A CONNECTION BETWEEN A LARGE RADIO OUTBURST AND THE LARGE X-RAY FLARE FROM SGR A* ON 2002-10-3

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Abstract

Sgr A*, a compact radio source at the Galactic center, provides a unique astrophysical laboratory for us to study connections between X-ray and radio emission from low luminosity active galactic nuclei. In this paper, we summarize and discuss the physical properties of a large radio outburst at 7 mm from Sgr A* observed during the Very Large Array weekly monitoring program at 2 cm, 1.3 cm and 7 mm, coincident with the largest X-ray flare detected to date with the *XMM-Newton* X-ray Observatory on 2002-10-03. The X-ray flare appears to be special in many aspects. Besides the high luminosity and softer spectrum at X-ray, a large radio outburst at 7 mm was detected within the same day showing the radio spectral index $\alpha = 2.4^{+0.3}_{-0.6}$ ($S \propto \nu^{\alpha}$), consistent with an optically thick non-thermal synchrotron source. Since the radio source is well confined within a size of 50 Schwarzschild radii of the black hole with a mass of 4 million solar masses, the correlation is the first evidence for that the X-ray flare arises from the inner region of the accretion flow near the event horizon of the supermassive black hole at the Galactic center rather than from star-star collision or from the heated part of the disk via star-disk interaction. These results suggest that energetic electrons responsible for the radio outburst might be produced via a process associated with the X-ray flare, then transported to large radii, producing the observed radio outburst.

1 Introduction

Radio outbursts on a timescale of a few days to weeks have been observed at short wavelengths from a few centimeters to 1 mm from Sgr A*, the compact radio source in the Galactic center (Zhao et al., 1992; Wright & Backer, 1993; Miyazaki, Tsutsumi & Tsuboi, 1999; Zhao, Bower & Goss, 2001; Zhao et al., 2003; Herrnstein et al., 2004). Radio observations have shown variations as short as a few hours (Bower et al., 2002). With the *Chandra* and *XMM-Newton* observatories, X-ray flares with shorter variation time ($\sim$ 1 hour) have been frequently observed from the direction of Sgr A* over the past two years (Baganoff et al., 2001; Baganoff, 2003; Goldwurm et al., 2003; Porquet et al., 2003). Because both radio and X-ray emissions are presumably produced close to the black hole, where energetic electrons responsible for the emissions are

