *et al.* 1992; and Zhao & Goss 1993). The typical time scale of these radio flares is about a month. The observed large amplitude variations in flux densities at λ3 mm (Wright & Backer 1993; Tsuboi, Miyazaki and Tsutsumi 1999) are consistent with the wavelength-dependent train of the fluctuation amplitude as observed at centimeter wavelengths. Based on the radio-monitoring data obtained with the 3.5 km Green Bank Interferometer (GBI) at λ11 and 3.6 cm, a characteristic time scale of 50-200 days was derived at both wavelengths and the structure function of λ11 cm data suggested a quasi-periodic variation with a period of 57 days (Falcke 1999).

A presence of a 106 day cycle in the radio variability of Sgr A* was revealed based on an analysis of data observed with the VLA in the period of 1977-1999 (Zhao, Bower and Goss 2001). The periodic oscillation at a period around 100 days appears to be persist in the densely sampled light curves obtained with the

Fig. 1: The partially completed Sub-Millimeter Array (SMA) on Mauna Kea, Hawaii. The SMA is a collaborative project of Smithsonian Astrophysical Observatory and the Institute of Astronomy and Astrophysics of the Academia Sinica of Taiwan (Moran 1998).

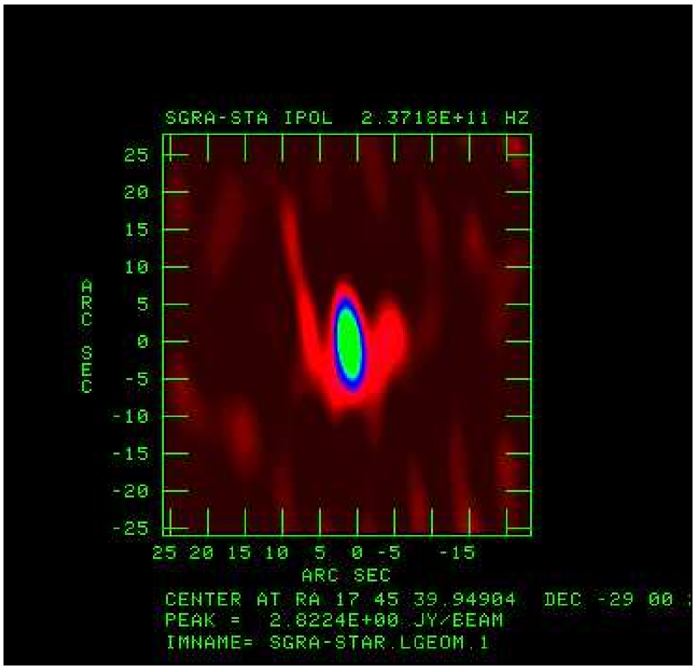

Fig. 2: A false-color image of Sgr A* (blue) and its vicinity (red) made from 3.5 hr observations using the four elements of the partially finished SMA on May 23, 2002. The total integration time on the source is about 1.5 hr. The r.m.s. noise is $\sim$30 mJy/beam. The FWHM beam is $7.4'' \times 2.3''$(P.A. = 7°).

VLA at $\lambda 2$, 1.3 and 0.,7 cm over the past two years (McGary *et al.* 2002). The period of the cycle appears to increase to 130 days suggesting a quasi-periodic nature of the variability in radio flux density (Bower *et al.* 2002; Zhao *et al.* 2002). In addition, a low frequency oscillation feature is also revealed (Zhao *et al.* 2002).

A monitoring program at $\lambda 2$ and 3 mm was carried out with the Nobeyama Millimeter Array (NMA) and several flares were observed in the period of 1996 to 2001 (Tsutsumi *et al.* 2002). The folded light curve of their $\lambda 2$ to 3 mm data with a module of 100-120 days shows that the flaring phase can be separated from that of the quiescent state. The NMA data provides additional evidence for a quasi-periodic fluctuation of the flux density at millimeter wavelengths.

The radio variabilities are likely to be associated with the activities occurring in the accretion region around the supermassive black hole. Observations at wavelengths from short- to sub-millimeters can penetrate into the deep region of this intriguing source. Critical information about inner accretion region near the black hole can be obtained by decoding the light curves.

Good news is that the Sub-Millimeter Array (SMA) is now coming on line (see Fig. 1). With this powerful sub-millimeter array (Moran 1998), we have started a trial program in monitoring Sgr A* at short- to sub-millimeter wavelengths. In this article, we summarize the preliminary results obtained from the SMA observations of Sgr A*.

