JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
38: 261 ~ 266, 2005

VLBI STUDIES OF Sgr A*

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(Received February 1, 2005; Accepted March 15, 2005)

ABSTRACT

This paper reviews the progress in the VLBI (Very Long Baseline Interferometry) studies of Sgr A*, the best known supermassive black hole candidates with a dark mass concentration of 4×10^6 $M_\odot$ at the center of the Milky Way. The emphasis is on the importance of the millimeter and sub-millimeter VLBI observations in the detection of Sgr A*'s intrinsic structure and search for the structural variation.

Key words : Galaxy: center — galaxies: individual (Sagittarius A*) — techniques: interferometric

I. INTRODUCTION

Located at the galactic center, the extremely compact non-thermal radio source Sgr A* which was first unambiguously detected in February 1974 (Balick & Brown 1974), is a best candidate for a single supermassive black hole (SMBH) from both the observational studies and the theoretical models (cf. Melia & Falcke 2001). The presence of a black hole that serves as an energy source for the luminosity observed towards the galactic center was first proposed by Lynden-Bell & Rees (1971), who further suggested the detection of Sgr A* with VLBI observations as one of critical observations. The extinction due to the intervening dust in the Galactic disk can be up to 30 magnitudes at optical wavelengths, eventually blocking our optical view of the galactic center. Fortunately, the dust extinction is not a serious problem for the observations at other wavelengths like radio, infrared, X-ray and γ-ray. Immediately after its discovery in 1974 with the high-resolution radio interferometric observations, Sgr A* was thought to actually define the galactic center (Balick & Brown 1974).

Since then, with ever-increasing sensitivity and resolution from the rapid development of astronomical facilities such as the X-ray space telescopes (Chandra and XMM-Newton) and the ground large instruments (VLT and Keck etc), Sgr A* had already been successfully detected at X-rays (Baganoff et al. 2001; Porquet et al. 2003) and near-infrared wavelengths (Genzel et al. 2003; Ghez et al. 2004). Recently, there were several reports on the possible detection of TeV γ-rays by the CANGAROO (Tsuchiya et al. 2004), Whipple (Kosack et al. 2004) and HESS (Aharonian et al. 2004) groups. All the observations in the last three decades strongly support the SMBH nature of Sgr A*. The infrared observations went even one step further to suggest that Sgr A* should be spinning (Genzel et al. 2003).

Nowadays, the best estimate of the compact dark mass is about 4×10^6 $M_\odot$ with a radius of about 100 astronomical units (AU). This is based on the determination of the orbital motions of those early-type stars within the vicinity of Sgr A* measured at infrared wavelengths (Schödel et al. 2002; 2003; Eisenhauer et al. 2003; Ghez et al. 2003; 2005). On the other hand, the VLBI measurements of the position of Sgr A* with respect to the extragalactic radio sources show that the possible intrinsic proper motion of Sgr A* itself which is perpendicular to the galactic plane is only about -0.4 ± 0.9 km s^{-1}, inferring a lower limit of 0.4×10^6 $M_\odot$ to the mass directly associated with Sgr A* (Reid & Brunthaler 2004). Future improvements in the measurements of both the orbital motions of stars and the proper motion of Sgr A* should be able to reduce the uncertainty in the determination of Sgr A*'s mass. Therefore, we can say that we have known the mass of Sgr A* to a great extent, the main uncertainty being the exact distance to the galactic center.

The accurate measurements of both Sgr A*'s mass (as a gravitational source) and structure (as a radiative source) are of great importance in testing its SMBH hypothesis. In this paper, we present an overview of the measurements of the structure of Sgr A* from the high-resolution VLBI observations, with the emphasis on the observations made at millimeter (mm) wavelengths.

II. VLBI OBSERVATIONS IN GENERAL

VLBI observations can provide the highest angular resolution achievable with any astronomical instruments (Kellermann & Moran 2002). At a distance of 8 kpc to the galactic center (Reid 1993), an angular separation of 1 milli-arcsecond (mas) corresponds to a linear size of 8 AU. The Schwarzschild radius (R_{sc}) of a 4×10^6 $M_\odot$ SMBH is 0.08 AU or 10 micro-arcsecond (μas) in angular size. For comparison, the Schwarzschild radius of two well-known SMBH candidates NGC 4258 (Miyoshi et al. 1995) of 39×10^6 $M_\odot$ at 7.2 Mpc

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Proceedings of *the 6th East Asian Meeting of Astronomy*, held at Seoul National University, Korea, from October 18-22, 2004.

and M 87 (Junor, Biretta & Livio 1999) of 3×10^9 $M_\odot$ at 14.7 Mpc is about 0.1 and 4 μas, respectively. Thus, Sgr A* is the closest SMBH candidate with the largest angular size of its Schwarzschild radius on the sky. Together with its rising spectrum (c.f. Falcke et al. 1998) of ~1 Jy at about 10–20 GHz, Sgr A* is undoubtedly one of the best prime targets for the VLBI observational study.

