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Dayton L. Jones

Ann E. Wehrle

David L. Meier

B. Glenn Piner

Whittier College, gpiner@whittier.edu

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THE RADIO JETS AND ACCRETION DISK IN NGC 4261

DAYTON L. JONES

Jet Propulsion Laboratory, California Institute of Technology, Mail Code 238-332, 4800 Oak Grove Drive, Pasadena, CA 91109; dj@bllac.jpl.nasa.gov

ANN E. WEHRLE

Jet Propulsion Laboratory, California Institute of Technology, Mail Code 301-486, 4800 Oak Grove Drive, Pasadena, CA 91109; aew@ipac.caltech.edu

DAVID L. MEIER

Jet Propulsion Laboratory, California Institute of Technology, Mail Code 238-332, 4800 Oak Grove Drive, Pasadena, CA 91109; dlm@cena.jpl.nasa.gov

AND

B. GLENN PINER

Jet Propulsion Laboratory, California Institute of Technology, Mail Code 238-332, 4800 Oak Grove Drive, Pasadena, CA 91109; glenn@herca.jpl.nasa.gov

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ABSTRACT

The structure of active galactic nucleus (AGN) accretion disks on subparsec scales can be probed through free-free absorption of synchrotron emission from the base of symmetric radio jets. For objects in which both jet and counterjet are detectable with very long baseline interferometry (VLBI), the accretion disk will cover part of the counterjet and produce diminished brightness whose angular size and depth as a function of frequency can reveal the radial distribution of free electrons in the disk. The nearby (41 Mpc, independent of H_0) FR I radio galaxy NGC 4261 contains a pair of symmetric kiloparsec-scale jets. On parsec scales, radio emission from the nucleus is strong enough for detailed imaging with VLBI. We present new Very Long Baseline Array (VLBA) observations of NGC 4261 at 22 and 43 GHz, which we combine with previous observations at 1.6 and 8.4 GHz to map absorption caused by an inner accretion disk. The relative closeness of NGC 4261 combined with the high angular resolution provided by the VLBA at 43 GHz gives us a very high linear resolution, approximately 2×10^{-2} pc \approx 4000 AU \approx 400 Schwarzschild radii for a $5 \times 10^8 M_\odot$ black hole. The jets appear more symmetric at 1.6 GHz because of the low angular resolution available. The jets are also more symmetric at 22 and 43 GHz, presumably because the optical depth of free-free absorption is small at high frequencies. At 8.4 GHz, neither confusion effect is dominant and absorption of counterjet emission by the presumed disk is detectable. We find that the orientation of the radio jet axis is the same on parsec and kiloparsec scales, indicating that the spin axis of the inner accretion disk and black hole has remained unchanged for at least 10^6 (and more likely $>10^7$) yr. This suggests that a single merger event may be responsible for the supply of gas in the nucleus of NGC 4261. The jet opening angle is between $0^\circ.3$ and 20° during the first 0.2 pc of the jet and must be less than 5° during the first 0.8 pc. Assuming that the accretion disk is geometrically and optically thin and composed of a uniform 10^4 K plasma, the average electron density in the inner 0.1 pc of the disk is 10^3 – 10^8 cm $^{-3}$. The mass of ionized gas in the inner pc of the disk is 10^1 – $10^3 M_\odot$, sufficient to power the radio source for $\sim 10^4$ – 10^6 yr. Equating thermal gas pressure and magnetic field strength gives a disk magnetic field of $\sim 10^{-4}$ to 10^{-2} gauss at 0.1 pc. We include an appendix containing expressions for a simple, optically thin, gas-pressure-dominated accretion disk model that may be applicable to other galaxies in addition to NGC 4261.

Subject headings: accretion, accretion disks — galaxies: active —
galaxies: individual (NGC 4261, 3C 270) — galaxies: jets — galaxies: nuclei