2. Observations and Calibrations

The observations of Sgr A* at $\lambda 1.3$ mm and 0.87 mm were done using the partially completed SMA with three or four antennas ranging the baselines from 7 to 55 kilo wavelengths at $\lambda 1.3$ mm. A total of 25 epochs of observations were made in reasonable good weather conditions (the atmospheric opacity less than 0.3 at $\lambda 1.3$ mm). The observations were carried out with a total bandwidth of 328 MHz for each sideband. A typical r.m.s. noise of ~ 20 mJy can be achieved from an observation with four antennas for an on-source integration time of 2 hrs. The sensitivity of the partially completed SMA is already adequate for monitoring a variable source in a flux density > 1 Jy at $\lambda 1.3$ mm. In each epoch of observation, the flux density scale was determined by observing a compact planet (Neptune and Uranus). Sgr B2-north ($\sim$50 Jy at $\lambda 1.3$ mm) was used to check the fringe and the first order of absolute flux density calibration. Further calibration was done by observing two nearby QSOs, OV236 and NRAO 530. The systematic errors, such as errors due to a poor pointing model, were corrected and minimized in the calibration process.

In addition, Sgr A* is located in the complex, extended source Sgr A West. Based on the SMA image (Fig. 2), we find that, for baselines $\sim 20\mathrm{k}\lambda$ or longer, Sgr A* is dominant in the correlated flux density and the confusing flux density at $\lambda 1$ mm from the surrounding free-free and dust emission is less than 0.3 Jy. The flux density measurements were done initially in the visibility domain and were then double checked by constructing images using the visibility data. The typical uncertainty at $\lambda 1$ mm is in a range of 10 to 20%.

3. Results

3.1 Light Curve and Flares

Fig. 3 shows the SMA light curve at $\lambda 1.3$ mm suggesting that Sgr A* varies significantly. The light curve of Sgr A* appears to be characterized with a few "flares" while the calibrators show secular variation with opposite drifts in flux density over the past year. Three "flares" were observed over a 1-year period. Both the 2001-March and 2002-February flares (Flare 1 and Flare 3 as marked in Fig. 3) were partially observed in their dropping phase while the 2001-July flare (Flare 2) was observed covering its entire cycle from its rising to maximum and then a slow decrease. Flare 1 (started from 4.1 ± 0.5 Jy after an unseen peak and decreased to 1.1 ± 0.15 Jy in three months) appeared to be relatively stronger than others. The rising time in Flare 2 took about 2 weeks, reaching a peak of 3.2 ± 0.3 Jy on July 10, 2001. Then, a slow decrease lasted about 3 months. Then we were not able to observe Sgr A* for next 3 months for the solar avoidance restricted by the current SMA system. The monitoring program was resumed in early February 2002. A tail of a possible flare (Flare 3) appeared to be observed in early 2002.

In addition, we checked variations in short time scales and found no evidence for significant variations

