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MULTIWAVELENGTH VLBI OBSERVATIONS OF THE GALACTIC CENTER[1]

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ABSTRACT

VLBI observations of the galactic center compact radio source at 6, 3.6, 2.8, and 1.35 cm were carried out in an attempt to determine the source structure. At 6 cm and 3.6 cm, the sizes were approximately 0".05 and 0".015, respectively. The 0".001 core component reported by Kellermann *et al.* at 3.8 cm was not detected at 3.6 cm. The observations do not allow a distinction between the suggestions that the apparent size of the radio source is controlled by interstellar electron scattering or free-free self-absorption. Thus, the source structure is not yet known despite the measured sizes, but an absolute upper limit of 10^{15} cm can be set to the linear size. This poses a severe constraint on possible physical models of the underlying energy source. The plausibility of various models is discussed.

Subject headings: galaxies: nuclei — interferometry

I. INTRODUCTION

The compact nonthermal radio source at the galactic center is of particular interest because it has properties similar to the extragalactic radio sources associated with radio galaxies and quasars. Furthermore, because of its proximity (60 times closer than the nearest external galactic nucleus), it can be studied in great detail. However, this weak source (< 1 Jy) is embedded in the strong radio source Sgr A, making its study difficult. The detailed source structure is still unknown. There is a probable upper limit to its size of 0".001, which implies a brightness temperature of $\gtrsim 10^{10}$ K (Kellermann *et al.* 1977).

We report here VLBI observations of the galactic center compact source at 6.0, 3.6, 2.8, and 1.3 cm, carried out between 1977.4 and 1978.8, in an attempt to determine the source structure.

To set a proper context, we review previous observations in the next section (§ II). We present our observations in § III and the results in § IV. In § V, we discuss the implications of the observations. In § VI, we discuss the plausibility of various physical models. Finally, in § VII we discuss future observations which would be helpful to further understanding of the object.

[1]Based in part on a talk presented by K. Y. Lo at the URSI Symposium on Very Long Baseline Interferometry held in Heidelberg, Germany, 1978 August 12.

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II. PREVIOUS OBSERVATIONS

Table 1 summarizes prior observations of the galactic center compact radio source.

In 1973 and 1974, the NRL 26 m and NRAO[5] 43 m telescopes were used to study fine-structure in compact H II regions (Lo 1974) at 6 cm, including the strong source, Sgr A. A marginal detection of 0.1 Jy correlated flux density towards Sgr A, at the limit of the sensitivity of the interferometer, was noted. The result was not published, pending confirmation by further observations.

At the same time, Balick and Brown (1974), also while studying compact H II regions at high angular resolution using the NRAO 35 km interferometers, detected unambiguously a compact radio source in Sgr A at both 3.7 and 11 cm and set an upper limit of 0".1 to the source size.

Subsequently, the compact source was observed and detected using the NASA 64 m (MARS) telescope and the Owens Valley Radio Observatory (OVRO) 40 m telescope at 3.7 cm. This set an upper limit of 0".02 to the source size (Lo *et al.* 1975). However, this posed a puzzle as to why the compact radio source was only marginally detected at 6 cm on the NRL–NRAO interferometer which has a fringe spacing of 0".05.

At Jodrell Bank, Davies, Walsh, and Booth (1976) were studying the galactic center using radio-linked interferometers and reported source size measurements of 0".5 and 1".5 at 18 and 31 cm, respectively. They noted

[5]The National Radio Astronomy Observatory is operated by the Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

SUMMARY OF PREVIOUS OBSERVATIONS

DATE OF OBSERVATION	λ OBS (cm)	SOURCE PARAMETERS Θ^a (″)	S_0^b (Jy)	INTERFEROMETER USED[c]	RESOLUTION (″)	REFERENCES
(1) 1973.83 } 1974.58 }	6	...	<0.2	NRAO–NRL	0.05	1
(2) 1974.17	3.7	<0.1	0.8	NRAO 35 km	0.3	2
	11.0		0.6		0.9	
(3) 1975.42	3.7	<0.02	0.7	OVRO–MARS	0.03	3
(4) 1974.5 }..	18.0	0.5	0.6	Jodrell Bank	1.5	4
1975.25–.75 }..	31.0	1.5	0.25		2.7	
(5) 1974.42 }	3.8	0.017	0.6	NRAO–HSTK	0.009	5
1974.92 }		0.001	0.2	{ MARS–HSTK	0.002	
				{ MARS–NRAO	0.002	
(6) 1976.25	3.7	0.014±0.002	0.9	MARS–OVRO	0.03–0.13	6
		(0.001)	<0.1	MARS–HSTK	0.002	
(7) 1976.92	6	...	<0.2	NRAO–NRL	0.05	7
(8) 1977.50	3.8	0.015	...	NRAO–HSTK	0.009	8
		0.001		MARS–NRAO	0.002	

