

RADIO VARIABILITY OF SAGITTARIUS A*—A 106 DAY CYCLE

JUN-HUI ZHAO,¹ G. C. BOWER,² AND W. M. GOSS²

Received 2000 July 20; accepted 2000 November 3; published 2001 January 17

ABSTRACT

We report the presence of a 106 day cycle in the radio variability of Sagittarius A* based on an analysis of data observed with the Very Large Array over the past 20 years. The pulsed signal is most clearly seen at 1.3 cm with a ratio of cycle frequency to frequency width $f/\Delta f = 2.2 \pm 0.3$. The periodic signal is also clearly observed at 2 cm. At 3.6 cm the detection of a periodic signal is marginal. No significant periodicity is detected at both 6 and 20 cm. Since the sampling function is irregular, we performed a number of tests to ensure that the observed periodicity is not the result of noise. Similar results were found for a maximum entropy method and a periodogram with a CLEAN method. The probability of false detection for several different noise distributions is less than 5% based on Monte Carlo tests. The radio properties of the pulsed component at 1.3 cm are a spectral index $\alpha \sim 1.0 \pm 0.1$ (for $S \propto \nu^\alpha$), an amplitude $\Delta S = 0.42 \pm 0.04$ Jy, and a characteristic timescale $\Delta t_{\text{FWHM}} \approx 25 \pm 5$ days. The lack of a VLBI detection of a secondary component suggests that the variability occurs within Sgr A* on a scale of ~ 5 AU, suggesting an instability of the accretion disk.

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

On-line material: color figures

1. INTRODUCTION

The compact radio source Sagittarius A* is suggested to be associated with a supermassive black hole at the Galactic center (Eckart & Genzel 1997; Ghez et al. 1998; Backer & Sramek 1999; Reid et al. 1999). The flux density variability of Sgr A* has been puzzling since the discovery of this intriguing radio compact source at the center of the Galaxy in 1974 (Brown & Lo 1982; Zhao et al. 1989). We monitored Sgr A* with the Very Large Array (VLA) during the period of 1990–1993. Fluctuations in flux density suggested that the amplitude of variation increased toward short wavelengths and that the rate of outbursts is about three per year (Zhao et al. 1992; Zhao & Goss 1993). Large-amplitude fluctuations in the flux density have been observed at millimeter wavelengths (Wright & Backer 1993; Tsuboi, Miyazaki, & Tsutsumi 1999). Based on the radio-monitoring data obtained with the 3.5 km Green Bank Interferometer (GBI) at 11 and 3.6 cm, Falcke (1999) reported that at both wavelengths a characteristic timescale of 50–200 days is observed while the structure function of 11 cm data suggests a quasi-periodic variation with a period of 57 days.

2. OBSERVATIONS AND DATA REDUCTION

Regular observations were made during 1990.1–1991.5 with various sampling intervals in a range from 1 day to 28 days at 3.6, 2, and 1.3 cm in the A, B, C, D, and hybrid configurations of the VLA. Less regular observations at the same frequencies were made at the same frequencies between 1991.5 and 1993.5. The largest gap between observations in these data was 120 days. In addition to these regularly sampled data from 1990 to 1993 discussed previously by Zhao et al. (1992), we have collected all the observations of Sgr A* at 20, 6, 3.6, 2, and 1.3 cm from the VLA archive for the past two decades. We accepted only the observations with baselines long enough (>80 k λ) to separate

Sgr A* from the extended H II emission. This limit corresponds to a 3'' resolution.

The primary flux density calibration was performed in the standard way using 3C 48 or 3C 286. The flux density scale was then bootstrapped to one of several nearby compact radio sources, typically J1733–130, J1744–312, or J1751–253. Most of the flux densities presented in this Letter were determined in the visibility domain, from the long baseline data. In a few cases in which the length of baselines was marginal in separating the point source in the visibility domain, we determined the flux densities of Sgr A* in the image plane. Then the flux density of Sgr A* was measured by subtracting the confusion from the extended emission. In the cases in which the telescope pointing was offset from Sgr A*, both the primary-beam and synthesis-beam effects are corrected.