1. INTRODUCTION

The structure of accretion disks in the inner parsecs of active galactic nuclei can be probed on subparsec scales through very long baseline interferometry (VLBI) observations of free-free absorption of synchrotron radiation from the base of radio jets. The nearby radio galaxy NGC 4261 (3C 270) contains a pair of highly symmetric kiloparsec-scale jets (Birkinshaw & Davies 1985), and optical imaging with *Hubble Space Telescope* (*HST*) has revealed a large (~ 300 pc), nearly edge-on nuclear disk of gas and dust (Ferrarese, Ford, & Jaffe 1996). This suggests that the radio axis is close to the plane of the sky. Consequently, relativistic beaming effects should be negligible. This orientation also prevents gravitational lensing by the central black hole from affecting the observed jet-to-counterjet brightness (Bao & Wiita 1997). In addition, the central milliarcsecond (mas) scale radio source is strong

enough for imaging with VLBI (Jones, Sramek, & Terzian 1981). The combination of high angular resolution provided by VLBI at 43 GHz and the relative closeness of NGC 4261 (41 Mpc; Faber et al. 1989) give us a very high linear resolution, approximately 0.1 mas \approx 0.02 pc \approx 4000 AU \approx 400 Schwarzschild radii for a $5 \times 10^8 M_\odot$ black hole. Thus, NGC 4261 is a good system both for the study of an edge-on accretion disk and for intrinsic differences between a jet and counterjet.

Our previous 8.4 GHz Very Long Baseline Array (VLBA) image of NGC 4261 (Fig. 4 in Jones & Wehrle 1997, hereafter JW, reproduced here as Fig. 1) showed the inner parsec of the jet and counterjet, including a surprising narrow gap in emission at the base of the counterjet, which we suspected was caused by free-free absorption in an accretion disk. The central brightness peak at 8.4 GHz was identified as the core by JW, based on its inverted spectral index between 8.4

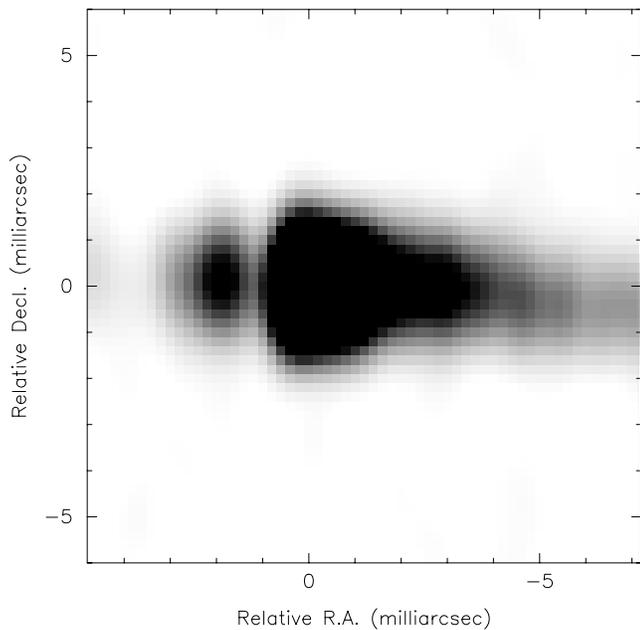


FIG. 1.—Gray-scale image of NGC 4261 at 8.387 GHz showing the bright core and first parsec of the main jet (*pointing west*) plus fainter emission farther along the main jet and near the base of the (*east-pointing*) counterjet. Note the narrow region of reduced brightness just to the east of the bright core, at the apparent base of the counterjet. From Jones & Wehrle (1997).

and 1.6 GHz. The gap seen at 8.4 GHz is similar to the even more dramatic gap seen in the center of NGC 1052 (0238–084) at 15 GHz by Kellermann et al. (1998). We report here 22 and 43 GHz VLBA observations that were made to map this gap with higher resolution. Our goals were to derive the physical characteristics of the disk, namely the allowed ranges of thickness, diameter, electron density, and magnetic field strength.

2. OBSERVATIONS

We observed NGC 4261 using nine stations of the VLBA with full tracks on 1997 September 7, alternating 22 minute scans between 22.2 and 43.2 GHz. Good quality data were obtained from the Hancock, Fort Davis, Pie Town, Kitt Peak, Owens Valley, and Mauna Kea stations, while rain affected North Liberty and Los Alamos and technical problems occurred at Brewster. The Saint Croix antenna was stowed because of hurricane Erika. Left circular polarization was recorded at both frequencies, with a total bandwidth of 64 MHz. Phase offsets between frequency channels were determined and corrected using both 3C 273 and 1308+326.