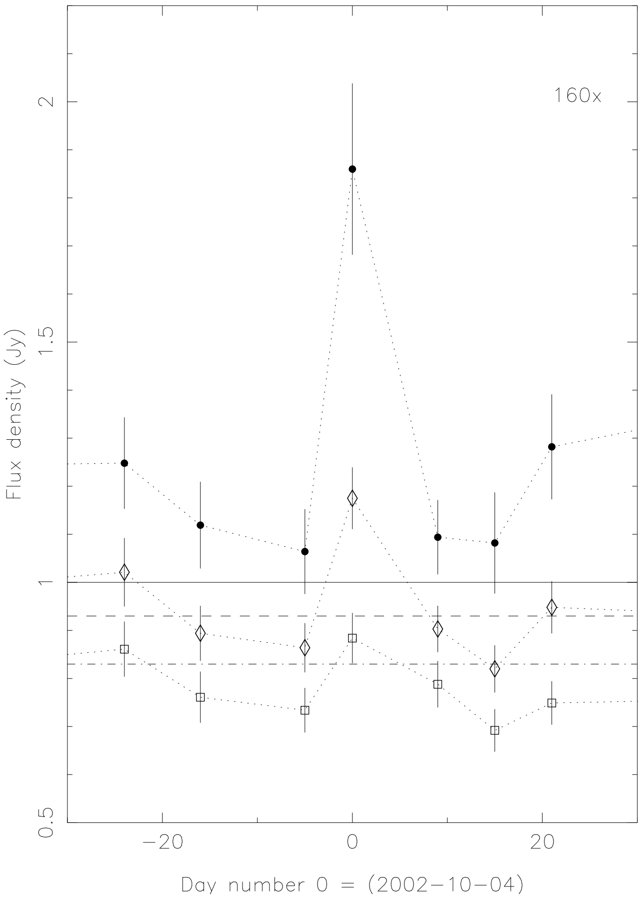

Figure 1: The flux density measurements made from the VLA observations at 2 cm (open squares), 1.3 cm (open diamonds) and 7 mm (solid dots) 30 days before-and-after the 2002-10-03 X-ray flare. The error bars mark the 1σ uncertainty in the variability measurements. The horizontal lines (solid, dash, and dash-dot-dash) mark the mean values at 7 mm, 1.3 and 2 cm, respectively.

produced due to dissipation of the gravitational energy of the accreting plasma, the lack of correlated variation between radio and X-ray emission poses a number of theoretical challenges (Baganoff, 2003). Recently, Sgr A* has been detected in the infrared (IR) band showing the variation in flux density on two timescales: (1) a few days to a week similar to that of the radio outbursts (Ghez et al., 2003b) and (2) ~ 1 hour for the IR flares (similar to X-ray flares) (Genzel et al., 2003). A simultaneous IR/X-ray detection of a small flare from Sgr A* was made on June 19, 2003 (Eckart et al., 2004).

On 2003-10-03, a giant X-ray flare from Sgr A* was detected with a peak luminosity 160 times higher than the quiescent value (Porquet et al., 2003). No X-ray flare with such a high luminosity has been previously detected. With the high sensitivity of *XMM-Newton*, it was shown that the flare was variable on a time scale of 200 seconds, corresponding to an emission region no larger than $5r_S$, where $r_S = 1.2\times10^{12}$ cm is the Schwarzschild radius of the black hole with a mass of $4\times10^6\ M_\odot$ (Ghez et al., 2003a). Moreover, the flare has a soft photon spectrum with an spectral index of $\Gamma = 2.5\pm0.3$, distinguishing itself from other relatively weaker and more frequent X-ray flares with $\Gamma = 1.3^{+0.5}_{-0.6}$ (Baganoff, 2003).

Coincidentally, one observation of the weekly Very Large Array (VLA) monitoring program was carried out ~ 0.5 day after the X-ray observation and a radio outburst was detected at 7 mm. The observations and detailed properties of the radio outburst on 2002-10-03 was reported (Zhao et al., 2004). In this paper, we discuss a possible connection between the super X-ray flare and the large radio outburst.

2 An optically thick radio outburst corresponding to the large X-ray flare on 2002-10-03

Figure 1 shows measurements of flux densities at 2 cm, 1.3 cm and 7 mm obtained from the weekly monitoring program (Herrnstein et al., 2004) one month before and after the 2002-10-03 X-ray event (see Fig. 2). The flux density at 7 mm showed at least a 4σ increase on 2002-10-03. Variations in flux density at 1.3 cm and 2 cm were 3σ and $< 1\sigma$, respectively.

We summarize the radio property for the radio outburst corresponding to the X-ray flare on 2002-10-03. The mean radio flux densities were $< \mathrm{S} > = 0.83\pm0.01$, 0.93 ± 0.01, 1.00 ± 0.01 Jy at 2, 1.3 and 0.7 cm, respectively. The total flux densities of $\mathrm{S_t} = 0.88\pm0.05$, 1.18 ± 0.06 and 1.86 ± 0.18 Jy were observed on 2002-10-03 for the three observing wavelengths, respectively. The spectral index of $\alpha = 0.71\pm0.11$ ($\mathrm{S} \propto \nu^\alpha$) derived from the total flux densities appears to be significantly greater than the spectral index of 0.2 ± 0.02 derived from the mean flux densities observed over the past three years (June 2000 - October 2003). The increase in the spectral index of the 2002-10-03 event is consistent with the general correlation between spectral index and flux density at 7 mm (Herrnstein et al., 2004).