Figure 1 shows the radio light curves at the five wavelengths for Sgr A*. At all wavelengths, determination of the absolute flux density scale dominates the errors. There are also contributions due to the thermal noise, separation from the extended H II region Sgr A west for low angular resolution data, and uncertainty in the atmospheric opacity at 2 and 1.3 cm. Uncertainty at long wavelengths is less than 5%. For long tracks, this uncertainty can be minimized by removing the attenuation of the gain as a function of elevation. The correction for this effect is no more than 10% at 1.3 cm based on several observations with an 8 hr tracking time. Most of the observations used in this Letter were in a snapshot mode (10–20 minutes in integration). For these short observations, we can assess the uncertainty based on observations of the stable, nearby (4° away from Sgr A*) calibrator J1751–253 (Fig. 1, *right panels*). The 7% fluctuation of the flux density at 1.3 cm for J1751–253 reflects the uncertainty in the calibration.

3. DATA ANALYSIS AND RESULTS

3.1. Power Spectrum and a Period of 106 Days

We carried out a power spectral density (PSD) analysis of the light curves in order to identify periodic signals. With a simple Fourier analysis, the irregular sampling of the VLA archive data

¹ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 78, Cambridge, MA 02138; jzhao@cfa.harvard.edu.

² National Radio Astronomy Observatory, New Mexico Array Operations Center, P.O. Box 0, 1003 Lopezville Road, Socorro, NM 87801; gbower@nrao.edu, mgoss@nrao.edu.

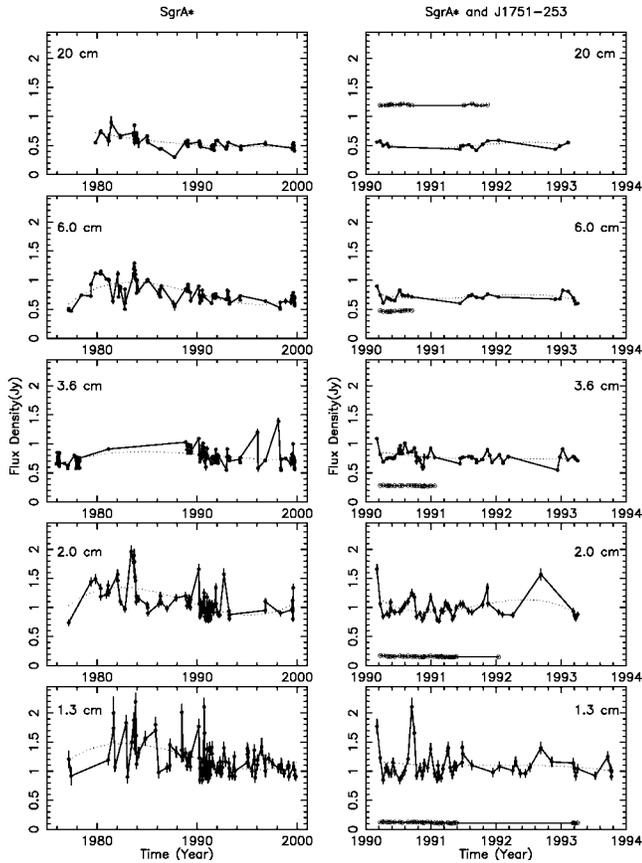


FIG. 1.—*Left panels:* Radio light curves of Sgr A* observed with the VLA at 20, 6, 3.6, 2, and 1.3 cm over the past two decades. The solid lines connect two successive data points (*filled circles*). The vertical error bar indicates 1σ . The dotted curves indicate the third-order polynomial baselines that are removed from the data prior to the periodic analysis as discussed in Table 1 and Figs. 2 and 3. *Right panels:* Radio light curves of Sgr A* (*filled circles*) and a calibrator J1751–253 (*open circles*) observed during 1990–1993. The calibrator J1751–253 is a compact (less than $0''.1$), steep spectrum source. The flux density of J1751–253 was stable in this period as compared with those of Sgr A*. The mean flux density and standard deviation ($S \pm \delta S$) are 1.20 ± 0.01 , 0.470 ± 0.009 , 0.278 ± 0.005 , 0.157 ± 0.007 , and 0.116 ± 0.008 Jy for J1751–253 and 0.513 ± 0.049 , 0.710 ± 0.072 , 0.783 ± 0.099 , 0.99 ± 0.18 , and 1.10 ± 0.23 Jy at 20, 6, 3.6, 2, and 1.3 cm for Sgr A*, respectively, during this period. [See the electronic edition of the Journal for a color version of this figure.]