[a] Full-width at half-power of a Gaussian model.
[b] Component flux density.
[c] Parameters of the interferometer are described in Walker *et al.* (1976). OVRO: Owens Valley Radio Observatory 40 m telescope. HSTK: Haystack Observatory 37 m telescope. NRAO: National Radio Astronomy Observatory 43 m telescope. MARS: Goldstone Deep Space Station, NASA, 64 m telescope. NRL: Naval Research Laboratory 26 m telescope.

REFERENCES.—(1) Lo *et al.* 1974. (2) Balick and Brown 1974. (3) Lo *et al.* 1975. (4) Davies *et al.* 1976. (5) Kellermann *et al.* 1977. (6) Lo *et al.* 1977. (7) Lo and Johnston 1976. (8) Geldzahler *et al.* 1979.

that the observed source size of the compact source varied as λ^2, where λ is the observing wavelength, and they suggested that the apparent size is controlled by interstellar scattering. They also pointed out that the wavelength dependence of the observed source size could explain the puzzle of the 6 cm results.

Kellermann *et al.* (1976) measured a size of 0″017 at 3.8 cm and reported the detection of a 0″001 core component with 25% of the total flux of the compact radio source. Lo *et al.* (1977) observed the compact source at 3.7 cm in 1976 but could detect only the larger component and determined a source size of 0″014. However, Geldzahler, Kellermann, and Shaffer (1979) reported results consistent with the model of Kellermann *et al.* (1976).

Thus, it seemed that the structure of the compact source was somewhat ambiguous. The suggestion of interstellar scattering by Davies, Walsh, and Booth (1976) needed confirmation because their measurements at 18 and 31 cm could be confused by compact H II regions known to exist in the region (e.g., Balick 1972). Moreover, the existence of a core component makes the interstellar scattering interpretation more complex (cf. Backer 1978). Thus, even such a basic quantity as source size was still unsettled.

In an attempt to delineate better the source structure of the compact radio source at the galactic center, we initiated the series of VLBI observations at 6, 3.6, 2.8, and 1.3 cm which are described in the next section.

III. OBSERVATIONS AT 6.0, 3.6, 2.8, AND 1.3 CENTIMETERS

All the VLBI observations were made using the standard Mk II recording terminals with a bandwidth of 2 MHz. Maser frequency standards were used at all sites. The observations at different wavelengths were made with different combinations of telescopes, summarized in Table 2. The parameters of the interferometers formed are described in Table 3. The observational procedure and calibration are described below.

a) 6 cm

The 6 cm observations were made using the OVRO 40 m telescope and the University of California Berkeley Radio Astronomy Laboratory 26 m telescope at Hat Creek (HTCK). Three sets of observations were made, two on consecutive days in 1977.34 and one in 1977.94. The experimental setup was identical on all three days and the observing frequency was 4850 MHz.

The fringe amplitude of Sgr A was calibrated relative to that of NRAO 530. The single telescope flux density of NRAO 530 was measured at the 40 m telescope relative to Vir A and Cyg A, with assumed flux densities of 73.8 Jy and 376.5 Jy respectively. The flux density of NRAO 530 was determined to be 5.4 Jy and 5.5 Jy in 1977.34 and 1977.94, respectively.

Figure 1 shows the (u, v)-track of the HTCK–OVRO interferometer for observing Sgr A. For comparison, the

TABLE 2

PARAMETERS OF TELESCOPE SYSTEMS

Telescopes	Diameter (m)	Wavelength (cm)	Sensitivity (Jy/K)	System Temperature toward Sgr A (K)	Receivers Used
HSTK.......	37	3.6	6.7	115	Cooled paramp
		2.8	6.7	110	Cooled paramp
		1.35	17.0	140	Maser
NRAO	43	3.6	4.9	100	Cooled paramp
		2.8	4.8	140	Cooled paramp
		1.35	17.0	120	Maser
MARS	64	3.6	1.6	60	Maser
OVRO	40	6.0	5.2	150	Paramp
		3.6	5.3	225	Paramp
		2.8	5.4	110	Cooled paramp
HTCK[a]	26	6.0	10.7	100	Cooled paramp
		3.6	11.6	220	Paramp[b]

[a]HTCK: Radio astronomy Laboratory, U. C. Berkeley, 26 m telescope at Hat Creek.
[b]Borrowed from OVRO.