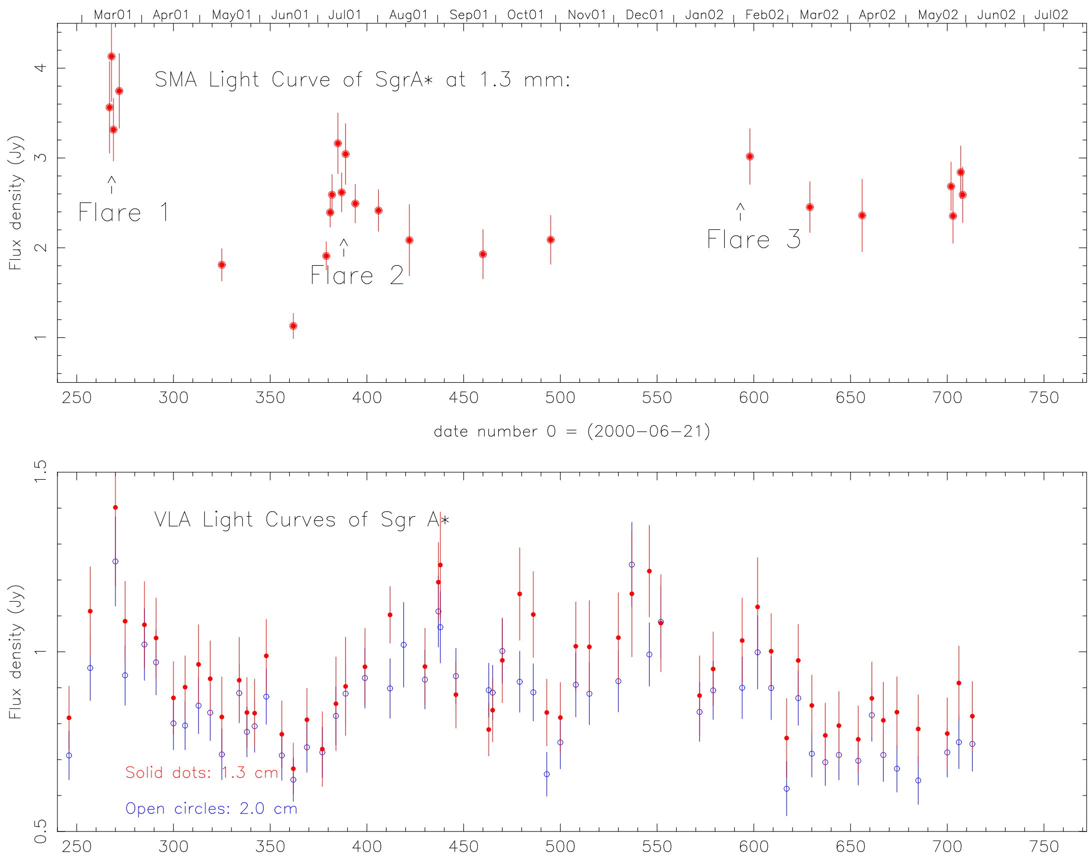

Fig. 3: The SMA light curve at λ1.3 mm observed in the period between March 2001 and May 2002 (upper panel). In the same period, the densely sampled radio light curves at λ1.3 and 2 cm were observed with the VLA (lower panel, McGary 2002).

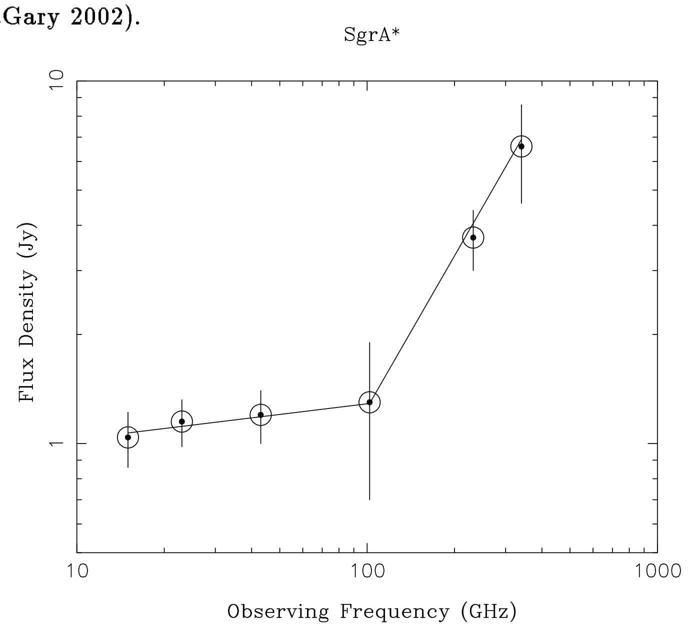

Fig. 4: A spectrum of Sgr A* made from the observations near the peak of Flare 1. The λ0.87 and 1.3 mm measurements were made with the SMA. The measurements at λ3 mm were obtained from Nobeyama observations (Tsutsumi *et al.* 2002). The data at λ0.7, 1.3 and 2 cm were from McGary *et al.* (2002).

($2\frac{[S_{max}-S_{min}]}{[S_{max}+S_{min}]} < 40\%$) in a time scale of 1 hr.

3.2 Spectrum during A "Flare"

We also observed Sgr A* at λ0.87 mm with the SMA on March 22, 2001. We made the first measurement of Sgr A* ($S_{\lambda 0.87\mathrm{mm}} = 6.7 \pm 1.5$ Jy) at the sub-millimeter band using the three-element array of the partially completed SMA. Fig. 4 shows a spectrum derived from the mean flux density observed near the peak of Flare 1. The spectrum suggests a break frequency at 100 GHz (or a break wavelength at $\sim \lambda$3 mm). The spectral index is about 0.1$\pm$0.1 below 100 GHz, and 1.4$\pm$0.4 above 100 GHz. The intensity of the flare appeared to be highly pulsed towards sub-millimeter wavelengths. A flux density excess at sub-millimeter wavelengths has been observed (Zylka, Mezger, & Lesch 1992; Serabyn *et al.* 1997; Falcke *et al.* 1998). The flare spectrum shows a large excess in flux density at sub-millimeter wavelengths, suggesting that flares at sub-millimeter are more prominent.