However, because of the diffraction effect due to the interstellar electrons along the line of sight to the galactic center, the scattering angle ($\theta_{\rm sca}$) of a point source varies with wavelength (λ) as $\theta_{\rm sca} \propto \lambda^{2.0}$. As a result, for the Sgr A* which has an intrinsic finite (angular) size ($\theta_{\rm int}$), the observed apparent angular size ($\theta_{\rm obs}$) can be expressed as

$$\theta^2_{\rm obs} = \theta^2_{\rm sca} + \theta^2_{\rm int} \ , \qquad (1)$$

Obviously, as the scattering angle $\theta_{\rm sca}$ is far greater than the intrinsic size $\theta_{\rm int}$, i.e. $\theta_{\rm sca} >> \theta_{\rm int}$, the measured apparent size $\theta_{\rm obs}$ is dominated by the scattering effect; therefore it is very difficult to estimate the intrinsic size. In fact, this is the case for the VLBI observations of Sgr A* carried out at centimeter (cm) wavelengths since the observed apparent size can be reasonably fitted by a λ^2 dependence. This suggests that Sgr A*'s cm emission comes from a region much smaller than the scattering angle.

It should be mentioned that while VLBI techniques have been applied to delineate the structure of Sgr A* ever since it was discovered in 1973, Sgr A* has not been imaged properly prior to the availability of the Very Long Baseline Array (VLBA) in 1990s, mainly due to poor (u,v) coverage from the lack of sufficiently short baselines. At that time, the size scale and its wavelength dependence were mainly derived from FWHM (Full Width at Half Maximum) diameter of (circular) Gaussian models fitted to visibility data of Sgr A* that were inadequate for obtaining an image. With the advent of the VLBA, several images have been produced at different wavelengths, confirming the approximately East-West elongated elliptical Gaussian structure with an axial ratio of ~ 0.5 (Bower & Backer 1998; Backer et al. 1993; Lo et al. 1993; Alberdi et al. 1993; Jauncey et al. 1989; Lo et al. 1985).

In 1997, we launched the first quasi-simultaneous VLBA plus an antenna from the VLA (Very Large Array) observations of Sgr A* at five wavelengths (6.0, 3.6, 2.0, 1.35 and 0.7 cm) (Lo et al. 1998). With standard procedure of hybrid imaging, images for Sgr A* were successfully produced at all five wavelength. The consistent East-West elongation of source structure was seen at all wavelengths. Furthermore, for the first time the λ-dependence of the scattering along the minor axis was determined as

$$\theta^{\rm min}_{\rm sca} = (0.76 \pm 0.05)\lambda^2 \ {\rm mas} \ , \qquad (2)$$

where λ in cm. The scattering angle along the major axis is given by

$$\theta^{\rm maj}_{\rm sca} = (1.43 \pm 0.02)\lambda^{1.99\pm0.03} \ {\rm mas} \ , \qquad (3)$$

in good agreement with the previous results of $1.42\lambda^2$ (Alberdi et al. 1993) or $1.40\lambda^2$ (Rogers et al. 1994). Then, we can extrapolate these relations to get the scattering angular size at any other wavelengths. It can been seen that because of the quadratic size-wavelength relation, the scattering angle reduces very fast with the wavelength. The scattering angle along the major axis at 1 mm, only 1% of that at 1 cm, is less than 15 μas or less than $1.5R_{\rm sc}$ of Sgr A*. Since the emission region cannot be much smaller than the event horizon, the scattering angular size at mm wavelength is comparable to the intrinsic size of Sgr A*, i.e. $\theta_{\rm sca} \sim \theta_{\rm int}$. An immediate important implication is that at mm wavelength the source intrinsic size will come to play with the scattering effect to cause a deviation of $\theta_{\rm obs}$ from $\theta_{\rm sca}$ (see Eq. (1)). This announced the feasibility and importance of exploring the intrinsic shape and size of Sgr A* radiation at mm waveband with an key prerequisite that we can measure the apparent structure with a high enough accuracy.