TABLE 3

PARAMETERS OF INTERFEROMETER PAIRS

Wavelength (cm)	Pair	Baseline (km)	Range of Fringe Spacings (milli-arcsec)	1σ Sensitivity toward Sgr A[a] (Jy)
6.0	OVRO–HTCK	399	27–150	0.037
3.6	MARS–OVRO	240	30–110	0.025
	MARS–HTCK	735	10–45	0.035
	NRAO–HSTK	845	9–32	0.045
	MARS–NRAO	3260	2.2–2.7	0.015
	MARS–HSTK	3900	1.8–2.1	0.019
2.8	NRAO–HSTK	845	7–25	0.060
	NRAO–OVRO	3325	1.6–1.8	0.055
	HSTK–OVRO	3930	1.4–1.8	0.055
1.35	NRAO–HSTK	845	3.4–12	0.45[b]

[a]Coherent integration time of 5, 15, 10, and 2.7 min at 6, 3.6, 2.8, and 1.35 cm, respectively.
[b]This includes the effects of atmospheric attenuation and cross-polarization between linear and circular feeds.

(u, v)-track of the NRL–NRAO interferometer is also shown. Because of the favorable orientation of the HTCK–OVRO interferometer, the projected baseline is quite short as the source rises, making the detection of the compact radio source at 6 cm possible.

b) *3.6 cm*

The 3.6 cm observations were made on January 24 1978 using five telescopes: NASA 64 m (Mars), NRAO 43 m, OVRO 40 m, Haystack 37 m (HSTK), and HTCK 26 m. Feeds to receive right-circular polarization were used on all telescopes.

The five telescopes form five interferometers (cf. Table 3) with sufficient sensitivity to detect the compact source in Sgr A. Amplitude calibration was made relative to NRAO 530 which was measured to have a flux density of 5.4 Jy with the NRAO interferometer at Green Bank on the same day (R. L. Brown, private communication). Typically, the galactic center was observed for 45 minutes and then NRAO 530 for 15 minutes, and the same cycle was repeated several times during the whole period of common visibility of Sgr A (~7 hours for telescopes on the same coast and only ~3.5 hours for telescopes on opposite sides of the continent.)

Telescope pointing corrections determined for NRAO 530 were applied towards the compact radio source. The weather was generally good at all sites during the observing period.

c) *2.8 cm*

The 2.8 cm (10650 MHz) observations were made in 1977.56 and 1977.94 using three telescopes: the NRAO

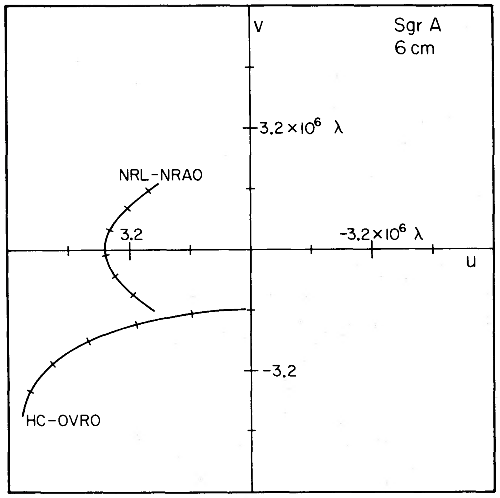

FIG. 1.—The (u, v) coverage of the NRL-NRAO and HC-OVRO interferometers in the direction of Sgr A (HC = Hat Creek).

43 m, HSTK 37 m, and the OVRO 40 m. The telescopes were set up to receive left-circular polarization. Observational procedures were similar to those adopted during the 3.6 cm observations.

d) *1.35 cm*

The 1.35 cm observations were carried out on 1977.93 using the HSTK 37 m and the NRAO 43 m telescopes. At both sites during the observations, the sky was clear and the atmospheric attenuation was low, with zenith optical depth of 0.05. The telescope pointing was optimized using NRAO 530 and the Sgr B2 H_2O source, and the same pointing corrections were used on the galactic center. Observations of the galactic center were alternated with NRAO 530 and the Sgr B2 H_2O source.