3.3 Correlation with The VLA Data

The SMA data at λ1 mm appears to show a correlation with the light curves observed with the VLA. The SMA light curve presented about three "flares" from Sgr A* in the past year. Based on the sparsely sampled data points from the SMA observations alone, one can not make any conclusive confirmation on the quasi-periodic fluctuations in flux density. The existing SMA light curve is suggestive. Considering the nature of the "flares" with a strong pulsing intensity towards sub-millimeter wavelengths, studying the variability of Sgr A* is an excellent scientific project to the newly built SMA. On the other hand, the excellent site condition on Mauna Kea, the angular resolution and the sensitivity of the array, the SMA is an important telescope for solving the puzzling nature of Sgr A*.

With available data obtained with the SMA during the past year, we are now able to derive some interesting results from a cross-correlation analysis of the SMA data with the VLA data at λ1 cm. Because of the large "sampling gaps" in the SMA light curve, we are still seeking for an effective tool to derive a global cross-correlation properties of the light curves. Meanwhile, we can break the light curves into three "flaring" segments (see Fig. 5). Cross-correlation analysis suggests that the SMA data at λ1 mm in all the three segments tend to have negative lags with respective to the VLA data at λ1 cm although there is a large uncertainty in the lags for Flares 1 and Flare 3 due to their unseen peaks. Flare 2 does show a significant lag ($t_{\mathrm{lag}} = -24 \pm 8$ days).

There appears to be a tendency that the flares at λ1 mm peak first and the delay time at λ1 cm seems to be proportional to the intensity of the flares.

The tendency of short wavelength flaring first is also suggested by the increase of lags towards long wavelength based on an analysis of the the new VLA data at λ2, 1.3 and 0.7 cm (Bower *et al.* 2002). In addition, the strong X-ray flare of time scale of $\sim$1 hr observed by Baganoff *et al.* (2001) was about 10 days earlier than a radio peak observed in all three VLA monitoring bands. During Flare 2 (July 2001), Chandra observed Sgr A* on July 14, 2001, a few days past the λ1 mm peak, showing no X-ray flares. The X-ray flux level was consistent with that of a quiescent state (Baganoff 2001, private communication).

4. Discussion & Summary

The SMA observations have shown that Sgr A* varies significantly at λ1 mm during the course of SMA monitoring in the past year. The derived lags from a cross-correlation analysis appear to be good evidence for that the flaring component is inside out starting from short wavelengths and then passing to long wavelengths. A recent work by Yuan, Markoff & Falcke (2002) provides a way to link a jet outflow (e.g. Falcke *et al.* 1993) with the ADAF (Narayan *et al.* 1998). The Jet-ADAF model appears to fit reasonably well to the overall spectrum of Sgr A* from radio, sub-millimeter, IR to the X-ray. In the Jet-ADAF model, the sub-millimeter excess is thought to be a result from a sum of the synchrotron radiation from both the ADAF and the nozzle of the jet.

On the other hand, from the observations with SMA and other interferometer arrays, further constraints on the models are discussed. Taking a mean delay time of 2 weeks and the source size of 40 R_{sc}, an expansion velocity, $v_{\mathrm{exp}} \sim$200 km s^{-1} or < 0.001 c, is inferred. The specific kinetic energy ($\frac{1}{2}v_{\mathrm{exp}}^2 \sim 5 \times 10^{-7}$ c^2) in

