Radio Variability of the Supermassive Black Hole at Galactic Center:

Double Quasi-Periodic Oscillation in Radio Flux Density and Flares at 1 Millimeter Wavelength

Jun-Hui Zhao

(*Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 78, MA 02138, USA*)

ABSTRACT With the densely sampled light curves observed with the Very Large Array (VLA) over the past two years, we have confirmed the previous finding of the periodic signals with a period of 100 d from the VLA archival data. In addition, we have found an additional periodic signal with a period of 2.4-2.5 times longer than the short period, revealing the nature of double periodic oscillation in flux density of Sgr A*. Our observations also suggest that the individual oscillation periods of the double features are drifting in time while the ratio of the periods appears to remain in a constant. The double periodic oscillation of Sgr A* suggests that a dynamic system consisting of a supermassive black hole, an accretion flow, and an orbiting object is subject to an orbital resonance which may periodically trigger central activities. The observed drifts in the periods suggest that this dynamic system (or the Sgr A* system) must have been substantially disturbed by a nearby gravitational source.

With the partially finished Sub-millimeter Array on Mauna Kea, a total of 25 epochs of observations were carried out over the past 15 months. Noticeable variations in flux density at 1.3 mm were observed showing three "flares". The SMA observations suggest that Sgr A* is highly peaked towards sub-millimeter wavelengths during a flare suggesting the presence of a break wavelength around 3 mm. A cross-correlation of the SMA data at 1 mm with the data obtained with the VLA at 1 cm shows a global delay of two weeks, suggesting that sub-millimeter wavelengths tend to peak first. The SMA observations suggest that Sgr A* might have been regularly powered via the flares. Any periodicity in flares at 1 mm needs to be confirmed with further better sampled observations.

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 $\sim 2.6\times10^6\ M_\odot$. Sgr A* represents an extremely dim galactic nucleus. Because of its compactness, we have known little about its intrinsic structure. The apparent structure at radio wavelengths up to 3 mm appears to be mainly dominated by the scattering structure due to the ISM. Its intrinsic size measured at 3 mm is less than 0.27 mas (Doeleman et al. 2001) suggesting that a characteristic source size at 3 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.

In this invited talk, we summarize the new results from the VLA monitoring program and the observations with the SMA.