IV. RESULTS

The results from the VLBI observations at the various wavelengths are summarized in Table 4. Calibrator sources were detected during all the observations, while the galactic center compact radio source was detected at 6 and 3.6 cm only.

At 6 cm, the compact radio source was detectable during the first two hours after source-rise when the projected baseline of the HTCK-OVRO interferometer is short (cf. Fig. 1). The variation of fringe amplitude with the projected baseline length during both the 1977.34 and 1977.94 observing sessions could be fitted by a single circular Gaussian model with full width at half-power (FWHP) of 0″049±0″015 (Fig. 2). The maximum correlated flux density measured was 0.6 Jy during both sessions. If we extrapolate the fitted Gaussian model to zero spacing, the total flux density of the compact radio source was 1.1±0.2 Jy for both sessions. This agrees within the errors with the flux density measured on 1977.95 using the 5-10 km spacings of the Very Large Array, 0.9±0.05 Jy (C. Bignell, private communication).

At 3.6 cm, fringes were detected on the OVRO-MARS and HTCK-MARS interferometers. However, a problem in the local oscillator chain at HTCK prevented the fringe amplitudes on the HTCK-MARS interferometer from being calibrated. The fringe amplitudes on the OVRO-MARS interferometer were fitted with a Gaussian model with FWHP of 0″018±0″002 (Fig. 3). This is consistent with the detection of fringes on the HTCK-MARS baseline. The extrapolated total flux density was 0.9±0.1 Jy. The flux density of the compact radio source measured on the same day on the NRAO 35 km interferometer at 3.7 cm was 0.73±0.1 Jy (R. L. Brown, private communication). The galactic center compact source was not detected on the other interferometers at 3.6 cm. The data were coherently

TABLE 4

SUMMARY OF OBSERVATIONS

Date of Observations	λ obs (cm)	Source Parameters: Θ[a] (″)	Source Parameters: S_c[b] (Jy)	Interferometer Used	Resolution (″)
1977.93	1.35	...	<1.5	HSTK-NRAO	0.003-0.010
1977.55 }..........	2.8	...	<0.2	OVRO-HSTK	0.002
1977.84 }..........			<0.2	HSTK-NRAO	0.007-0.025
1978.07	3.6	0.018±0.002	0.7	MARS-OVRO	0.03-0.11
		(0.001)	<0.06	MARS-NRAO	0.002
			<0.08	MARS-HSTK	0.002
			<0.17	HSTK-NRAO	0.009-0.03
1977.34	6	0.05±0.01	0.5	OVRO-HTCK	0.025-0.125

[a] Θ: Full-width at half-power of Gaussian fit.

[b] S_c: Maximum correlated flux density; upper limits are 4 σ.

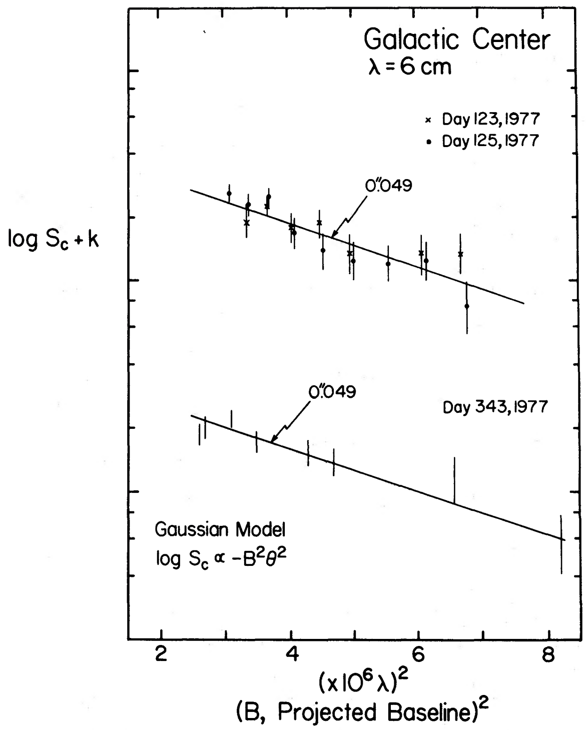

FIG. 2.—A plot of the logarithm of the fringe amplitudes of the compact radio source at 6 cm versus the square of the projected baseline. A Gaussian model is represented by a straight line whose slope depends on the square of the scale size. For the flux density scale, see text (§ IV).

averaged for up to 15 minutes at a range of trial fringe rates to search for the fringe. The coherence time of 15 minutes was verified by coherently averaging data on a calibrator source and checking that the fringe amplitude of the calibrator was not degraded. The upper limits given in Table 4 correspond to 4 times the rms minimum detectable fringe amplitude.