produces strong sidelobes, leading to confusion in the identification of spectral features. In addition, large gaps in the sampling can produce an alias of a periodic signal to lower frequency lags, weakening the power of the true signal and producing aliased signals. To minimize the sidelobes, we estimated the PSD with the maximum entropy method (MEM; Press et al. 1989) and with a classic periodogram augmented with CLEAN. The results from both approaches are completely consistent.

In order to overcome the aliasing problem due to large gaps in time, we used the following procedure. This procedure determines the period from a well-sampled but small data set, folds

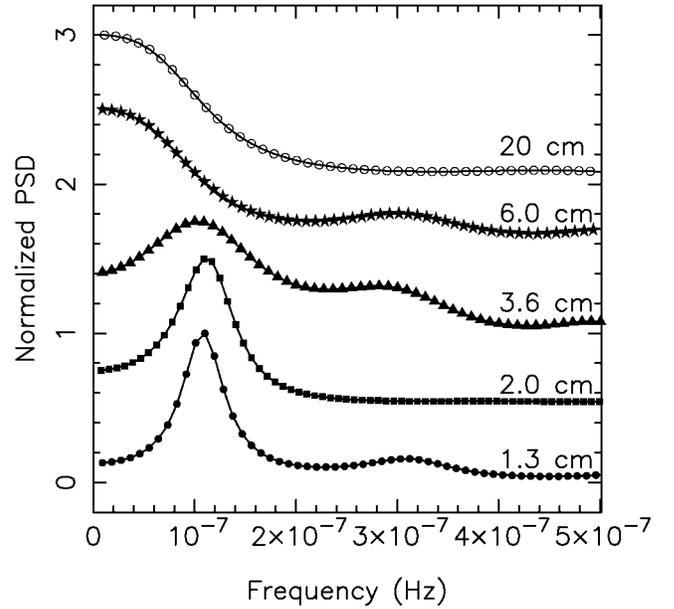


FIG. 2.—PSD profiles derived from all the data folded into 6 cycles of the period 106 days at each wavelength. Each profile along the vertical axis is normalized by its peak value and is modified by adding 0, 0.5, 1.5, and 2.0 at 1.3, 2, 3.6, 6, and 20 cm, respectively. A peak near 1×10^{-7} Hz is clearly detected at 1.3–2 cm, while the detection at 3.6 cm is marginal ($<3\sigma$). The width of the spectral feature increases as the wavelength increases. No significant periodicities from the 20 and 6 cm data were detected.

an irregularly sampled but larger data set with that period, and then searches for a new period. We considered three subsets of the full light curves: 1990–1991, 1990–1993, and 1977–1999 (i.e., the full set). We removed a third-order polynomial from each of these data sets. This baseline represents slow variations in the flux density of Sgr A*. In the 1990–1991 subset, the maximum sampling gap (28 days) corresponds to the Nyquist critical frequency of $f_c = 2.1 \times 10^{-7}$ Hz. Using the zero-leveled subset 1990–1991, we calculated a PSD profile. At 1.3 cm, we found a spectral peak at the frequency $f = 1.07 \times 10^{-7}$ Hz, corresponding to a period $P = 107$ days. This frequency is well within the range of the Nyquist critical frequency.

