The Astrophysical Journal, 603:L85–L88, 2004 March 10

A RADIO OUTBURST NEARLY COINCIDENT WITH THE LARGE X-RAY FLARE FROM SAGITTARIUS A* ON 2002 OCTOBER 3

Jun-Hui Zhao,[1] R. M. Herrnstein,[1,2] G. C. Bower,[3] W. M. Goss,[4] and S. M. Liu[5]
Received 2003 December 17; accepted 2004 January 22; published 2004 February 16

ABSTRACT

A large radio outburst from Sgr A* was observed during the Very Large Array weekly monitoring program at 2 cm, 1.3 cm, and 7 mm, nearly coincident with the brightest X-ray flare detected to date with the *XMM-Newton* X-ray observatory on 2002 October 3. The flux density of 1.9 ± 0.2 Jy measured at 7 mm exceeds the mean value (1.00 ± 0.01 Jy) by a factor of ∼2, one of the two highest increases observed during the past 3 yr (2000 June–2003 October), while less significant increases in flux densities were observed at 1.3 and 2 cm. The radio observation started 13.5 hr after the onset of the X-ray flare (which had occurred over a 45 minute duration) and continued for 1.3 hr. During the observation, there was no significant ($<3\ \sigma$) change in the radio flux densities at all three wavelengths, indicating that the radio outburst varied on a timescale of greater than 1 hr. A spectral index of $\alpha = 2.4^{+0.3}_{-0.6}$ ($S \propto \nu^{\alpha}$) was derived for the outburst component, consistent with an optically thick nonthermal synchrotron source. 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. The observation is the first evidence for a correlated variation in the radio and X-ray emissions from Sgr A*.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — Galaxy: center — radio continuum: galaxies

1. INTRODUCTION

Radio "flares" or outbursts (hereafter) 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, 2003; Wright & Backer 1993; Miyazaki, Tsutsumi, & Tsuboi 1999; Zhao, Bower, & Goss 2001; 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 times (∼1 hr) have been frequently observed from the direction of Sgr A* over the past 2 yr (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 produced owing 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 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 hr for the IR flares (similar to X-ray flares; Genzel et al. 2003).

On 2003 October 3, 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 s, corresponding to an emission region no larger than $5r_{\rm S}$, where $r_{\rm S} = 1.2 \times 10^{12}$ cm is the Schwarzschild radius of the black hole with a mass of $4 \times 10^6\ M_{\odot}$ (Ghez et al. 2003a). Moreover, the flare has a soft photon spectrum with a spectral index of $\Gamma = 2.5 \pm 0.3$, 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 days after the X-ray observation, and a radio outburst was detected at 7 mm. In this Letter, we report detailed properties of the radio outburst on 2002 October 3. The radio observations in the epochs close to the other weaker X-ray flares are also presented.

2. OBSERVATIONS AND CALIBRATIONS

The observations and data reduction for the VLA weekly monitoring program are discussed and reported by Herrnstein et al. (2004). On 2002 October 3, Sgr A* was observed at 2 cm, 1.3 cm, and 7 mm with a total bandwidth of 100 MHz. The total observation time was 2 hr, including observations of the primary calibrator 3C 286 and QSOs 1741−312, 1817−254, and 1730−130 for phase and amplitude corrections. Scans on calibrator 1817−254 were interleaved between Sgr A*'s scans (∼5 minutes each) at the three observing wavelengths. Three scans were made on both Sgr A* and 1817−254 at each wavelength over a period of 1.3 hr.

The absolute flux scale was determined from 3C 286. The final fractional uncertainties from a conservative estimate for the day-to-day variability are 6.1%, 6.2%, and 9.2% at 2 cm, 1.3 cm, and 7 mm, respectively (Herrnstein et al. 2004). The intrahour variability of 1817−254 appeared to be small during the observation on 2002 October 3. Any variation was less than 5% during the 1.3 hr at 7 mm and less than 2% at 2 and 1.3 cm. In addition to measurements on 2002 October 3, measurements of radio flux densities at the three wavelengths cor-

[1] Harvard-Smithsonian Center for Astrophysics, MS 78, 60 Garden Street, Cambridge, MA 02138; jzhao@cfa.harvard.edu.
[2] Department of Astronomy, Columbia University, Mail Code 5246, 550 West 120th Street, New York, NY 10027.
[3] Radio Astronomy Laboratory, University of California at Berkeley, 601 Campbell Hall, Berkeley, CA 94720.
[4] National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.
[5] Center for Space Science and Astrophysics, Stanford University, Stanford, CA 94305-4060.