III. MILLIMETER VLBI OBSERVATIONS

Over the past decade or so, VLBI experiments have been carried out steadily at mm wavelengths (7 and 3.5 mm). However, unlike the cm-VLBI observations, the mm-VLBI observations are severely limited by the atmosphere. The fact that Sgr A* has a southerly declination (~ $-30°$) and most existing VLBI antennas are located in the Northern Hemisphere means that most of the observational data of Sgr A* were taken at low elevation angles ($10° - 20°$) where atmospheric effects are substantial. As a consequence, this introduces a large atmospheric absorption due primarily to spectral line transitions of water vapor and oxygen at mm wavelengths. And such an absorption increases with the decreasing elevation angle, i.e. the lower elevation, the larger and more variable opacity. Furthermore, the short and variable coherence time at mm wavelength, combined with the compromised sensitivity due to the high system temperature and the lower antenna efficiency of mm VLBI antennas, seriously limits the high signal-to-noise-ratio (SNR) detections of mm-VLBI observations of Sgr A*. Thus, there could be large uncertainties in the results obtained from the widely used conventional imaging process, i.e. the self-calibration technique for VLBI imaging, whose biggest drawback is its non-uniqueness when the SNR is poor.

We have already known that at mm wavelength, the intrinsic size of Sgr A* should be comparable to the scattering size, and thus a deviation of $\theta_{\rm obs}$ from $\theta_{\rm sca}$ is expected. However, the significance of such a deviation is highly dependent on the accuracy of the size measurements. Currently, the angular resolution of a typical mm-VLBI observation is a few times larger than the scattering size, making it very difficult to reduce the errors of the measurements with the traditional imaging and model-fitting methods. So, any possible deviation seen in the previous data has been ascribed to the errors in the calibration of the VLBI data.

In order to minimize the calibration errors and finally to obtain the most accurate estimates of the source structure, we tried two things in the mm-VLBI observations and data analysis. First, mm-VLBI observation of Sgr A* must be done dynamically, i.e., the exact observing date is not fixed, but depends on the weather condition at most antenna sites which usually are separated by a few thousand kilometers. This is to minimize the atmospheric effects. While observing, a frequent antenna pointing check observations of compact and strong SiO maser sources, roughly in every 10 minutes, is necessary to maintain the best reference (offset) pointing and calibration. Furthermore, in about every 10 minutes, the spectral-line observations are carried out towards the nearby compact SiO maser source VX Sgr. This is to obtain time-dependent relative antenna gains as a function of observing time (elevation) by the least-squares fit of the autospectra of the SiO maser at different elevation to a well calibrated total-power spectrum. Compared to the amplitude self-calibration based on the clean models of Sgr A*, this offers a much better amplitude calibration to the visibility data. Second, in order to obtain a reliable quantitative description of Sgr A*'s structure, we developed a method of model-fitting to the visibility amplitude directly without self-calibration imaging (Shen et al. 2003). The basic idea is to make use of the closure amplitudes, which are free of any errors, as the constraint to the model-fitting. This is very effective for the data analysis of Sgr A* whose emission can be well represented by an elliptical Gaussian model. This is because VLBI observations of Sgr A* have shown that the closure phases are consistent with zero value, suggesting that Sgr A*'s radiation has a symmetric structure and the size would be fully decided by the visibility amplitudes. It should be mentioned that it is necessary to perform the correction to the measured visibility amplitude bias which is always positive and is a function of SNR with a stronger bias at a lower SNR (c.f. Shen et al. 2004). In our analysis by implicitly using the closure amplitude relation, the absolute amplitude information will not be kept, just like the lose of absolute position in the self-calibration imaging.

We have applied this model-fitting procedure to the existing archival VLBI data to obtain the two-dimension apparent structure of Sgr A*. We then obtained the best fitted relation between the scattering angle and wavelength as follows (Shen et al. 2004),

$$\theta_{\rm sca}^{\rm maj} = 1.39\lambda^2 \text{ mas} , \qquad (4)$$

and

$$\theta_{\rm sca}^{\rm min} = 0.76\lambda^2 \text{ mas} , \qquad (5)$$

Our results are consistent with that through directly fitting to the closure amplitudes (Bower et al. 2004). Compared with previous results (equations (2) and (3)), new results show an about 3% decrease in the scattering angular size along the East-West direction, while for the minor axis along the North-South direction, both are in good agreement.