At both 2.8 cm and 1.35 cm, no fringes were detected on Sgr A, while all calibrators were detected. The upper limits quoted in Table 4 correspond to coherent integration times of 10 minutes (2.8 cm) and 2.7 minutes (1.35 cm.)

V. IMPLICATIONS OF OBSERVATIONS

a) *Wavelength-dependence of Observed Sizes*

When we plot the 3.6 and 6 cm measurements of the scale size of the galactic center compact radio source versus observing wavelength along with the measured sizes at 31 and 18 cm reported by Davies, Walsh, and Booth (1976), the points fall quite close to the λ^2 curve (Fig. 4). The negative results at 2.8 and 1.3 cm do not contradict the λ^2-dependence. Davies, Walsh, and Booth (1976) suggested that the λ^2-dependence of the apparent size could be due to scattering by interstellar electrons. An alternate explanation is that of an inhomogeneous synchrotron source with internal absorption by thermal electrons, spatially distributed with a $1/r$ radial dependence (de Bruyn 1976).

It is impossible to distinguish between the two alternative explanations of the wavelength dependence of the

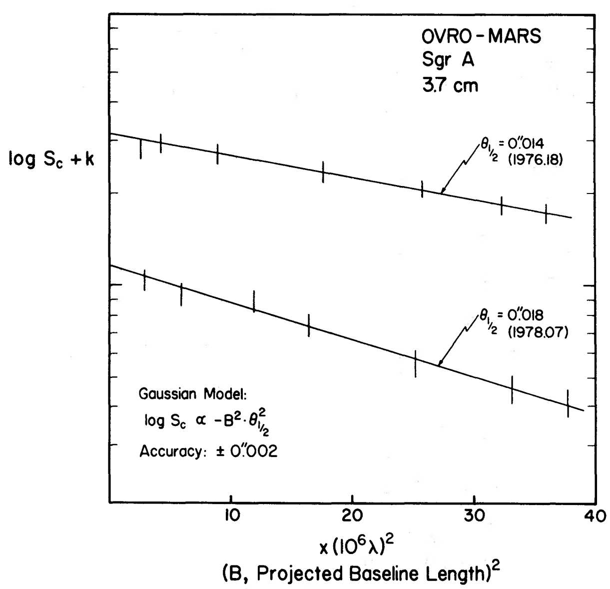

FIG. 3

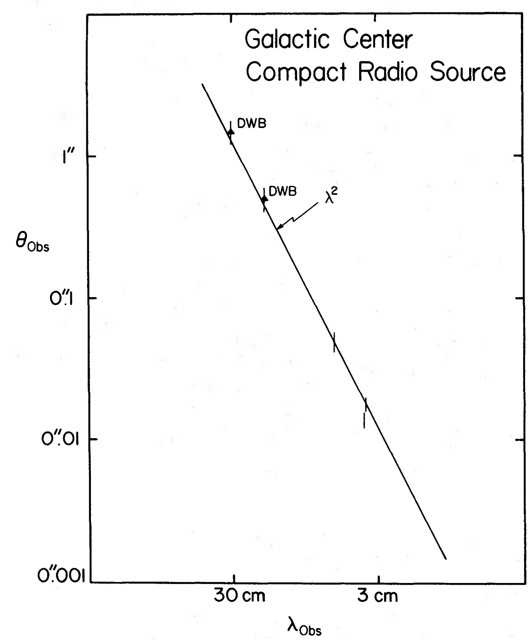

FIG. 4

FIG. 3.—Same plot as Fig. 2, but for data at 3.6 cm. For the flux density scale see text (§ IV).