To verify the periodic signals, we examined the 1990–1993 and 1977–1999 subsets folded into N_{cyc} cycles of period P_{in} . The 1990–1993 subset consists of 59 observations during the period 1990.1–1993.8, containing $\sim \frac{1}{2}$ of the total data points in 1977–1999. The maximum gaps in the sampling are 120 and 1350 days for the subsets 1990–1993 and 1977–1999, respectively. The number N_{cyc} is chosen as the largest number such that the maximum sampling gap (Δt_{max}) in the new folded time series is smaller than half the value of the period. Taking the new folded time series of these subsets, we calculate PSD profiles. Table 1 and Figure 2 summarize the results. The peak frequencies (f) derived from these three data sets are consistent, with a mean value of 1.09×10^{-7} Hz. The uncertainty $\sigma_f \sim$

TABLE 1
THE RESULTS OF POWER SPECTRAL FITTING FOR SGR A*

λ (cm)	$f(\sigma_f)$ ($\times 10^{-7}$ Hz)	$\Delta f(\sigma_{\Delta f})$ ($\times 10^{-7}$ Hz)	$f/\Delta f(\sigma_{f/\Delta f})$	$P(\sigma_p)$ (days)	$\Delta S(\sigma_{\Delta S})$ (Jy)	$\Delta S/S(\sigma_{\Delta S/S})$ (%)	$\Delta t(\sigma_{\Delta t})$ (days)
1.3	1.09 (0.03)	0.50 (0.07)	2.2 (0.3)	106 (3)	0.42 (0.04)	34 (9)	25 (5)
2.0	1.12 (0.10)	0.80 (0.12)	1.0 (0.2)	104 (9)	0.28 (0.02)	25 (6)	40 (10)
3.6	1.10 (0.01)	>3	<0.4	106 (1)	0.16 (0.01)	20 (4)	~ 100

3×10^{-9} Hz (3 days) of the peak frequency is estimated from the maximum deviation of the peak frequencies derived from the three data subsets. The FWHM (Δf) of the PSD feature is 9×10^{-8} Hz derived from both 1990–1991 and 1990–1993 subsets. For the 1977–1999 subset, the FWHM is reduced by a factor of 2 ($\Delta f = 5 \times 10^{-8}$ Hz). The uncertainty of the FWHM is $\sim 15\%$. The ratio of $f/\Delta f$ is $\sim 2.2 \pm 0.3$.

For the 2 cm data, we followed the same procedure. The mean peak frequency is consistent with the result obtained from the 1.3 cm data. The power spectral feature derived from all the data at 2 cm appears to be broadened by a factor of ~ 2 as compared with that at 1.3 cm. The ratio of $f/\Delta f$ is $\sim 1.0 \pm 0.2$ at 2 cm.

At 3.6, 6, and 20 cm, we folded the data with a period of 106 days. We used two subsets of the data for the 3.6 cm data, 1990–1993 and 1988–1999, and the whole data set for the 6 and 20 cm data. At 3.6 cm, a spectral feature with a period of 106 days is marginally detected. This feature has a ratio of peak frequency to width $f/\Delta f < 0.4$. No significant features are detected in the 6 and 20 cm data.

Using the procedure discussed above, we also folded the 1.3 cm data into a number of cycles with a small period in order to check if the PSD feature observed is an aliased signal from a higher frequency periodic variation. We have checked the periods ranging from 1 to 56 days that are outside the highest Nyquist frequency $f_c = 2.1 \times 10^{-7}$ Hz provided by the VLA observations. No spectral features from the folded data sets are stronger or narrower than the 1×10^{-7} Hz feature. No periodic signals from the calibrator J1751–253 are found, confirming that the periodic variation is not caused by calibration errors.

There is a probability that the periodic signal discussed above could be a false detection due to a combination of a random process and the irregular sampling function. To provide a quantitative estimate, we have carried out Monte Carlo tests with data sets created from various noise sources using the sampling function of the real data and the procedure outlined above. Our noise functions included white noise, Gaussian noise around a mean, and a Poisson distribution of flares. These flares were modeled as δ -function rises in flux density that occurred with a probability p and decayed with an exponential time constant t_d . We searched the ranges $0.001 < p < 0.27$ and $1 \text{ day} < t_d < 90$ days. We also considered sets of data in which we reordered (or scrambled) the actual measured flux densities. This test assumes no knowledge of the parent distribution of the flux density. Based on the 1990–1993 data at 1.3 cm, we find that the probability of false detection due to a random process is less than 5% for all of these cases. False detection occurs when the ratio $f/\Delta f$ of the noise data set exceeds that of the true data set with the same sampling function.