The residual flux densities for the outburst component ($\Delta\mathrm{S} = \mathrm{S_t} - < \mathrm{S} >$) are 0.05 ± 0.05, 0.15 ± 0.06, and 0.86 ± 0.18 Jy at 2, 1.3 and 0.7 cm. A spectral index

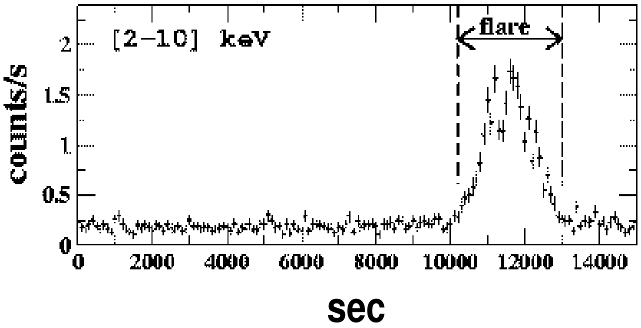

Figure 2: The super X-ray flare was detected by the *XMM-Newton* on October 3, 2002, showing the peak X-ray luminosity a factor of 160 times greater than the quiescent level (Porquet et al., 2003).

of $\alpha \approx 2.4^{+0.3}_{-0.6}$ was derived for the outburst component, which is consistent with an optically thick, non-thermal synchrotron source.

The sampling period of the VLA monitoring program was about 1 week. The measurements a week before and after the outburst showed that the flux densities were consistent with the mean value of the flux densities averaged over the past three years (June 2000 - October 2003). Therefore, the timescale of the radio outburst at 7 mm must be less than two weeks for this event. The X-ray light curve observed with *XMM-Newton* showed a larger flare (160 x) (Porquet et al., 2003).

The X-ray observation started at UT 07h18m08s on 2002-10-3 (Porquet 2003, private communication). The X-ray flare onset occurred at UT 10h05m and lasted for about 45 minutes. Our VLA observation started on 2002-10-03 at 23h30m, about 13.5 hours after the onset of the X-ray flare, and ended on 2002-10-04 at 00h45m with three 5 minute scans on Sgr A* and the calibrator. Based on the three measurements averaged on each scan over a 1.3 hour, we found that there were no significant variations in flux density ($< 3\sigma$) during the VLA observation at all the three observing wavelengths. A time scale for significant change ($> 3\sigma$) in radio flux density was likely greater than 1 hour for the radio outburst.

3 Discussion

3.1 A correlation between X-ray and radio

The large X-ray flare on 2002-10-03 appeared to be special in many aspects. In addition to a high luminosity and softer X-ray spectrum, a large radio outburst at 7 mm was detected within the same day. Based on the fact that we only detected two large (2x) radio outbursts at 7 mm from observations of 121 epochs weekly sampled over the past 3year period between June 2000 to October 2003, the probability of detecting such a large (2x) radio outburst within a time interval of Δt appears to be $P_R \sim 0.01 \frac{\Delta t}{\Delta t_{\rm sampling}}$, where $\Delta t_{\rm sampling} \sim 1$ week, the radio sampling interval. On the other hand, during the past three years overlapping with the period of VLA monitoring program, observations of a few hundred hours were carried out at X-ray with both *Chandra* and *XMM-Newton* to search for X-ray flares, but to date only one large (160x) X-ray flare has been detected. Considering the typical duration of $\Delta t_X \sim 1$ hour for the X-flares, then the detection probability of a large flare (160x) within Δt appears to be $P_x < 0.01 \frac{\Delta t}{\Delta t_X}$. A large uncertainty in estimate of P_X is owing to the sparse observations at X-ray and a large chance to have a stellar X-ray transient in the large *XMM-Newton* beam. However, if both the radio and X-ray events were randomly produced from two independent processes, then the probability of detecting large radio and X-ray events within a time-scale of the radio outburst Δt_R would be $P = P_R \times P_X < 0.0001 \frac{\Delta t_R^2}{\Delta t_X \Delta t_{\rm sampling}}$. Based on our observations, the time-scale on the radio outburst is well constrained in a range of 1 hour $< \Delta t_R \leq 1$ week. For $\Delta t_R \leq 1$ week, the probability is $< 2\%$. For Δt_R about a few days, a reasonable guess for the time-scale of the radio outburst, then the probability would be 0.1 - 0.3%. Statistically, we have a good confidence to reject the hypothesis that the two events were produced from two independent random processes. The two large events observed at radio and X-ray appeared to be related.