FIG. 4.—A plot of the logarithm of the FWHP of the fitted Gaussian models versus the observing wavelength. DWB: measurements by Davies, Walsh, and Booth 1976.

observed size based on these observations. Any intrinsic polarization in the radiation from the compact source would be unaffected by interstellar scattering but would probably be completely depolarized by the thermal electrons, so that polarization measurements are important. A detailed map of the source brightness distribution may also help to distinguish between the two alternatives, since conventional models of interstellar scattering of a point source predict a Gaussian brightness distribution. It should be noted that all the size measurements so far have involved a small number of fringe amplitudes along one or two loci in the (u, v) plane. Any structure that deviates from the simple circular Gaussian models may have escaped detection.

b) The Core-Halo Model

Kellermann *et al.* (1977) proposed a core-halo model for the galactic center compact radio source, with diameters of 0″001 and 0″017 and total flux densities of 0.2 and 0.6 Jy for the core and the halo, respectively. We have failed in our 3.6 cm observations to detect fringes on the NRAO–HSTK, MARS–NRAO, and MARS–HSTK interferometers, yielding an upper limit of 0.12 Jy (4σ) for the total flux density of the 0″001 component.

An upper limit of 0.1 Jy (4σ) from the core component had been obtained on the MARS–HSTK interferometer on 1976.18 at 3.7 cm (Lo *et al.* 1977). However, Geldzahler, Kellermann, and Shaffer (1979) reported 3.6 cm measurements at 1977.5 on the NRAO–HSTK, MARS–NRAO, and MARS–HSTK interferometers with results that are consistent with the core-halo models proposed previously by Kellermann *et al.* (1977). The differences might be due to time variation in the flux density of the core component. More observations have to be made to verify the variability of the core component.

c) Interstellar Scattering by Extremely Small Scale Irregularities

To reconcile the core-halo model for the galactic center compact radio source and the presence of interstellar scattering, Backer (1978) invoked extremely small scale irregularities (1 km or less) in the interstellar electron distribution within a few parsec of the galactic center, and presented a set of model visibility curves at various wavelengths based on this model. In particular, the model visibility curves predict that the correlated flux density on baselines 800 km long (e.g., the HSTK–NRAO interferometer) would be 0.45 and 1 Jy at 2.8 and 1.35 cm respectively. While the 1.35 cm observations were not sensitive enough to check the predictions, the upper limit to the 2.8 cm correlated flux density obtained on the HSTK–NRAO interferometer does not confirm the model visibility curve. However, rapid motions of gas clouds in the galactic center (Lacy *et al.* 1979) may allow rapid changes in the scattering.

d) Time Variation in Measured Source Size (?)

Figure 3 shows size measurements with the same interferometer made two years apart. The observed change of 0″004 may not be significant and has to be confirmed by further observations. If the observed change were real and intrinsic to the source, it would imply an expansion velocity of 100 km s^{-1}. If, on the other hand, the observed size was due to interstellar scattering, the characteristics of the anomalous scattering medium must have changed in two years. As the gas near the galactic center has radial velocities as high as 300 km s^{-1} (Lacy *et al.* 1979), the scale size of the scattering medium over which the scattering characteristics change would be on the order of 100 AU.

VI. SOURCE MODELS

The compact radio source at the galactic center, with $T_b > 10^9$ K, is most likely an incoherent synchrotron source. (The observational parameters of the source are summarized in Table 5.) Since both the source size and the turnover frequency in the radio spectrum are uncertain, the physical parameters of the radio source are not well defined, although a discussion of the constraints has been given by Brown, Lo, and Johnston (1978). It is the smallest known synchrotron source located in a galactic nucleus ($l < 10^{14} - 10^{15}$ cm). Similar to the core radio source in M87, the galactic center source has a relatively steady flux density over several years.

A strong constraint on the source model is the very small scale size of the radio source. While observations so far have provided an upper limit of 10–100 AU, inverse Compton scattering would set a lower limit to the source size: For an isotropic source, this limit is 0.5 AU (0″00005). There are at least three possible models —pulsars, binary stars, and massive collapsed objects—meeting the size limit. In the following, we consider their plausibility.

a) Pulsars

Davies, Walsh, and Booth (1976) suggested that the compact radio source could be a pulsar. The energy source for the radio source would be rotation of the neutron star. While there is sufficient energy available