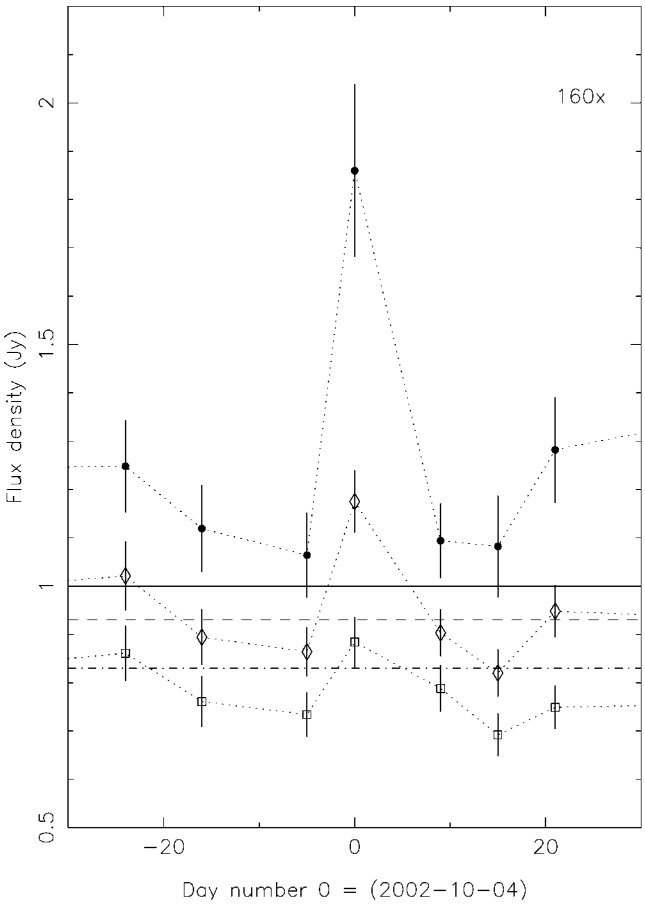

FIG. 1.—Flux density measurements made from the VLA observations at 2 cm (*open squares*), 1.3 cm (*open diamonds*), and 7 mm (*filled circles*) 30 days before and after the 2002 October 3 X-ray flare. The error bars mark the 1 σ uncertainty in the variability measurements. The horizontal solid, dashed, and dash-dotted lines mark the mean values at 7 mm, 1.3 cm, and 2 cm, respectively.

responding to other X-ray events with a change in amplitude by a factor of 20 or greater were also made.

3. RESULTS

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) 1 month before and after the 2002 October 3 X-ray event. The flux density at 7 mm showed at least a 4 σ increase on 2002 October 3. Variations in flux density at 1.3 cm and 2 cm were 3 σ and less than 1 σ, respectively.

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 3 yr (2000 June–2003 October; see Table 1). Therefore, the timescale of the radio outburst at 7 mm must be less than 2 weeks for this event. The X-ray light curve observed with *XMM-Newton* showed a larger flare (160 times; Porquet et al. 2003). The X-ray observation started at UT $7^h18^m8^s$ on 2002 October 3 (D. Porquet 2003, private communication). The X-ray flare onset occurred at UT 10^h5^m and lasted for about 45 minutes. Our VLA observation started on 2002 October 3 at 23^h30^m, about 13.5 hr after the onset of the X-ray flare, and ended on 2002 October 4 at 0^h45^m with three 5 minute scans on Sgr A* and the calibrator. Based on the three measurements averaged on each scan over

TABLE 1
RADIO PROPERTIES OF THE OUTBURST ON 2002 OCTOBER 3

λ (cm) (1)	$\langle S \rangle$ (Jy) (2)	S_t (Jy) (3)	ΔS (Jy) (4)
2.0	0.83 ± 0.01	0.88 ± 0.05	0.05 ± 0.05
1.3	0.93 ± 0.01	1.18 ± 0.06	0.25 ± 0.06
0.7	1.00 ± 0.01	1.86 ± 0.18	0.86 ± 0.18
	α ($S \propto \nu^\alpha$)		
2.0/1.3/0.7	0.20 ± 0.02	0.7 ± 0.1	$2.4^{+0.3}_{-0.6}$

1.3 hr, we found that there were no significant variations in flux density (<3 σ) during the VLA observation at all three observing wavelengths. A timescale for significant change (>3 σ) in radio flux density was likely greater than 1 hr for the radio outburst.