The data were calibrated and fringe-fitted using standard routines in AIPS,¹ and imaging, deconvolution, and self-calibration were carried out in Difmap (Shepherd, Pearson, & Taylor 1994). Amplitude calibration of VLBI data at 22 and 43 GHz is often problematic because of rapidly changing tropospheric water vapor content. We checked our a priori amplitude calibration by comparing short-baseline flux densities of 3C 273 with total flux density measurements made at 22 and 37 GHz with the 14 m Metsäehovi

antenna. In both cases our flux densities agree with those from Metsäehovi to within 15%.

An 8.4 GHz image of NGC 4261, made in a similar manner from VLBA data obtained in 1995 April, is shown in Figure 2 for comparison with our newer, higher frequency images. The beam size at 8.4 GHz was 1.84×0.80 mas with the major axis almost exactly north-south. Figure 3 illustrates a possible geometry of the central region that is consistent with the radio morphology seen in Figures 1 and 2.

The full-resolution (uniform weighting, no taper) VLBA images at 22 and 43 GHz are shown in Figures 4 and 5, respectively. The beam sizes at 22 and 43 GHz are 1.06×0.29 mas and 0.61×0.16 mas, with the major axis within 20° of north-south. We also made naturally weighted images at both frequencies to search for more extended emission, but no detectable emission was found outside of the area shown in Figures 4 and 5. In addition, Figure 6 shows the 43 GHz image after convolution with the same restoring beam as that used in Figure 4 to allow spectral index measurements. The same field of view is shown in Figures 4 and 6.

The wide range of baseline lengths provided by the VLBA should make it possible to obtain sufficient overlap of the (u, v) coverage between 22 and 43 GHz for spectral index determinations. However, the correct offset between our 22 and 43 GHz images is not known a priori, because we do not have absolute positions. A range of plausible offsets was tried. However, we found that relatively small

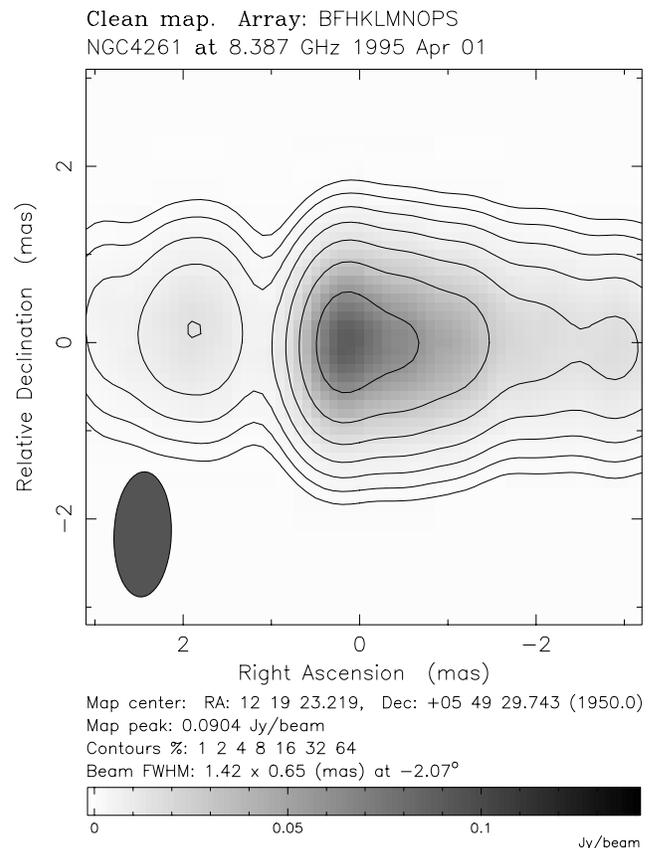


FIG. 2.—VLBA image of NGC 4261 at 8.387 GHz. The contour levels are 1%, 2%, 4%, 8%, 16%, 32%, and 64% of the peak surface brightness ($101 \text{ mJy beam}^{-1}$). The restoring beam is 1.84×0.80 mas with the major axis along position angle $-1^\circ 1$.

¹ The Astronomical Image Processing System was developed by the National Radio Astronomy Observatory.