TABLE 5

OBSERVED PARAMETERS OF THE COMPACT RADIO SOURCE

Scale size	$10^{14} - 10^{15}$ cm
Radio luminosity	3×10^{33} ergs s^{-1}
Brightness temperature	$\gtrsim 4 \times 10^9$ K
Spectral index	0.2
Turnover frequency	$\gtrsim$23 GHz
X-ray luminosity	$< 1.5 \times 10^{36}$ ergs s^{-1}
Upper limit to mass	$\lesssim 5 \times 10^6 M_{\odot}$
Flux variability, $\Delta S/S_{\min}$	< 1.0 over 6 years

from a rotating neutron star, the radiation mechanism of the compact radio source must be different from that of an ordinary pulsar: (1) the spectral index of pulsar radiation, α, ($S_\nu \propto \nu^\alpha$) generally lies in the range $-3<\alpha<-1$ (Sieber 1973), whereas that of the compact radio source is 0.2 (Brown, Lo, and Johnston 1978); and (2) the most luminous pulsar known—the Crab pulsar—has an average radio luminosity $\sim 3\times 10^{30}$ ergs s^{-1}, about 1000 times less than that of the compact radio source.

The radiation from the compact source could be incoherent synchrotron radiation from a source like the Crab nebula in a very small volume, but such a source would expand in a very short time unless confined by some mechanism. Reynolds and McKee (1980) suggested that the observed radiation is synchrotron emission from a relativistic wind or jet and proposed that the synchrotron radiation originates just outside the shock in the surroundings of a pulsar caused by the relativistic wind from the pulsar (Rees and Gunn 1974). The emission is confined to a region 10^{15} cm by ram pressure due to the pulsar moving ($v \sim 300$ km s^{-1}) through a dense interstellar cloud ($n \sim 10^5$ cm^{-3}).

However, if the pulsar has a high space motion, it seems coincidental that the source should be nearly coincident ($<1''$) with the 2 μ source, IRS 16, presumably the mass center of the galactic nucleus (Becklin *et al.* 1978). For a characteristic age of 10^6 years for the pulsar, a transverse motion of 100 km s^{-1} would have displaced the source by 0°5 since its birth.

b) *Binary Stellar Radio Sources*

Radio sources associated with binary stellar systems are known to be very compact: for example, VLBI measurements of large radio outbursts in Algol (Clark, Kellermann, and Shaffer 1975; Clark *et al.* 1976) indicate that the radio source size is 0.1 AU or 10^{12} cm. Also, the spectra of the binary radio sources typically rise with frequency ($\alpha>0$) (Gibson 1976). Thus, the galactic center compact radio source could be identified with a binary stellar system: Brown, Lo, and Johnston (1978) suggested that it may be similar to Cyg X3.

However, the galactic center compact radio source differs from the binary radio sources in three respects: time variability, the radio luminosities, and X-ray luminosities. Radio emission from both the X-ray emitting and non–X-ray emitting binary stars is characterized by frequent, large outbursts (Gibson 1976): $\Delta S/S_{\rm min}$ is often 10 or more. By contrast, the galactic center source has displayed no significant ($\Delta S/S_{\rm min}>$ 1.0) outbursts over six years (Ekers 1980).

The galactic center compact radio source has a radio luminosity of $\sim 10^{33.5}$ ergs s^{-1}. The non–X-ray emitting binary stellar radio sources typically have a radio luminosity of 10^{27} ergs s^{-1} (e.g., Gibson 1976). The X-ray emitting binary radio stars have luminosities more comparable to that of the galactic center source: e.g., Cyg X3 has a steady radio luminosity as high as 10^{32} ergs s^{-1}. On the other hand, while the binary stellar X-ray sources generally have X-ray luminosity $>10^{37}$ ergs s^{-1}, the X-ray luminosity of the galactic center compact source is not more than 10^{36} ergs s^{-1} (Cruddace *et al.* 1978).

The galactic center compact source could be similar to the intriguing stellar system, SS 433 (Margon *et al.* 1979). Recent VLA and VLBI observations indicate that the structure of the SS 433 radio source is similar to the structure seen in powerful radio sources (Walker *et al.* 1980; Hjellming and Johnston 1981). However, the SS 433 radio source is different from the galactic center compact source in that it has a negative spectral index ($\alpha<0$) (Walker *et al.* 1981) and varies significantly in flux density (Johnston *et al.* 1980).

c) *Massive Collapsed Object*

The properties of the compact radio source at the galactic center are similar to those of compact nuclear radio sources in external galaxies (Jones, Sramek, and Terzian (1981), in particular, M81 (de Bruyn 1976; Kellermann *et al.* 1976; Preuss *et al.* 1977) and M104 (de Bruyn 1976; Shaffer and Marscher 1979). Although