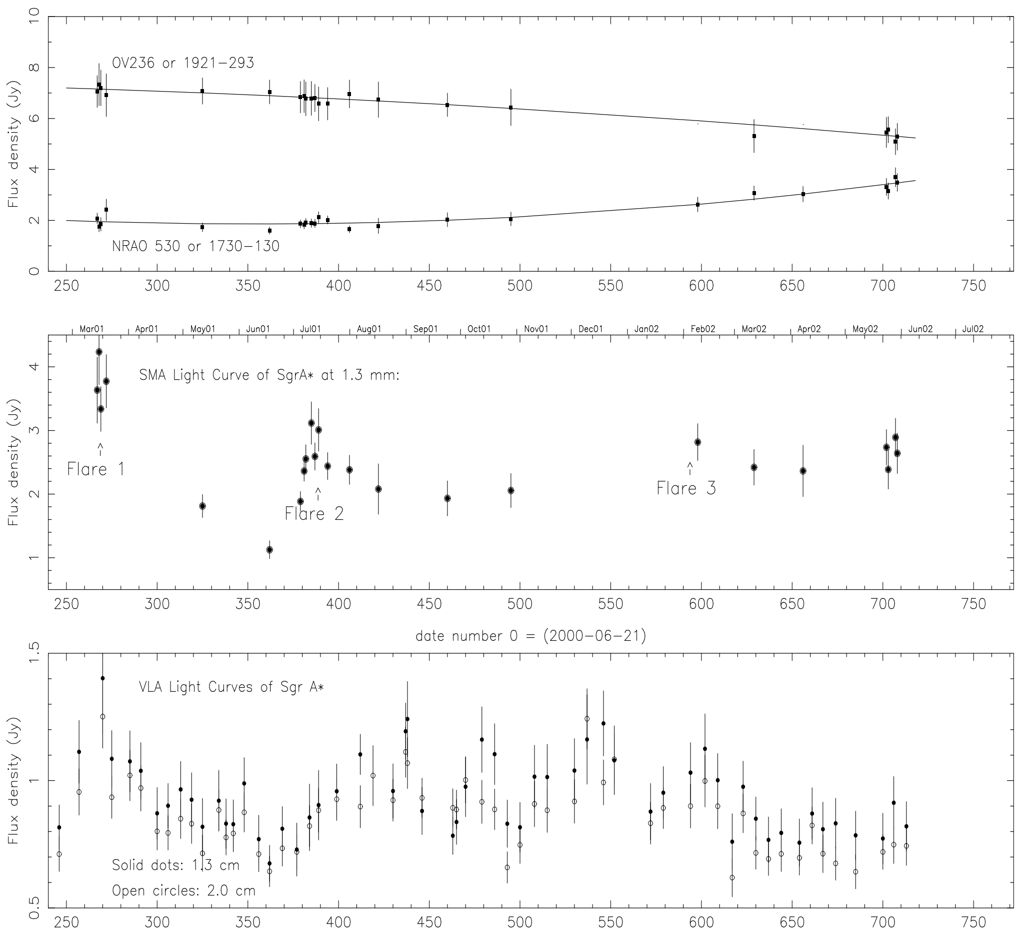

Fig. 1 The SMA light curves at 1.3 mm observed in 2001-03 and 2002-05 for the calibrators (upper panel) and Sgr A* (middle panel). Bottom panel: the densely sampled VLA light curves at 1.3 and 2 cm were observed in the same period (McGary 2002).

2 New Observations & Radio Light Curves

2.1 VLA observations

We briefly reported the preliminary results in the AAS Meeting 199 (Bower et al. 2002). The details of the reduction procedure along with data and more results will be reported elsewhere (Zhao et al. 2002a; McGary et al. 2002). A part of the VLA light curves at 1.3 and 2 cm is shown in Fig. 1 (the bottom panel). Multiple "flares" are seen when the flux density of Sgr A* rises by at least 30%. Sgr A* now appears to be in a relatively quiet mode as compared to that in the period of 1980's and early 1990's (Zhao et al. 2001).

2.2 SMA Observations

We observed Sgr A* at 1.3 mm and 0.87 mm using the partially finished SMA with three or four antennas and baselines ranging from 7 to 55 kilo wavelengths at 1.3 mm. The details of data reduction are described in Zhao et al. (2002b).

Fig. 1 shows the SMA light curve at 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 variations with opposite drifts in flux density over the past year (see the upper panel of Fig. 1). 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. 1) 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 for Flare 2 was about 2 weeks, reaching a peak of 3.2±0.3 Jy on 2001 July 10. Then, a slow decrease lasted about 3 months. We were not able to observe Sgr A* for next 3 months due to the solar avoidance restricted by the current SMA system. The monitoring program was resumed in early 2002 February. A tail of a possible flare (Flare 3) appeared to be observed in early 2002.

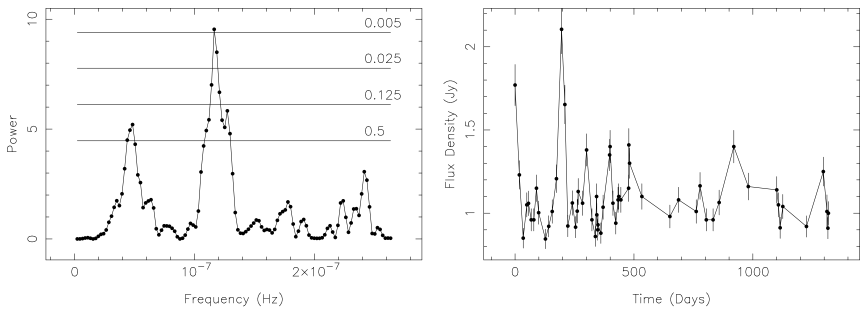

Fig. 2 Left panel: the PSD derived from the VLA archival data over the period between 1990 March to 1993 October (Right panel) using Lomb PSD Algorithm. Two significant PSD features at 1.16×10^{-7} Hz (or 100 d) and 0.48×10^{-7} Hz (or 240 d) can be identified. The horizontal lines mark the significant levels.