3.2. The Mean Profiles of the 106 Day Cycle

Figure 3 shows the mean profiles of the 106 day cycle constructed by folding the time series data (1990.1–1993.8) into a 106 day period. Again, the long-term baselines were removed before folding. The zero levels reflect the mean flux densities of Sgr A* as listed in the caption to Figure 1. The 0 phase in the plots corresponds to a reference day (1991 December 4). Because of the uncertainty in period (3% from the 1.3 cm data), the phase uncertainty for folding long time baseline data becomes large. The maximum uncertainty of the phase in the mean profile for the period 1990.1–1993.8 is ~ 20 days. The radio properties of the 106 day cycle are summarized in Table 1. Both the absolute (ΔS) and fractional ($\Delta S/S$) amplitudes of the “pulsed” component appear to increase toward short wavelengths. The mean spectral

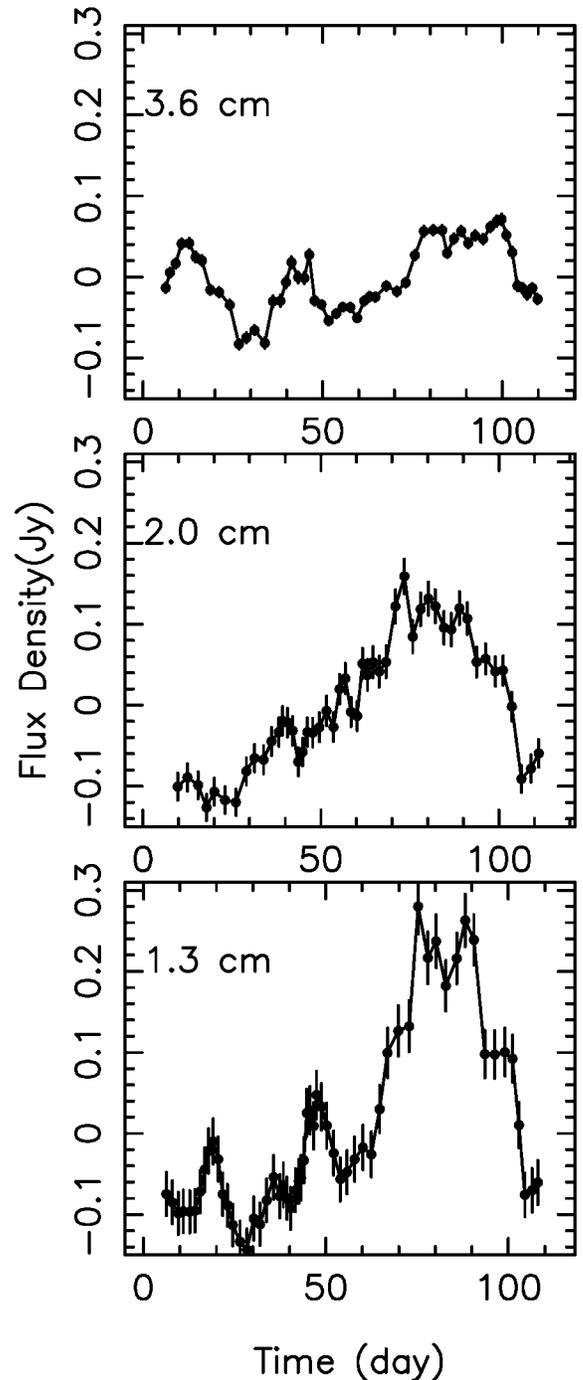


FIG. 3.—Mean profiles of the 106 day cycle at 3.6, 2, and 1.3 cm obtained by folding the data obtained during 1990.1–1993.8 (Fig. 1, right panels) into one single cycle. The profiles are smoothed. The mean spectral index of the pulsed components is about $\alpha \sim 1$ ($\Delta S \propto \nu^\alpha$). The long-term baseline (the third-order polynomial) has been taken out in the PSD-fitting and cycle-folding processes. The zero levels here reflect the mean flux densities of Sgr A* as listed in the caption to Fig. 1. [See the electronic edition of the Journal for a color version of this figure.]

index in the pulsed component is $\alpha \approx 1.0 \pm 0.1$ ($S \propto \nu^\alpha$). The phase transition from minimum to maximum appears to be sharper at 1.3 cm than at 2 cm, although we could not observe any significant phase offsets. The FWHM ($\Delta t \pm \sigma_{\Delta t}$) of the mean profile is roughly 25 ± 5 and 40 ± 10 days for 1.3 and 2 cm, respectively. There are multiple peaks in the 3.6 cm profile indicating

the typical timescale (Δt) of individual periodic events is comparable to the period (106 days) at this wavelength. In addition, the FWHM of the periodic feature increases as the wavelength increases, as shown in Figure 2. The periodic fluctuation appears to diminish at the longer wavelengths.