The shortest (routine) VLBI observing wavelength is 3.5 mm (86 GHz). In April 1999, 3.5 mm VLBI observations with six CMVA (Coordinated Millimeter VLBI Array) antennas are believed to be best modelled by a circular Gaussian (Doeleman et al. 2001). This is mainly because of the lower sensitivity and heterogeneous CMVA data could not warrant a model more complex than the circular Gaussian. In November 2002, we successfully carried out the first 3.5 mm VLBA imaging observation (Shen & Lo 2004). As a result, the first 3.5 mm VLBI image of Sgr A* was produced. This observation, with its dynamic scheduling and the highest sensitivity, has for the first time determined its elliptical shape of Sgr A* roughly along the East-West direction at 3.5 mm, consistent with the morphology seen at longer wavelengths. The best fitted structure is $0.21(^{+0.02}_{-0.01})$ mas by $0.13(^{+0.05}_{-0.13})$ mas with a position angle $79(^{+12}_{-33})^\circ$. Due to the poor spatial resolution along North-South (i.e. the minor axis) direction, the minor axis size has a quite large error bars, however, the major axis is very well determined. By comparing the measured major axis size with the extrapolated scattering angle at 3.5 mm, we can derive an intrinsic size (FWHM) of Sgr A*'s emission at 3.5 mm about 1 AU, equivalent to about $13R_{\rm sc}$. Therefore, 30 years after its discovery, we have finally detected its most compact emission region. Assuming its circular symmetry, we derive a lower limit to the mass density of 6.5×10^{21} $M_\odot pc^{-3}$. Here, a lower limit to the central dark mass of 0.4×10^6 $M_\odot$ from the absolute proper motion study of Sgr A* by the VLBA (Reid & Brunthaler 2004) was used to avoid possibly extended mass distribution at the scale of about 10 mas of near-IR observations. This is the highest mass density ever measured in any celestial object and strongly argues the SMBH nature of Sgr A*. The results have been confirmed by our new 3.5 mm VLBA observation in September 2003 (Shen et al. 2004). A lower bound to the intrinsic brightness temperature is about 10^{10} K, in favor of the non-thermal origin of the radiation.

It has been realized that the resolution of the VLBA observations of Sgr A* is too poor to determine the minor axis size along the N-S direction. It can be shown that the addition of the GBT (Green Bank Telescope) of the NRAO (National Radio Astronomy Observatory) into the VLBA observations can greatly improve the resolution in N-S by a factor of 3 (Shen et al. 2003). In March 2004, two-epoch 7 mm VLBA plus the just commissioned GBT observations of Sgr A* were carried out. This actually is the first VLBI observations to make use of the GBT at 7 mm. The results are consistent with the previous ones, but with much better accuracies. Thus, we are able to obtain a reliable estimate of the intrinsic size along the major axis of 2.1 AU or about 27R$_{sc}$ (Shen et al. 2004), consistent with the detections by Bower et al. (2004).

We can further obtain the wavelength dependence , $\theta_{\rm int} \propto \lambda^{1.09}$, of the intrinsic major axis size through fitting to the detected intrinsic sizes at both 7 and 3.5 mm. This shows that the emission of Sgr A* is stratified with the shorter wavelength emission coming from the region closer to the central engine. The lower limits to the intrinsic size of 0.008 and 0.02 mas inferred from the absence of refractive scintillation at wavelengths of 0.8 and 1.3 mm, respectively (Gwinn et al. 1991) are also consistent with the extrapolation of this intrinsic size - wavelength relation. It is interesting that the extrapolated intrinsic size at about 1 mm will reach the last stable orbit (LSO) radius of 3R$_{sc}$ for a non-rotating (Schwarzschild) SMBH. For a rotating SMBH, the radius of LSO could be smaller, but in any case, a break in the wavelength-dependent intrinsic size is inevitable with the decreasing wavelength. The fitted Sgr A*'s intrinsic size vs wavelength can be naturally explained by the jet related models (e.g., Falcke & Markoff 2000; Yuan, Markoff & Falcke 2002), or the pure accretion model with the existence of non-thermal electrons (Yuan, Quataert & Narayan 2003).