Table 1 summarizes the radio property for the radio outburst corresponding to the X-ray flare on 2002 October 3. The mean radio flux densities of $\langle S \rangle$ (col. [2]) and the total flux densities S_t observed on 2002 October 3 (col. [3]) for the three observing wavelengths are given in columns (2) and (3), respectively. The flux densities for the outburst component ($\Delta S = S_t - \langle S \rangle$) are given in column (4). The spectral index of $\alpha = 0.71 \pm 0.11$ ($S \propto \nu^\alpha$) 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 3 yr (2000 June–2003 October). The increase in the spectral index of the 2002 October 3 event is consistent with the general correlation between spectral index and flux density at 7 mm (Herrnstein et al. 2004). A spectral index of $\alpha \approx 2.4^{+0.3}_{-0.6}$ was derived for the outburst component, which is consistent with an optically thick, nonthermal synchrotron source.

In addition to the 2002 October 3 X-ray event, Figure 2 shows a fraction of radio light curves covering a period ±30 days for each of the other three X-ray flares (a factor of 20 greater than a quiescent level) detected in the past 3 yr.

For the 2000 October 27 X-ray flare observed with *Chandra* (Baganoff et al. 2001), the peak X-ray flux was a factor of 45 greater than the quiescent level. Radio observations made 3 days before and 4 days after the X-ray event showed no significant increase in radio flux density measured in the two epochs close to this large X-ray event. However, the flux densities measured 9 days after the X-ray event showed ~3 σ increase in the radio flux densities at 2 and 1.3 cm and ~2 σ at 7 mm.

For the 2001 September 4 event, the beginning phase of this X-ray flare was observed with *XMM-Newton* (Goldwurm et al. 2003); the amplitude of this flare was a factor of 20 greater than the quiescent level. There were two observations at radio wavelengths carried out 3 and 4 days before the X-ray event. The flux densities were 2–3 σ higher than the mean flux density at all the three observing wavelengths. The flux densities measured 5 days after the X-ray event appeared to be consistent with the mean flux densities.

During 2002 May, there was a multiwavelength campaign that coincided with 100 hr of *Chandra* observations. During that period, the *Chandra* observations showed that flares with a factor of 5 greater in amplitude occur once every day and larger flares with a factor of 10 greater occur once every 2 days (Baganoff 2003). A large flare (20 times) occurred on 2002 May 29. However, the radio measurements made 3 days before and 4 days after the 2002 May 29 event showed no significant variations in flux density. There were also no significant variations observed at 7, 3, and 1.3 mm using the Very Long Baseline Array, the Australia Telescope Compact Array, and the Submillimeter

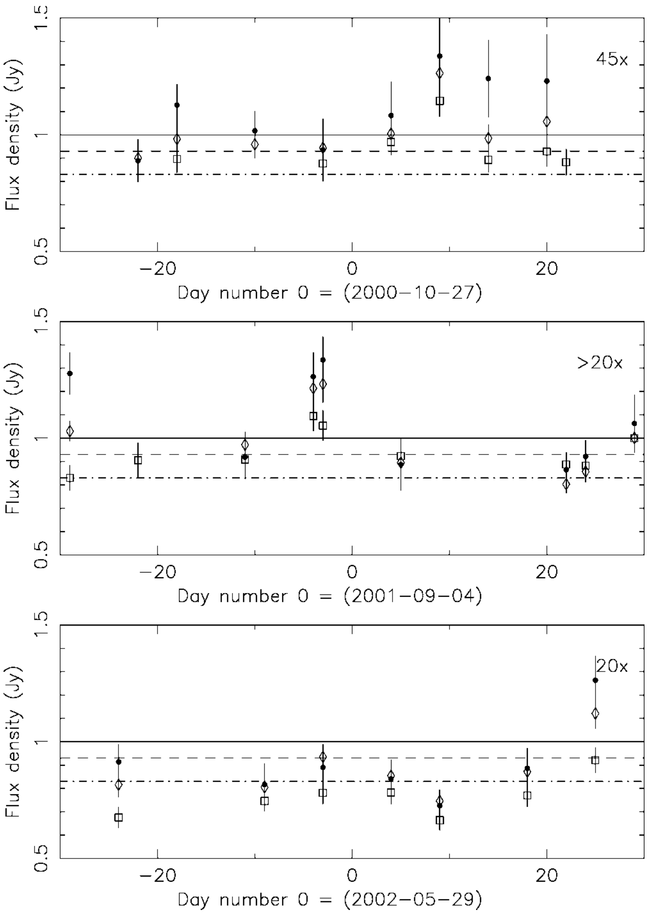

FIG. 2.—Flux density measurements made from the VLA observations at 2 cm (*open squares*), 1.3 cm (*open diamonds*), and 7 mm (*filled circles*) 30 days before and after the three X-ray flares detected on 2000 October 27 (*t op*), 2001 September 4 (*middle*), and 2002 May 29 (*bottom*). The solid, dashed, and dash-dotted lines mark the mean values at 7 mm, 1.3 cm, and 2 cm, respectively. The X-ray flares were observed with peak flux a factor of 20 greater than the value of the quiescent state. The error bars mark the 1 σ uncertainty in the variability measurements. The origin of the horizontal axis corresponds to the date of each X-ray flare.