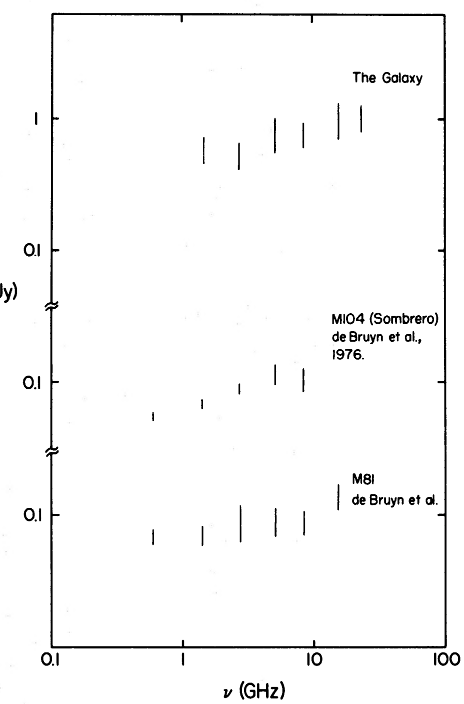

FIG. 5.—Radio spectra of the galactic center compact radio source, M104, and M81. The points of M104 and M81 are taken from de Bruyn 1976. For the Galaxy, the 20, 6, 2, and 1.3 cm points were measured with the VLA in 1979.9 (Lo, Johnston, and Brown 1979), and the 11 and 3.7 cm points were measured with the NRAO 35 km interferometers in 1978.07 (R. L. Brown, private communications).

the galactic center radio source is much less luminous ($10^{33.5}$ compared to 10^{37}–10^{38} ergs s^{-1}), similarities include the radio spectrum (Fig. 5) and the weak variability (de Bruyn 1976; Ekers 1980). If the similarities of the nuclear radio sources in the Galaxy, M81, M104, and the other galaxies are based on the same kind of underlying energy source but with increasing power output, a pulsar or a binary star is clearly ruled out as the energy source.

To account for the infrared dust emission from the nuclear region, Lynden-Bell and Rees (1971) suggested that there may be a black hole in the galactic center. From their spectroscopic studies of the distribution of the 12.8 μ Ne II line in the galactic center, Lacy *et al.* (1980) suggested that the most probable mass distribution responsible for the observed gas motion includes a central pointlike mass of several times 10^6 $M_{\odot}$.

While it is not understood in detail how radio emission is produced by a massive collapsed object, the observed properties of the compact radio source at the galactic center seem consistent with the general picture of the energy being provided by the accretion of matter onto a collapsed object of several times 10^6 $M_{\odot}$.

VII. FURTHER OBSERVATIONS

It seems clear that current observations are insufficient for defining the energy source and that further observations are necessary. To decide whether the energy source for the compact radio source is massive or stellar, one would have to determine the mass of the object. One practical means of probing this question is by measuring the proper motion of the compact radio source. A stellar mass may have acquired a substantial space velocity; a transverse motion of 100 km s^{-1} corresponds to a proper motion of 0\".002 per year at the distance of the galactic center. Such accuracy is achievable with present techniques. A program to measure the proper motion was started by one of us (D. C. B.) in 1975.

Another method is to determine the velocity dispersion of the central star cluster that the compact radio source may be associated with. The extended 2 μ source, IRS 16, which is nearly coincident with the source, is probably the best candidate for such a star cluster. Because of the very high extinction along the line of sight to the galactic center, this would have to be done at the near-infrared wavelength.

Polarization measurements would be useful for defining further the properties of the compact radio source: If the apparent brightness temperature of 10^9 K were intrinsic to the source, the radio emission might be due to gyrosynchrotron radiation by mildly relativistic electrons and significant circular polarization could be present (cf. Hjellming and Gibson 1980). However, inspection of existing measurements with the 35 km interferometers at 11 cm and with the VLA at 6 and 2 cm shows that circular polarization, if present, is less than a few percent.

For more detailed comparison with the extragalactic nuclear sources, it is important to obtain brightness distribution maps at as high a frequency as possible, to minimize both the effects of interstellar scattering and the optical depth due to internal thermal electrons that may be present. Making such maps will have to await a VLB array for the necessary sensitivity and (u, v) coverage.

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