Since the radio outburst component of the 2002-10-03 event had a spectral index of $2.4^{+0.3}_{-0.6}$, it is likely that the large X-ray flare was associated with an optically thick, non-thermal synchrotron component in Sgr A*. With an upper limit of 8 km s^{-1} for the intrinsic proper motion of Sgr A* determined from Very Long Baseline Interferometry (VLBI) measurements, a lower limit on the mass of Sgr A* of 4×10^5 $M_\odot$ (Reid et al., 2003) is placed. This limit along with the compactness of Sgr A* with an intrinsic size of 0.24 mas or $24 r_S$ (Bower et al., 2003) suggests that Sgr A* is very likely associated with the putative supermassive black hole at the Galactic center. If the radio outburst component was confined within $< 24 r_S$ from the black hole, then the X-ray flares must arise from the inner region of the accretion flow near the event horizon of the supermassive black hole rather than from star-star collision (Baganoff et al., 2001) or from the heated part of the disk via star-disk interaction (Nayakshin et al., 2003).

3.2 Radio outburst powered by X-ray flare

A radio outburst observed at 7 mm coinciding in about 0.5 day with the most luminous X-ray flare appeared to show an intimate relation between the two events. The significant variability on a timescale of 200 seconds observed during the X-ray flare indicates that the size of the X-ray emitting region is about $5\mathrm{r_S}$. The observed optically thick non-thermal outburst component was likely produced from a region with a size $> 5\mathrm{r_S}$ as suggested by the following facts.

The lack of significant variation in flux density during the radio observation of the outburst suggests that its variation time scale should be longer than one hour, which is about twenty times greater than the variation timescale of the X-ray flare.

If the outburst component is indeed a self-absorbed non-thermal synchrotron source with a turnover frequency $\nu_m > 43$ GHz, then a peak flux density $\mathrm{S_m} \sim 0.86$ Jy $(\nu_m/43\ \mathrm{GHz})^{2.5}$. The turnover frequency is likely $\nu_\mathrm{m} \sim 300$ GHz (or $\lambda_m \sim 1$ mm) based on previous observations of Sgr A* at submillimeter wavelengths (Zhao et al., 2003; Serabyn et al., 1997). The brightness temperature of the outburst component can be calculated:

$$T_B \approx 3.2 \times 10^{11}\mathrm{K} \left(\frac{\nu_m}{43\ \mathrm{GHz}}\right)^{0.5} \left(\frac{\mathrm{D}}{8\ \mathrm{kpc}}\right)^2 \left(\frac{5\mathrm{r_S}}{\mathrm{d}}\right)^2 \tag{1}$$

where D is the distance to Sgr A* and d is the diameter of the source. The brightness temperature could break the inverse Compton scattering limit for self-absorbed synchrotron source (Readhead, 1994; Sincell & Krolik, 1994) if $\nu_m \sim 300$ GHz and $\mathrm{d} \sim 5\mathrm{r_S}$. If the onset of the radio outburst indeed arose from the X-ray region with a size of $\mathrm{d} \sim 5\mathrm{r_S}$, the outburst component must expand substantially to reach a size of $\mathrm{d} \sim 24\mathrm{r_S}$ as observed with VLBI (Bower et al., 2003) so that a drastic energy loss from the self-synchrotron inverse Compton scattering (SSC) (Falcke & Markoff, 2000) lasted only for a short period, perhaps, of ~ 1 hour as suggested by the duration of the X-ray flare. On the other hand, for a spherical, optically thick synchrotron source, the magnetic field (B) can be estimated from the source angular size ($\theta = \frac{\mathrm{d}}{\mathrm{D}}$), $\mathrm{S_m}$ and ν_m (Marscher, 1983):