3 Data Analysis and Results

3.1 Power Spectral Density (PSD) Analysis And Periodic Signals

In the initial discovery paper (Zhao et al. 2001), we identified a periodic signal in the power spectral density (PSD) using maximum entropy (all poles) method (MEM). We used the lower resolution (or a smaller number (N=10) of poles) MEM to find the 106 day period in the archived data. The advantage of lower resolution MEM is suppression of the noise and improved S/N for the dominant features. However, the MEM requires re-griding of the unevenly sampled light curve to an evenly separated grid which might artificially introduce an uncertainty in the reconstruction of the light curves. Also, weak features close to the dominant signal can be blended in the lower resolution PSD.

Instead, we now search for periodic signals in the power spectral density (PSD) of Sgr A*'s light curves with the Lomb Algorithm (Press et al. 1992). The Lomb PSD method is designed for unevenly sampled time series data and provides reliable results with significance level based on Monte Carlo simulation. The PSD results throughout this paper are derived using Lomb algorithm.

We calculated the PSD of the light curve of the VLA data observed at 1.3 cm during 1990 March to 1993 October over a 1300-d period (lower panel, published in Zhao et al. 2001). The mean sampling interval during this period is 28 d which is less than the Nyquist sampling limit for a periodic signal with a period of 100 d. In addition to the strong feature at ∼100 d, there is a weak periodic signal at ∼240 d (see Fig. 2).

We have also derived the PSD of the light curve of the VLA data observed at 1.3 cm during 2000 June to 2002 August over an 800-d period (Zhao et al 2002a). This PSD reveals the double periodic signals with a ratio of ∼2.5 in period. The long period oscillation in flux density can be clearly seen in the densely sampled light curves at 1.3 cm over a period of more than 2 complete 335-d cycles. This signal is very strong and completely dominates the PSD of the light curve. In addition, weak flares appear also to present on top of the long periodic modulation.

In short, the periodic signal at 100 discovered from the VLA archival data is confirmed with the Lomb algorithm and also persists in the new data taken from this monitoring program over the past two years. In addition, a new periodic feature at a period 2.4—2.5 times longer has also been revealed in both the archival data and the new light curves. The periods of the individual signals appear to drift to longer values over time but the ratio of the double periods appears to remain constant.

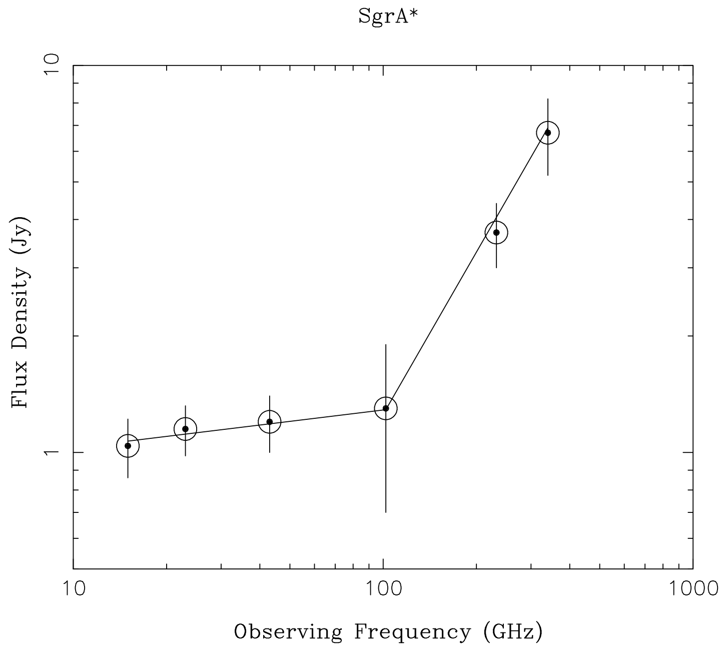

Fig. 3 A spectrum of Sgr A* made from the observations near the peak of Flare 1. The 0.87 and 1.3 mm measurements were made with the SMA. The measurements at 3 mm were obtained from observations with the Nobeyama Millimeter Array (NMA) (Tsutsumi et al. 2002). The data at 0.7, 1.3 and 2 cm were from McGary et al. (2002).

3.2 Flares at Short-/Sub-millimeter

3.2.1 Spectrum During A "Flare"

The SMA monitoring project is highly motivated by the fact that the sub-millimeter wavelengths can penetrate more deeply into the source and the radiation at the short wavelengths reflects the activities occurring in the inner region of the accretion disk near the supermassive black hole.