Array, respectively, in response to these multiple small X-ray flares (Baganoff 2003).

The lack of correlation in radio flux density at wavelengths ranging from 2 cm to 7 mm with the weaker X-ray flares has been puzzling. The weekly VLA monitoring program appeared to be not sensitive to the weaker X-ray flares. However, the large X-ray flare on 2002 October 3 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 detected only two large (2 times) radio outbursts at 7 mm from observations of 121 epochs weekly sampled over the past 3 yr period between 2000 June and 2003 October, the probability of detecting such a large (2 times) radio outburst within a time interval of Δt appears to be $P_R \sim 0.01\Delta t/\Delta t_{\rm sampling}$, where $\Delta t_{\rm sampling} \sim 1$ week, the radio sampling interval. On the other hand, during the past 3 yr overlapping with the period of the VLA monitoring program, observations of a few hundred hours were carried out at X-ray wavelengths with both *Chandra* and *XMM-Newton* to search for X-ray flares, but to date only one large (160 times) X-ray flare has been detected. Considering the typical duration of $\Delta t_{\rm X} \sim 1$ hr for the X-flares, the detection probability of a large flare (160 times) within Δt appears to be $P_{\rm X} < 0.01\Delta t/\Delta t_{\rm X}$. A large uncertainty in the estimate of $P_{\rm X}$ is due to the sparse observations at X-ray wavelengths and a large chance of having 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 timescale of the radio outburst Δt_R would be $P = P_R P_{\rm X} < 0.0001\Delta t_R^2/\Delta t_{\rm X}\Delta t_{\rm sampling}$. Based on our observations, the timescale on the radio outburst is well constrained in a range of 1 hr $< \Delta t_R \leq 1$ week. For $\Delta t_R \leq 1$ week, the probability is less than 2%. For $\Delta t_R \sim$ a few days, a reasonable guess for the timescale of the radio outburst, the probability would be 0.1%–0.3%. Statistically, we have a good enough 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 wavelengths appeared to be related.

Since the radio outburst component of the 2002 October 3 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, nonthermal synchrotron component in Sgr A*. With an upper limit of 8 km s^{-1} for the intrinsic proper motion of Sgr A* determined from VLBI measurements, a lower limit on the mass of Sgr A* of $4 \times 10^5\ M_\odot$ (Reid et al. 2004) is placed. This limit, along with the compactness of Sgr A* with an intrinsic size of 0.24 mas or $24 r_{\rm S}$ (Bower et al. 2004), 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 less than $24 r_{\rm S}$ 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, Cuadra, & Sunyaev 2004).

4. DISCUSSION

A radio outburst observed at 7 mm coinciding in about 0.5 days 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 s observed during the X-ray flare indicates that the size of the X-ray–emitting region is about $5r_{\rm S}$. The observed optically thick nonthermal outburst component was likely produced from a region with a size greater than $5r_{\rm S}$, 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 timescale should be longer than 1 hr, which is about 20 times greater than the variation timescale of the X-ray flare.

If the outburst component is indeed a self-absorbed nonthermal synchrotron source with a turnover frequency $\nu_m >$ 43 GHz, then a peak flux density $S_m \sim 0.86$ Jy$(\nu_m/43\ \mathrm{GHz})^{2.5}$. The turnover frequency is likely $\nu_m \sim 300$ 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:

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

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 a self-absorbed synchrotron source (Readhead 1994; Sincell & Krolik 1994) if $\nu_m \sim 300$ GHz and $d \sim 5r_{\rm S}$. If the onset of the radio outburst indeed arose from the X-ray region with a size of $d \sim 5r_S$, the outburst component must expand substantially to reach a size of $d \sim 24r_S$ as observed with VLBI (Bower et al. 2004) 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 hr 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 ($\theta = d/D$), S_m, and ν_m (Marscher 1983):

$$B \approx 0.035\ \mathrm{G} \left(\frac{8\ \mathrm{kpc}}{D}\right)^4 \left(\frac{d}{5r_S}\right)^4 \left(\frac{\nu_m}{43\ \mathrm{GHz}}\right)^5 \left(\frac{S_m}{1\ \mathrm{Jy}}\right)^{-2}$$

$$\approx 0.045\ \mathrm{G} \left(\frac{8\ \mathrm{kpc}}{D}\right)^4 \left(\frac{d}{5r_S}\right)^4. \quad (2)$$