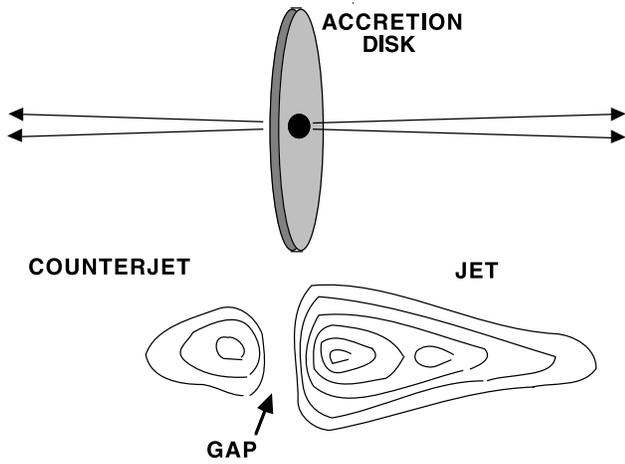


FIG. 3.—Schematic illustration of the central few parsecs in NGC 4261, showing the relative positions of the core (black hole), jet, counterjet, and inner accretion disk.

changes in offset (less than half the east-west beamwidth) produce large changes in the spectral index map. Offsets that do not produce unreasonably large or small spectral index values tend to show that the most inverted spectral slope occurs at the position of the presumed accretion disk absorption and not at the position of the bright compact core and that the spectrum becomes steeper away from the central core and accretion disk region. However, our data do not constrain the spectral index distribution in detail.

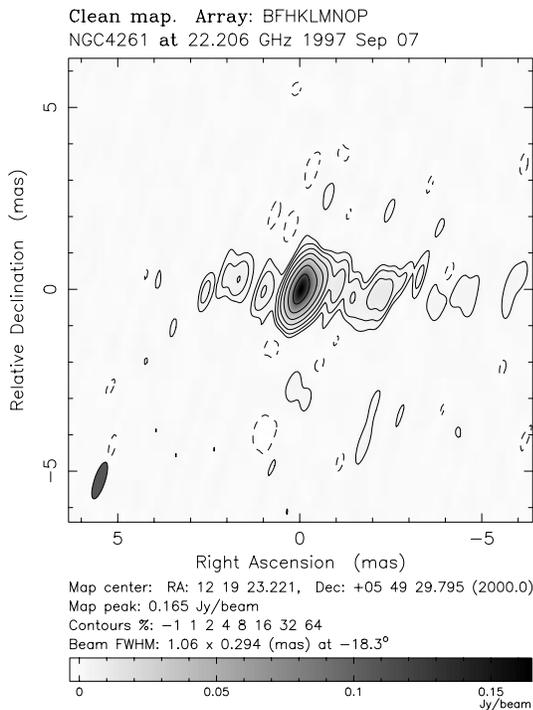


FIG. 4.—Full-resolution 22 GHz VLBA image, showing the first parsec of the radio jet and counterjet, as well as the bright, barely resolved core. The jet-to-counterjet brightness ratio at ± 1 mas from the core is significantly smaller at 22 GHz than at 8.4 GHz (see Figs. 1 and 2). The contours are -1%, 1%, 2%, 4%, 8%, 16%, 32%, and 64% of the peak (165 mJy beam⁻¹), and the restoring beam is 1.06 x 0.29 mas with the major axis along position angle -18.3°. The total flux density in the image is 388 mJy.

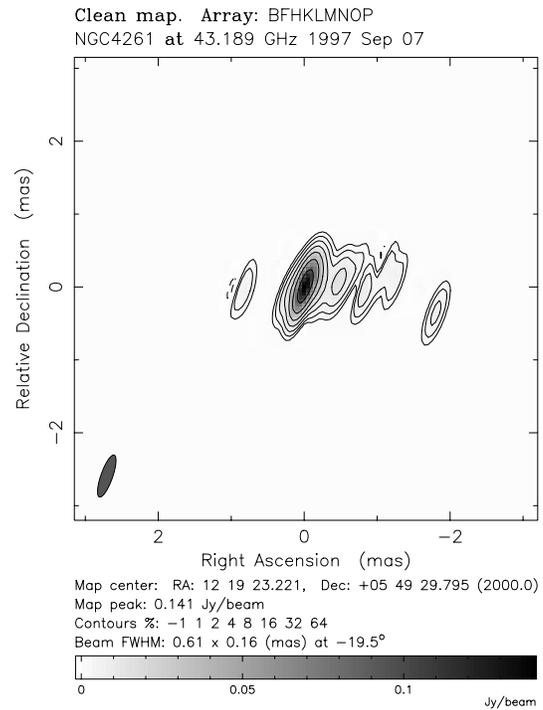


FIG. 5.—Full-resolution 43 GHz VLBA image. The contours are -1%, 1%, 2%, 4%, 8%, 16%, 32%, and 64% of the peak (141 mJy beam⁻¹), and the restoring beam is 0.61 x 0.16 mas with the major axis in position angle -19.5°. Figs. 2 and 5 have the same field of view. The total flux density in the image is 478 mJy.