Fig. 2 shows that the SMA light curve at 1.3 mm is characterized by a few "flares", suggesting that Sgr A* varies significantly. During the "Flare 1" (2001-March), the VLA, Nobeyama Millimeter Array (NMA) and the SMA observed Sgr A* within a period of two weeks. A spectrum (see Fig. 3) constructed using the mean flux densities measured at wavelengths ranging from 2 cm to 0.87 mm near the peak of Flare 1 shows a break frequency at 100 GHz (or a break wavelength at $\sim$ 3 mm). The intensity of the flare appeared to be highly peaked towards sub-millimeter wavelength, suggesting that flares at sub-millimeter wavelengths are more prominent.

3.2.2 Cross Correlation and Global Delay

We have found that flares at centimeter wavelengths appear to be correlated with increased flux densities at 1.3 mm (Zhao et al. 2002b). Fig. 2 shows a comparison of the light curves observed with the SMA at 1.3 mm and with the VLA at 1.3 and 2 cm. A quantitative analysis of cross-correlation properties between the light curves at 1.3 cm and 1.3 mm have been carried out. A global delay between 1.3 cm and 1.3 mm light curves has been searched using the z-transformed discrete correlation function (ZDCF) (Alexander 1997; Edelson & Krolik 1988). With no prior models assumed, the ZDCF is an efficient method in searching for delay in unevenly sampled sparse data. Fig. 4 shows the cross correlation function between SMA and VLA light curves at 1.3 mm and 1.3 cm. The peak in the correlation function corresponds to a lag of 4^{+2}_{-1} d while the correlation coefficient weighted mean of the hump near zero lag suggests a global delay of 14±8 d. This global delay indicates that flares at 1.3 mm starts first. In addition, the cross correlation function tends to show a periodic oscillation. With Lomb PSD analysis of the ZDCF, we derived a period of 134±5 d which appears to be consistent with what has been found from the VLA light curve at 1.3 cm. The periodic oscillation in the ZDCF suggests that the SMA data might contain the periodic signal. Any periodic signals at 1 mm needs to be confirmed with better sampled observations.

3.2.3 X-ray Flares

In 2000 October, an X-ray flare of Sgr A* was observed with *Chandra* (Baganoff, 2001). Following the X-ray flare, Sgr A* was observed to brighten at all three of our observed wavelengths and to peak in flux density on 2000 November 5, showing a delay of 10 days. The VLA monitoring data provides critical evidence for supporting the idea that the X-ray flare arises from the inner region of the accretion disk near the supermassive black hole instead of from other possible origins such as star-star collisions.

In addition, during the 1 mm Flare 2 (2001 July), Chandra observed Sgr A* on 2001 July 14, a few days past the 1 mm peak, showing no X-ray flares. The X-ray flux level was consistent with that of a quiescent state (Baganoff 2001, private communication).

More recently, both the SMA and the VLA participated in coordinated observations with Chandra, OVRO, ATNF, VLBA, Keck, VLT and other telescopes to observationally study the emission mechanism of the X-ray flares (Baganoff, Morris et al. 2002). The VLA monitoring project was used to schedule the observations based on our best estimate of the most likely time for a flare to occur. Several significant flares at X-ray wavelengths were observed during the week long campaign. Although we observed no significant flares at both 1 cm and 1 mm during the coordinated observations, a small flare was observed on 10 June 2002. The VLA data again shows a significant lag in flare as is compared to the X-ray data. In addition, the significant X-ray flares and no significant changes in the VLA flux density at centimeter and the SMA flux density at 1 mm during the multi-wavelength campaign appear to provide a critical information in distinguishing various emission models for the X-ray flares.