4. DISCUSSION

If the 106 day cycle is related to an orbital emitting object around the massive black hole, its distance to the central mass would be $1200 \times R_g$ (60 AU), where $R_g = 7.5 \times 10^{11}$ cm for $2.5 \times 10^6 M_\odot$. At a distance of 8 kpc, 60 AU corresponds to 8 mas. A 200 mJy compact object separated by 8 mas from Sgr A* is easily detected with the Very Long Baseline Array at wavelengths shorter than 3.6 cm. There is no evidence for a companion source in images of Sgr A* at any wavelength (e.g., Bower & Backer 1998). We can also demonstrate the unlikelihood of the specific case of an eccentric binary pair in which a wind from the secondary eclipses the primary as in the case for the pulsar PSR 1259–63 (Johnson et al. 1992). The opacity of free-free absorption $\tau_{\text{ff}} \sim \lambda^{-2.1}$ suggests that the periodic variability due to an orbiting body would be enhanced at longer wavelengths. At $\lambda \geq 6$ cm, Sgr A* would be completely absorbed in the eclipsed phase if $\tau \sim 0.5$, as inferred from the fraction of 40% in the flux density variation at 1.3 cm. Thus, the periodic variability is more likely intrinsic to Sgr A* and probably occurs within a few hundred R_g of the massive black hole.

Quasi-periodic variability in the radio flux density can be produced through jets or collimated flows. With a wealth of data observed at wavelengths between radio and X-ray, the microquasar GRS 1915+105 provides an excellent case showing two distinct states (“plateau” and “flare”) of the accretion process in a stellar mass black hole (Mirabel & Rodríguez 1999; Dhawan, Mirabel, & Rodríguez 2000). The current state of Sgr A* is similar to the plateau state of GRS 1915+105 in terms of a flat radio spectrum, a compact source size (AU scale), and periodic variability in the radio flux density. This state can be contrasted to the flare state, which is characterized by optically thin ejecta feeding large-scale jets (500 AU). The radio variability as correlated with the soft X-ray cycle in the plateau state of GRS 1915+105 suggests that the radio oscillations correspond to the thermal-viscous instability of the accretion disk (Dhawan et al. 2000). The analog of the radio fluctuations in the two sources suggests that the periodic flux density variations in Sgr A* are also related to an instability in the accretion disk. However, the

X-ray luminosity ($\sim 2 \times 10^6 L_\odot$) of GRS 1915+105 is 20 times greater than the Eddington limit for a $3 M_\odot$ black hole (Mirabel & Rodríguez 1999), and the radio jets are produced by the overwhelming radiation pressure. On the other hand, the low X-ray luminosity ($< 100 L_\odot$, ~ 10 orders of magnitude below the Eddington limit for a $2.5 \times 10^6 M_\odot$ object) of Sgr A* indicates that the gravity far exceeds the radiation pressure. Because of the strong gravity and weak radiation pressure, the consequence of the gasdynamics in Sgr A* on the AU scales would be different from GRS 1915+105. In fact, the time variability and the limit on the intrinsic source size (< 0.5 mas or $100 R_g$ or 5 AU) of Sgr A* from the 7 mm observations (Lo et al. 1998; Bower & Backer 1998) suggest that any variability in the jet occurs in a region where the gravitational field of the black hole dominates. Any collimations of jets or outflows related to the observed radio variability appear to be disrupted within Sgr A* on a scale of ~ 5 AU. A model consisting of a jet nozzle (e.g., Falcke 1996) seems useful for studying whether a self-consistent dynamic theory for the disk instability can be constructed.