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

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 hr after the onset of the X-ray flare, it is reasonable to suggest that the electrons producing the radio outburst were energized (Yuan, Quataert, & Narayan 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, Mannheim, & Biermann 1993; Yuan, Markoff, & Falcke 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 nonthermal 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 nonthermal electrons were still in energy equipartition with the magnetic field, the energy flux associated with the escaping nonthermal electrons should be larger than the energy flux of the photons. The X-ray luminosity between 2 and 10 keV during the flare was about 4×10^{35} ergs s^{-1}. Given the softness of the X-ray emission, the total X-ray luminosity could be around 10^{36} ergs s^{-1}. Thus, the total energy X-ray emission produced during the X-ray flare was about 10^{40} ergs. The energy carried by nonthermal electrons during the X-ray flare was then about 10^{40} ergs, which could sustain an outburst component of 0.86 Jy at 7 mm for a few days.

5. CONCLUSIONS

One of the two strongest radio outbursts observed over the past 3 yr appears to be related to the largest X-ray flare to date, which was observed on 2002 October 3. The correlation between the strong emissions at X-ray and radio wavelengths 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 the SSC process close to the supermassive black hole at the Galactic center.

We thank Delphine Porquet and Fulvio Melia for their communication and X-ray data. The VLA is operated by the NRAO. The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Baganoff, F. K. 2003, AAS HEAD Meeting, 35, 03.02
Baganoff, F. K., et al. 2001, Nature, 413, 45
Bower, G. C., Falcke, H., Herrnstein, R. M., Zhao, J.-H., Goss, W. M., & Backer, D. C. 2004, Science, submitted
Bower, G. C., Falcke, H., Sault, R., & Backer, D. C. 2002, ApJ, 571, 843
Falcke, H., Mannheim, K., & Biermann, P. L. 1993, A&A, 278, L1
Falcke, H., & Markoff, S. 2000, A&A, 362, 113
Genzel, R., Schödel, R., Ott, T., Eckart, A., Alexander, T., Lacombe, F., Rouan, D., & Aschenbach, B. 2003, Nature, 425, 934
Ghez, A. M., et al. 2003a, ApJ, 586, L127
———. 2003b, preprint (astro-ph/0309076)
Goldwurm, A., et al. 2003, ApJ, 584, 751
Herrnstein, R. M., Zhao, J.-H., Bower, G. C., & Goss, W. M. 2004, AJ, submitted
Liu, S., & Melia, F. 2002a, ApJ, 566, L77
———. 2002b, ApJ, 573, L23
Marscher, A. P. 1983, ApJ, 264, 296
Miyazaki, A., Tsutsumi, T., & Tsuboi, M. 1999, Adv. Space Res., 23, 977
Nayakshin, S., Cuadra, J., & Sunyaev, R. 2004, A&A, 413, 173
Porquet, D., Predehl, P., Aschenbach, B., Grosso, N., Goldwurm, A., Goldoni, P., Warwick, R. S., & Decourchelle, A. 2003, A&A, 407, L17
Readhead, A. C. S. 1994, ApJ, 426, 51
Reid, M. J., Menten, K. M., Genzel, R., Ott, T., Schödel, R., & Brunthaler, A. 2004, Astron. Nachr., in press
Serabyn, E., Carlstrom, J., Lay, O., Lis, D. C., Hunter, T. R., & Lacy, J. H. 1997, ApJ, 490, L77
Sincell, M. W., & Krolik, J. H. 1994, ApJ, 430, 550
Wright, M., & Backer, D. 1993, ApJ, 417, 560
Yuan, F., Markoff, S., & Falcke, H. 2002, A&A, 383, 854
Yuan, F., Quataert, E., & Narayan, R. 2003, ApJ, 598, 301
Zhao, J.-H., Bower, G. C., & Goss, W. M. 2001, ApJ, 547, L29
Zhao, J.-H., Goss, W. M., Lo, K. Y., & Ekers, R. D. 1992, in ASP Conf Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 295
Zhao, J.-H., Young, K. H., Herrnstein, R. M., Ho, P. T. P., Tsutsumi, T., Lo, K. Y., Goss, W. M., & Bower, G. C. 2003, ApJ, 586, L29