$$\begin{aligned} \mathrm{B} &\approx 0.035\ \mathrm{G} \left(\tfrac{8\ \mathrm{kpc}}{\mathrm{D}}\right)^4 \left(\tfrac{\mathrm{d}}{5\mathrm{r_S}}\right)^4 \left(\tfrac{\nu_\mathrm{m}}{43\ \mathrm{GHz}}\right)^5 \left(\tfrac{\mathrm{S_m}}{1\ \mathrm{Jy}}\right)^{-2} \\ &\approx 0.045\ \mathrm{G} \left(\tfrac{8\ \mathrm{kpc}}{\mathrm{D}}\right)^4 \left(\tfrac{\mathrm{d}}{5\mathrm{r_S}}\right)^4 \end{aligned} \tag{2}$$

For $\mathrm{d} \sim 24\mathrm{r_S}$, the typical size of Sgr A* as measured with VLBI at 7 mm, the inferred $\mathrm{B} \sim 24$ G is consistent with the characteristic magnetic field near the black hole as suggested in theory (Liu & Melia, 2002b). For $\mathrm{B} \sim 24$ G, the synchrotron cooling time at 43 GHz of ~ 0.5 d is inferred, which is consistent with our observations of no significant variations in flux density at 7 mm within the observing interval of 1 hour.

Thus, the 7 mm radio outburst was likely produced at a relatively large size scale with respect to the source size of the X-ray flare. Given that the radio outburst was observed about 13.5 hours after the onset of the X-ray flare, it is reasonable to suggest that the electrons producing the radio outburst were energized (Yuan et al., 2003) via a process associated with the X-ray flare and transported to larger radii via a diffusion process (Liu & Melia, 2002a; Zhao et al., 2003) if not a collimated jet (Falcke et al., 1993; Yuan et al., 2002). The correlation between radio spectral index and 7 mm flux density observed with the VLA (Herrnstein et al., 2004) and the frequent X-ray flares observed with *Chandra* (Baganoff et al., 2001; Baganoff, 2003) may also suggest that the non-thermal electrons responsible for the overall radio emission from Sgr A* are probably energized via a similar process.

To justify the above scenario for correlated variation between radio and X-ray emissions, the energetic electrons diffusing outward to a large radii must contain enough energy in order to sustain the radio outburst for a few days. Because the X-ray flare was probably produced via SSC in the model, to avoid drastic inverse Compton losses, the magnetic field energy density must be larger than the photon energy density near the black hole. If the non-thermal electrons were still in energy equipartition with the magnetic field, the energy flux associated with the escaping non-thermal electrons should be larger than the energy flux of the photons. The X-ray luminosity between 2–10 keV during the flare was about 4×10^{35} erg s^{-1}. Given the softness of the X-ray emission, the total X-ray luminosity could be around 10^{36} erg s^{-1}. Thus, the total energy X-ray emission produced during the X-ray flare was about 10^{40} erg. The energy carried by non-thermal electrons during the X-ray flare was then about 10^{40} erg, which could sustain an outburst component of 0.86 Jy at 7 mm for a few days.

4 Conclusions

One of the two strongest radio outbursts observed over the past three years appears to be related to the largest X-ray flare to date which was observed on 2002-10-03. The correlation between the strong emissions at X-ray and radio suggests that the radio outbursts are powered via an electron acceleration process during the X-ray flare. Our observations and analysis are consistent with the hypothesis that the X-ray flare originates from self-synchrotron inverse Compton scattering process close to the event horizon of the supermassive black hole at the Galactic center.

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