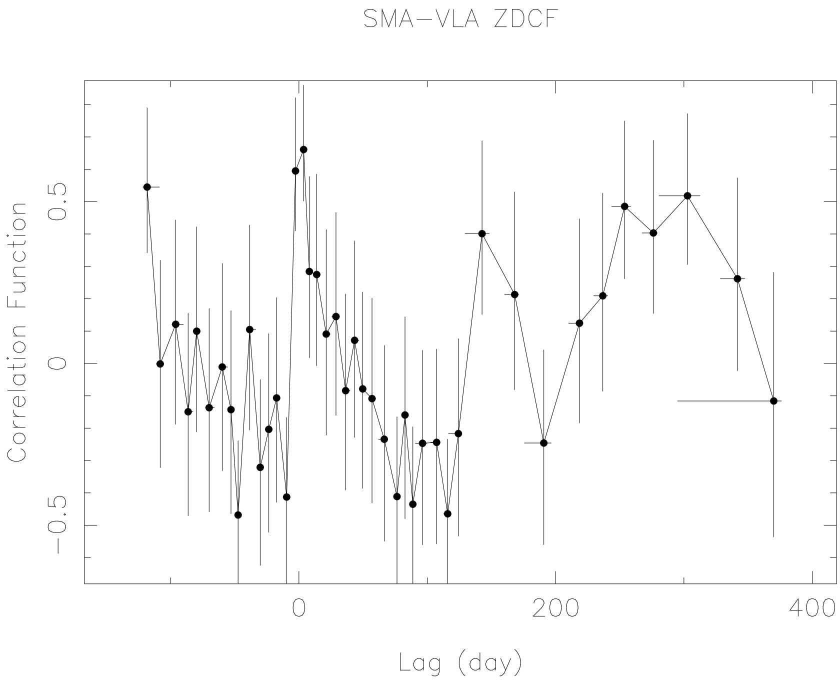

Fig. 4 The z-transformed discrete cross-correlation function (ZDCF) of the SMA data at 1.3 mm with the VLA data at 1.3 cm. The peak of ZDCF corresponds to a delay of 4^{+2}_{-1} d and global delay of 14±8d is inferred from a correlation coefficient weighted mean of the hump near the zero lag.

4 Astrophysical Implication and Discussion

4.1 Low Luminosity Nature and ADAF

The low luminosity nature of Sgr A* as a galactic nuclear source has been successfully explained by the low efficiency radiative ADAF model (Narayan et al. 1998). In the ADAF model, the high temperature protons that carry with the most of the energy and angular moment are advected all the way to the event horizon with little radiation. The emission from low temperature electrons in the advection dominated accretion flow make the main contribution to illuminate the source. However, the ADAF alone appears to be difficult in explaining the detailed activities observed at the wavelengths ranging from radio to X-ray.

4.2 Intrinsic Activity and Jet-ADAF

Alternatively, recent work by Yuan, Markoff & Falcke (2002) provides a model to link a jet outflow (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 the result of a sum of the synchrotron radiation from both the ADAF and the nozzle of the jet.

On the other hand, from the observations with the VLA, SMA and other interferometer arrays, further constraints on the models can be discussed. The global delay of 2 weeks determined from the cross-correlation between the SMA and VLA light curves and the source size of 40 R_{SC}, suggest a small expansion velocity of $V_{exp} \sim 200\,km\,s^{-1}$ or 0.001 c which is far below the escaped velocity of 0.1 c required to form a visible jet. In addition, the break wavelength around 3 mm also indicates that a large fraction of flaring plasma might well be confined within the characteristic radius at 3 mm although the possible outflow driven by the central activities tends to expand to a large scale.

4.3 Periodic Oscillation and Disk Precession

The existence of periodic fluctuation cycle around a period of $\sim$ 100 d appears to have been established with the extensive analysis of the VLA archival data and the densely sampled VLA observations in the new monitoring program. In addition, the two states (flare and quiescent) can be separated in the folded light curve with a module of 100 to 120 d based on the irregularly sampled data taken with the NMA at 3 mm over the past six years (Tsutsumi et al. 2002). The 3 mm result appears to be consistent with the centimeter data observed with the VLA. In addition, the global cross-correlation analysis of the VLA data at 1.3 cm and the SMA data at 1.3 mm has revealed a quasi-periodic oscillation in the cross-correlation function with a mean separation in lags between the cross-correlation peaks. Such a cross-correlation feature is a good evidence for the fact that the SMA sparse data does contain the periodic signal as observed at 1.3 cm with the VLA although the SMA data alone is not sufficient to extract such a signal due to a poor data sampling.