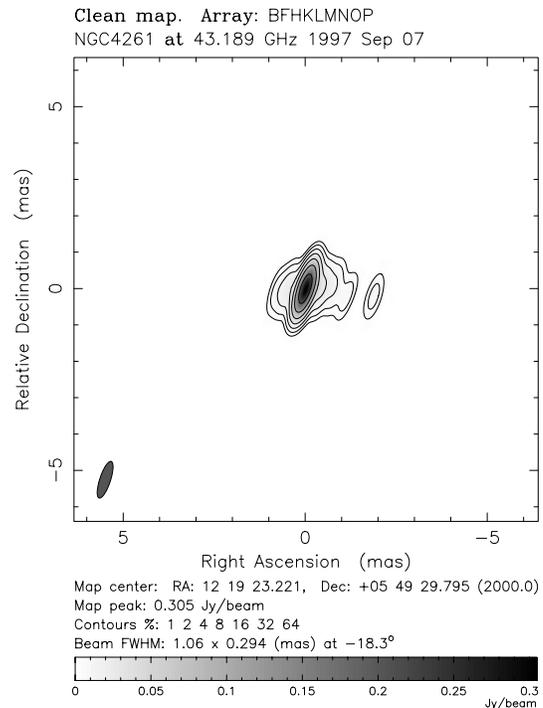


FIG. 6.—43 GHz image convolved with the same restoring beam as the 22 GHz image in Fig. 4 to allow spectral indices to be measured. The contours levels are 1%, 2%, 4%, 8%, 16%, 32%, and 64% of the peak (305 mJy beam⁻¹), with the major axis along position angle -18.3°. Residuals have not been included in this image. Note that Figs. 4 and 6 cover the same field of view. Although only the innermost parts of the jet and counterjet are detectable at 43 GHz, the brightness ratio near the core is closer to unity than it is at lower frequencies.

To see whether amplitude self-calibration had significantly changed the flux density scales of our 22 or 43 GHz images, we compared the peak surface brightness from images made with only phase self-calibration and images made with full amplitude and phase self-calibration. The resulting amplitude corrections applied to the data were 19% at 22 GHz and 12% at 43 GHz. Uncertainties in the absolute flux density scales can shift all of the values in a spectral index map by a constant amount but will not change the shape of the distribution.

3. RESULTS

3.1. *The Parsec-Scale Radio Jets*

The position angle of the jets is $87^\circ \pm 8^\circ$ in our VLBI images, and $88^\circ \pm 2^\circ$ on Very Large Array (VLA) images (Birkinshaw & Davies 1985). The orientation of the jet axis remains the same on kpc and subparsec scales, indicating that the spin axis of the inner accretion disk and black hole has remained unchanged for at least 10^6 yr (assuming an average expansion speed of $0.1 c$) and possibly much longer.

A comparison of our 8, 22, and 43 GHz VLBA images indicates that the region just east of the core, including the first half-parsec of the counterjet, has a highly inverted spectrum ($\alpha > 0$, where $S_\nu \propto \nu^\alpha$). It is plausible that free-free absorption by gas in the central accretion disk is responsible for this. The jet and counterjet both have steep radio spectra ($\alpha < 0$) far from the core, as expected. Note that if the free-free absorption model is correct, the most inverted spectrum may not be located at the position of the true core (the “central engine”).

We can set an upper limit for the jet opening angle by noting that the jet appears unresolved in the transverse (north-south) direction out to at least 4 mas from the absorption feature in Figure 2. Using one-quarter of the north-south beamwidth as an upper limit to the extent of emission in the transverse jet direction gives an upper limit of 5° for the full opening angle during the first 0.8 pc of the jet. A lower limit for the opening angle can be obtained by requiring that the angular size of emission at the location of the bright peak 1 mas from the absorption feature in Figure 2 be large enough to avoid synchrotron self-absorption. This requires an opening angle of less than 0.3° during the first 0.2 pc of the jet. Since we believe that the radio jets in NGC 4261 are nearly perpendicular to our line of sight, projection effects should be minimal and the intrinsic jet opening angle θ is $0.3^\circ < \theta < 20^\circ$ during the first 0.2 pc of the jet and $\theta < 5^\circ$ during the first 0.8 pc of the jet.