A convection process is now considered in the advection-dominated accretion flow (ADAF) that could well provide a reasonable dynamic model for the accretion disk and possible outflows (Narayan, Igumenshchev, & Abramowicz 2000; Quataert & Gruzinov 2000; Igumenshchev & Abramowicz 1999; Stone, Pringle, & Begelman 1999). In this theory, hot dense bubbles are produced in the inner part of a low-viscosity disk through convection caused by thermal instability. The most attractive result from the convective-ADAF theory is that quasi-periodic production of convective bubbles has been observed in numerical simulations, although the observed period and the small cycle frequency width have not been predicted in detail from the theory (Igumenshchev & Abramowicz 1999). The current results appear to favor the convective-ADAF model, although we cannot rule out the possibilities of an orbiting companion object that triggers periodic flares from a jet nozzle.

We thank Ramesh Narayan for his stimulating discussions concerning the convective-ADAF model and Ron Ekers for his helpful discussion and his initial suggestion of the VLA monitoring program in 1980. We thank Don Backer for helpful discussions and Heino Falcke for sharing recent data from the GBI. The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

- Backer, D. C., & Sramek, R. A. 1999, *ApJ*, 524, 805
 Bower, G. C., & Backer, D. C. 1998, *ApJ*, 496, L97
 Brown, R. L., & Lo, K. Y. 1982, *ApJ*, 253, 108
 Dhawan, V., Mirabel, I. F., & Rodríguez, L. F. 2000, *ApJ*, 543, 373
 Eckart, A., & Genzel, R. 1997, *MNRAS*, 284, 576
 Falcke, H. 1996, in *IAU Symp. 169, Unsolved Problems of the Milky Way*, ed. L. Blitz & P. Teuben (Dordrecht: Kluwer), 163
 ———. 1999, in *ASP Conf. Ser. 186, The Central Parsecs of the Galaxy*, ed. H. Falcke, A. Cotera, W. J. Duschl, F. Melia, & M. J. Rieke (San Francisco: ASP), 113
 Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, *ApJ*, 509, 678
 Igumenshchev, I. V., & Abramowicz, M. A. 1999, *MNRAS*, 303, 309
 Johnston, S., Manchester, R. N., Lyne, A. G., Bailies, M., Kaspi, V. M., Qiao, G., & D’Amico, N. 1992, *ApJ*, 387, L37
 Lo, K. Y., Shen, Z., Zhao, J.-H., & Ho, P. 1998, *ApJ*, 508, L61
 Mirabel, I. F., & Rodríguez, L. F. 1999, *ARA&A*, 37, 409
 Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, *ApJ*, 539, 798
 Press, W. H., Plannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1988, *Numerical Recipes* (Cambridge: Cambridge Univ. Press)
 Quataert, E., & Gruzinov, A. 2000, *ApJ*, 539, 809
 Reid, M. J., Readhead, A. C. S., Vermeulen, R. C., & Treuhaft, R. N. 1999, *ApJ*, 524, 816
 Stone, J. M., Pringle, J. E., & Begelman, M. C. 1999, *MNRAS*, 310, 1002
 Tsuboi, M., Miyazaki, A., & Tsutsumi, T. 1999, *ASP Conf. Ser. 186, The Central Parsecs of the Galaxy*, ed. H. Falcke, A. Cotera, W. J. Duschl, F. Melia, & M. J. Rieke (San Francisco: ASP), 105
 Wright, M. C. H., & Backer, D. C. 1993, *ApJ*, 417, 560
 Zhao, J.-H., Ekers, R. D., Goss, W. M., Lo, K. Y., & Narayan, R. 1989, *IAU Symp. 136, The Center of the Galaxy*, ed. M. Morris (Dordrecht: Kluwer), 535
 Zhao, J.-H., & Goss, W. M. 1993, *Sub-Arcsecond Radio Astronomy*, ed. R. J. Davis & R. S. Booth (Cambridge: Cambridge Univ. Press), 38
 Zhao, J.-H., Goss, W. M., Lo, K. Y., & Ekers, R. D. 1992, *ASP Conf. Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies*, ed. A. V. Filippenko (San Francisco: ASP), 295