A model to interpret such an interesting periodic signal has been proposed by Liu and Melia (2002) in an assumption of both a small Keplanian accretion disk (with an out radius of R_o) and a Kerr black hole with a specific spin of a/M. If the rotation axis of the disk offsets from the spin axis, then the spin black hole places an intrinsic torque on the accretion disk and causes the disk precession around the spin axis. The wabbling, opaque disk shadows the radio emission and produces periodic modulation in the radio light curves. Linking the disk precession period to the observed 100 day period P_{100d}, then the black hole spin can be inferred:

$$\frac{a}{M} \sim 0.1 \left[\frac{R_o}{30R_{SC}}\right]^{2.5} / P_{100d} \sim 0.1\,.$$

A small black hole spin (10% of a perfect Kerr black hole) is therefore inferred in this model.

4.4 Double Periodic Oscillation and Orbital Resonance

The discovery of double quasi-periodic oscillation in the VLA data suggests that the nature of the Sgr A* system is more complicated than originally thought. The mode of the double oscillation appears to vary in the following way:

1) The short periodic oscillation ($P_1 \sim 100$ d) that dominated in early 1990's has been weakened and the long periodic oscillation (P_2) now dominates in the radio light curves.

2) The periods of both oscillations drifts to long periods with a fractional period change rate of $\dot{P}/P \sim 0.0129\,\mathrm{yr}^{-1}$ while the ratio of the two oscillation period (P_2/P_1) keeps nearly constant (in a range of 2.4 to 2.5).

The constant ratio of the two oscillation periods suggests that an orbital resonance phenomenon might indeed occur in the Sgr A* system. If the P_2 corresponds to a modulation period of a tidal bulge in the emitting plasma surrounding the supermassive black hole due to an orbiting object, the mean orbital radius of 2200 R_{SC} (110 AU) is inferred. The orbiting object interacting with the accretion flow triggers a wave such as an epicyclic oscillation through parametric resonance instabilities (Kluzniak & Abramowicz 2001, 2002). The growing wave propagates inwards and periodically triggers the central activity in a resonant frequency of 2.5 times faster than the oribtal frequency of the orbiting object. This resonance system must be perturbed by a nearby gravitational source in order to explain for the oscillation frequency drifts.

4.5 Origin of the X-ray Flares

The lack of strong flares on a short time scales at the short-/sub-millimeter wavelengths places a critical constraint on the hypothesis of the inverse Compton scattering as is proposed for the emission mechanism for the short lived X-ray flares (Falcke & Markoff 2000). Alternatively, the X-ray flares can be naturally excited by the inward growing resonance wave triggered by the orbital star. The flares at the sub-millimeter to radio wavelengths might be a result of a collective mass ejections associated with the X-ray flares.

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References

Alexander T., in Astronomical Time Series, eds. D. Maoz, A. Sternberg, E. Leibowitz (Dordrect: Kluwer), 1997, p.163
Baganoff F.K., et al. Nature, 2001, 413, 45
Baganoff F.K., Morris M., et al. GC Workshop 2002, 2002
Bower G.C., McGary R.S., Zhao J.H., et al., American Astronomical Society meeting, Washington, DC, 2002
Doeleman S., Shen Z., Rogers A.E.E., et al., AJ, 2001, 121, 2610
Eckart A., Genzel R., MNRAS, 1997, 28, 576
Edelson R.A., Krolik J.H., ApJ, 1988, 333, 646
Falcke H., Mannheim K., Biermann P. L., A&A, 1993, 278, L1
Falcke H., Markoff S., A&A, 2000, 362, 113
Ghez A.M., Klein B.L., Morris M.,et al., , ApJ, 1998 509, 678
Kluzniak W., Abramowicz M.A., APP B32/11, 2001, p.3605
Kluzniak W., Abramowicz M.A., astro-ph 0203314, 2002
Liu S., Melia F., ApJ, 2002, 573, L23
McGary R., et al., 2002, in preparation
Narayan R., Mahadevan R., Grindly J.E., et al., ApJ, 1998, 492, 554
Press William, et al., Numerical Recipes in C, The Art of Scientific Computing, Second Edition, Cambridge University Press, 1992
Tsutsumi T., Miyazaki A., Tsuboi M., AAS Meeting 200, #44.09, 2002
Yuan F., Markoff S., Falcke H., A&A, 2002, 383, 854
Zhao J.H., Bower G.C., Goss W.M., ApJ, 2001, 547, L29
Zhao J.H., Pegg J., McGary R.S., et al., 2002a, in preparation
Zhao J.H., Young K.H., McGary R.S., et al. 2002b, in preparation for ApJ Letter