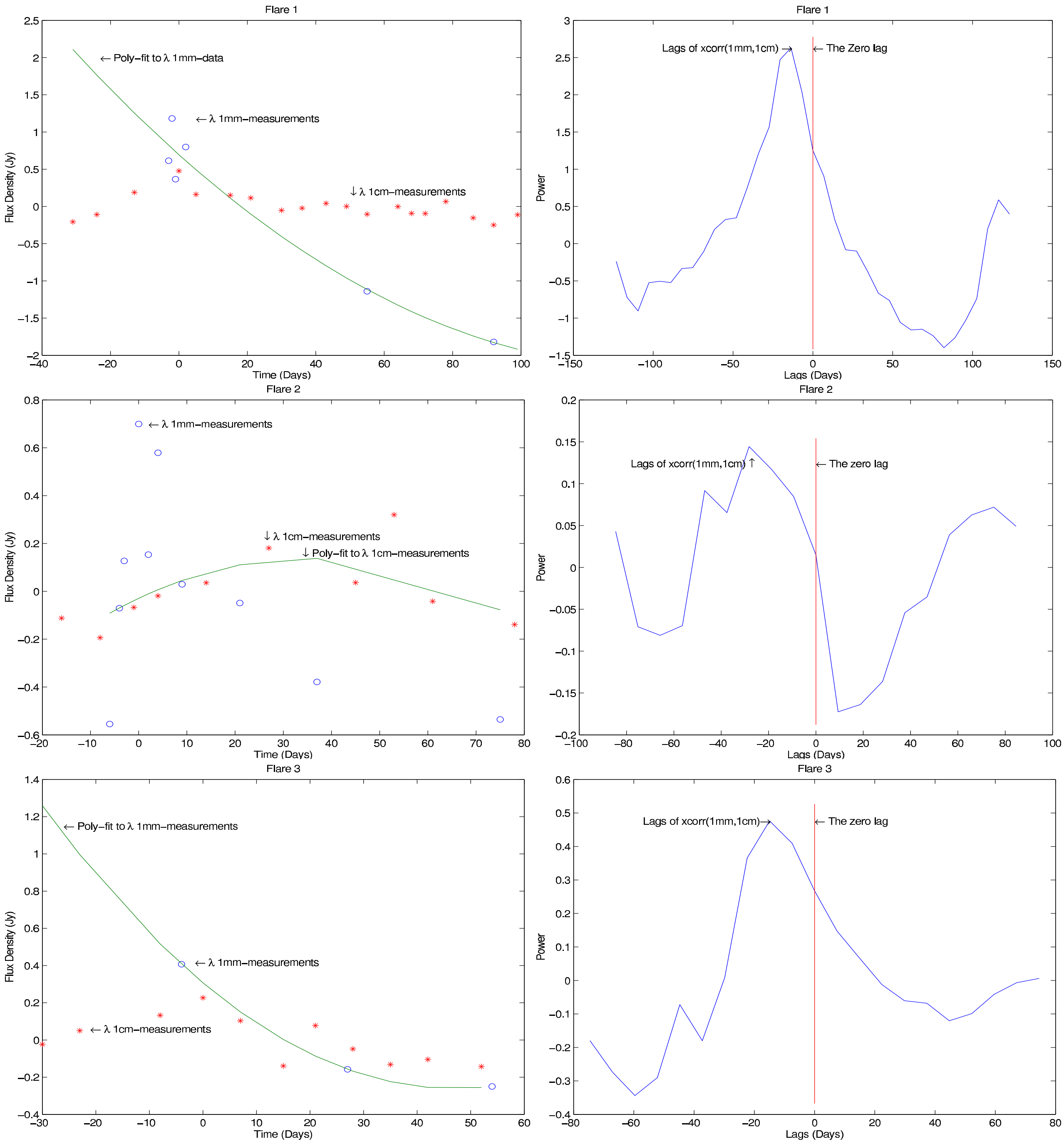

Fig. 5: The left panels are the segmental light curves at λ1.3 mm (open circles) and λ1.3 cm (asterisks) of each observed "flares" (Flare 1, Flare 2, and Flare 3). The right panels are the cross-correlations (blue curve) of the SMA data at λ1.3 mm with the VLA data at λ1.3 cm. The vertical red line marks the zero lag. The lags are $t_{\rm lag}$(Flare1) ~ -14 d, $t_{\rm lag}$(Flare2) $= -24 \pm 8$ d, and $t_{\rm lag}$(Flare3) ~ -15 d.

the outward bulk motion of the flaring plasma appears to be far below the gravitational potential energy ($\sim \left[\frac{GM}{r}\right]_{r=40R_{sc}} \sim 0.01c^2$) within the radius of 40 R_{sc} or the characteristic surface at λ3 mm. The bulk kinetic energy appears to be too small to power a noticeable jet in Sgr A*. In addition, the break wavelength around λ3 mm also indicates that a large fraction of the flaring plasma might well be confined within the characteristic radius at λ3 mm although the possible outflow tends to expand to a larger scale.

The sparse SMA data is not sufficient to confirm the periodic/quasi-periodic fluctuation in flux density around λ1 cm. The observed outburst rate ($\sim$ 3 times in a year) is consistent with that Sgr A* has been being regularly powered by the central engine.

The time scale (weeks) of λ1 mm flares differs from the time scale (1 hr) of the X-ray flare (Baganoff, 2001). The fact of a lack of strong flares in a short time scale at λ1 mm places a critical constraint on the hypothesis of the inverse Compton scattering as the emission mechanism for the short lived X-ray flares. Alternatively, the flares at sub-millimeter wavelengths might be a result of collective mass ejections associated with the X-ray flares.

Finally, the data obtained from the SMA monitoring program are critical to our diagnosis of the Sgr A* phenomenon and therefore to our understanding the accretion process and the active environment around a supermassive black hole in a low luminosity AGN.

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