IV. PROSPECTS

In 1982, the total flux density variation in Sgr A* was first reported at wavelengths 11 and 3.7 cm (Brown & Lo 1982). It has been well recognized that Sgr A* is a time variable source, with the temporal variation in its intensity seen at all the observable wavelengths, i.e., radio band from cm to sub-mm (c.f. Zhao 2003), infrared (Genzel et al. 2003; Ghez et al. 2004) and X-rays (Baganoff et al. 2001; Goldwurm et al. 2003; Porquet et al. 2003), on time scales from minutes, hours, days to months. Recently, an intra-day variability (IDV) in 2 mm flux density of Sgr A* has been found from the Nobeyama Millimeter Array (NMA) observations (Miyazaki et al. 2004). The flaring state that was first detected at near-IR and X-rays simultaneously can be conveniently explained with a Synchrotron Self-Compton model involving up-scattered sub-mm photons from a compact source component (Eckart et al. 2004). The observed intensity variations at radio and X-ray bands seem to be correlated. A strong radio outburst which was just 13.5 hrs after the onset of the X-ray flare observed by the XMM-Newton (Porquet et al. 2003) was picked up by the weekly VLA monitoring program at 7mm (Zhao et al. 2004). Thus, large X-ray flares could result in a significant radio outburst and if so, the radio outburst component must quickly expand to a large size in order to avoid drastic energy loss from Synchrotron Self-Compton scattering (Zhao et al. 2004). The correlation between flux density at 7 mm and spectral index suggests that the variation at the short radio wavelengths is intrinsic rather than due to the interstellar scintillation (Herrnstein et al. 2004). Therefore, it seems inevitable that the variability in the radio flux density of Sgr A* would accompanied by the structural change. An outstanding question then is whether Sgr A*'s structure is variable too.

In table 1 is a summary of the Sgr A* size measurements from the VLBI observations in the literature. Some fluctuations in the observed (apparent) source size of Sgr A* up to several σ can be seen. These fluctuations have so far been ascribed to uncertainties in the calibration of the VLBI data. In addition, the different VLBI array involved and quite large time spanning of the observations make the comparison very uncertain. However, we cannot rule out that the source size has varied substantially.

Because that such kind of variability appears to be more pronounced at shorter wavelengths with a relatively large amplitude fluctuation and that the interstellar scattering effect decreases with the wavelength, VLBA imaging at its highest available frequency is the most preferable. The future VLBI search for the structural variability in Sgr A* should make use of a as much wider recording bandwidth as possible to increase the detection sensitivity. Also, to minimize (eliminate) the possible long-term variation in the scattering screen, more frequent VLBI monitoring with a short time interval is necessary. A coordinated multi-wavelength (radio, infrared and X-ray) campaign would provide the unique opportunity to investigate whether or not the source size changes with the flux density variations at higher energy bands. Because it is still very difficult to predict the outbursts, it would be very helpful to use other monitoring observations (by the Sub-Millimeter Array (SMA) at 1.3 mm, the NMA at 2 and 3 mm and, the Australia Telescope Compact Array (ATCA) at 3 mm) as a trigger to the high-resolution VLBI observations. This will improve the probability of detecting the structural variation and further help us to better understand the relationship between the radio flares and the possible structural variation. Future joint mm-VLBI observations with the antennas from China, Japan and Korea are very promising for imaging and monitoring studies of the structure of Sgr A* (Shen & Fletcher 2002).

After considering all the general relativistic effects on the radiation in the very vicinity of the central black hole, the simulation shows that regardless of the exact emission model, the image always exhibits a shadow at the center (Falcke, & Melia 2000). Its characteristic diameter is about 5 times that of Schwarzschild radius. It is nearly 50 μas for Sgr A*. Obviously, Sgr A* will be the most important target for the future sub-mm VLBI experiment to test the general relativity. Such kind of shadow, if confirmed by future observations, would be the most direct evidence for the existence of SMBH. Our simulations (Miyoshi et al. 2004) show that we would be able to study the shadow by investigating the visibility distribution in the near future even before a complete sub-mm VLBI array is available.

These years great progress has been seen in the polarization-sensitive VLBI observations of active galactic nuclei (AGN). But it is quite different for Sgr A*. Only recently, has the linear polarization and its variation been convincingly detected at wavelengths of 2 mm and shorter by the James Clerk Maxwell Telescope (JCMT) and BIMA (Aitken et al. 2000; Bower et al. 2005). Circular polarization, which is very weak in AGN, however, has been first detected by the VLA (Bower, Falcke & Backer 1999) and then confirmed by the ATCA (Sault & Macquart 1999). We should keep in mind that these observations are not at the VLBI-scale. Our quasi-simultaneous, multi-wavelength VLBA imaging observations in 1997 can only set an upper limit to the linear polarization at wavelengths of 7 mm and longer. But the preliminary results seem to suggest a circular polarization detected at 7 mm with a fractional circular polarization of ~0.7%. Definitely, more sensitive high-resolution VLBI polarization observations are needed to verify this potentially intriguing results. And future VLBI polarization imaging at sub-mm wavelength, once available, will undoubtedly help us to better understand accretion disks, jets and magnetic fields surrounding the SMBH (Bromley, Melia & Liu 2001).

ACKNOWLEDGEMENTS

The author is grateful for the hospitality extended by the organizers of the EAMA6 conference. This work is supported by the One-Hundred-Talent Program of Chinese Academy of Sciences.

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Table 1.
Summary of Sgr A* size measurements

Epoch (yrs)	$S_{\rm VLBI}$ (Jy)	$\theta_{\rm major}$ (mas)	$\theta_{\rm minor}$ (mas)	Axial Ratio ($\theta_{\rm minor}/\theta_{\rm major}$)	P.A. (°)	References
			$\nu = 1$ GHz			
1975.5	0.26±0.03	1500±300	1500	1.0		3
			$\nu = 1.7$ GHz			
1974.42	0.56±0.06	500±100	500	1.0		3
			$\nu = 2.7$ GHz			
1974.12	0.6±0.1	180±30	180	1.0		1, 3
			$\nu = 5$ GHz			
1997.10	0.60±0.09	49.6±4.50	25.1±2.00	0.51±0.09	81±3	17
			$\nu = 8$ GHz			
1997.10	0.73±0.10	18.0±1.53	9.88±1.68	0.55±0.14	78±6	17
1991.90		17.5±0.5	8.5±1.0	0.49±0.06	87±5	12
1983.36		16.1±0.3	16.1	1.0		9
1983.35		15.5±0.1		0.55±0.25	98±15	7
1982.30		17.4±0.5		0.53±0.10	82±6	8
1978.07	0.7	18±2	18	1.0		6
1976.18	0.9±0.06	14±2	14	1.0		5
1975.38	0.6±0.1	15±4	15	1.0		2, 3
1974.50	0.6	17	17	1.0		4
			$\nu = 15$ GHz			
1997.10	0.68±0.06	5.84±0.48	3.13±1.14	0.54±0.21	73±14	17
			$\nu = 22$ GHz			
1997.10	0.74±0.04	2.70±0.15	1.50±0.59	0.56±0.25	81±11	17
1992.85	1.05±0.10	2.67±0.15	1.63±0.41	0.61±0.12	79±10	18
1991.49	0.98±0.05	2.6±0.2	1.3	0.5	87	12
1991.47	1.07±0.15	2.60±0.20	1.30±0.88	0.5±0.3	80±15	11
1985.11	1.2±0.4	1.8±0.09	1.8	1.0		9
1983.47	0.98±0.05	2.2±0.2	1.21±1.21	0.55±0.5	87±30	7
			$\nu = 43$ GHz			
1997.10	1.03±0.01	0.70±0.01	0.58±0.07	0.83±0.11	87±8	17
1994.75	1.28±0.10	0.76±0.04	0.55±0.11	0.73±0.10	77±7	16
1992.62	2.10±0.10	0.74±0.03	0.40±0.20	0.54±0.29	90±10	13
1992.40	1.42±0.10	0.75±0.08	0.75	1.0		10
			$\nu = 86$ GHz			
1999.27	1.4	0.34±0.14	0.17±0.02	0.50±0.26	22±20	20
	1.4	0.18±0.02	0.18	1.0		20
1995.18	1.80±0.30	0.19±0.03	0.19	1.0		15
1994.25	1.40±0.20	0.15±0.05	0.15	1.0		14
1993.27	1.25±0.35	0.22±0.19	0.22	1.0		19
			$\nu = 215$ GHz			
1995.17	3.1±0.1	0.15±0.04	0.15	1.0		15, 19
	2.0±0.2	0.11±0.06	0.11	1.0		15, 19

References.—(1) Balick & Brown 1974; (2) Lo et al. 1975; (3) Davies et al. 1976; (4) Kellermann et al. 1977; (5) Lo et al. 1977; (6) Lo et al. 1981; (7) Lo et al. 1985; (8) Jauncey et al. 1989; (9) Marcaide et al. 1992; (10) Krichbaum et al. 1993; (11) Alberdi et al. 1993; (12) Lo et al. 1993; (13) Backer et al. 1993; (14) Rogers et al. 1994; (15) Krichbaum et al. 1998; (16) Bower & Backer 1998; (17) Lo et al. 1998; (18) Marcaide et al. 1999; (19) Krichbaum et al. 1999; (20) Doeleman et al. 2001