Since emission from both the jet and the counterjet is detectable with VLBI, it may be possible to measure proper motions on both sides of the core in this source. If so, the orientation of the radio jets with respect to our line of sight can be found, and any resulting small relativistic beaming effects on the jet/counterjet brightness can be taken into account. A more sensitive 43 GHz VLBI image (where free-free absorption is minimal) can then be used to see just how similar the jet acceleration and collimation processes are on both sides of a “central engine” at the same epoch.

3.2. *The Inner Accretion Disk*

The fact that our 1.6 GHz image (see Fig. 1 in JW) is highly symmetric lets us set an upper limit to the angular size of any absorption feature. At this frequency the free-free optical depth should be large, so in order to avoid detection

the angular size of the absorption feature must be much smaller than our angular resolution at 1.6 GHz. The restoring beam in Figure 1 of JW has an east-west size of 9 mas. The jet/counterjet brightness ratio is unity from the core out to at least ± 25 mas. Using the observed brightness ratio of ≈ 1 at ± 10 mas ($\sim \pm 2$ pc), just larger than our resolution, tells us that the transverse size of any deep absorption feature is $\ll 2$ pc. It is expected that the inner pc or so of an accretion disk orbiting a massive ($\sim 10^8$ – $10^9 M_\odot$) black hole will be geometrically thin, and consequently we will assume a typical disk thickness of $\ll 0.1$ pc and a nominal line-of-sight path length through the inner disk of ~ 0.1 pc. We now use the H I and CO column densities measured by Jaffe & McNamara (1994), $\approx 10^{21} \text{ cm}^{-2}$, to estimate an electron number density of $n_e \geq 3 \times 10^3 (0.1/L) \text{ cm}^{-3}$, where L is the path length in parsecs. A slightly lower density would be deduced using the X-ray absorption column density of $N_H < 4 \times 10^{20} \text{ cm}^{-2}$ from Worrall & Birkinshaw (1994). In both cases it is assumed that there will be on average one free electron per nucleus. This is a conservative assumption since the inner 0.1 pc of the disk should be highly ionized and have a density at least as large as the outer neutral regions. The inclination of the disk is needed to further constrain the path length L and thus the average electron density n_e .

To get an upper limit for n_e , we note that the jet/counterjet brightness ratio at 43 GHz near the core in Figure 6 is also small (≈ 2). This implies a low optical depth at 43 GHz. Assuming an electron temperature of $\sim 10^4$ K (plausible at a disk radius of 0.1 pc), an optical depth $\tau < 1$ at 43 GHz requires $n_e < 4 \times 10^5 (0.1/L)^{1/2} \text{ cm}^{-3}$. However, the temperature of the disk increases at smaller radii, possibly reaching 10^7 – 10^8 K near the inner edge. At these temperatures, an electron number density of $\sim 10^8 (0.1/L)^{1/2} \text{ cm}^{-3}$ is needed to produce an optical depth of unity at 43 GHz. The upper limit for electron number density will be somewhere between $4 \times 10^5 (0.1/L)^{1/2}$ and $10^8 (0.1/L)^{1/2} \text{ cm}^{-3}$, depending on the actual range of electron temperatures along the line of sight.

Thus, the electron number density of the inner accretion disk, averaged over the line of sight, is

$$3 \times 10^3 (0.1/L) < n_e < 10^8 \sqrt{0.1/L} \text{ cm}^{-3}.$$

For comparison, the inner accretion disk believed to be responsible for the unusually inverted spectrum of the radio core in Centaurus A has an average electron number density of at least 10^5 cm^{-3} for a path length of 1 pc (Jones et al. 1996). Assuming a thin inner disk in NGC 4261 with a radius of 1 pc and a thickness of 0.01 pc, an average electron density of 10^6 cm^{-3} , and one proton per electron, the mass of ionized gas in the disk is $\sim 10^3 M_\odot$. Of course, a larger assumed thickness or radius would lead to a larger inner accretion disk mass. Even $10^3 M_\odot$ is sufficient to fuel the central engine for 10^6 yr at an accretion rate of $10^{-3} M_\odot \text{ yr}^{-1}$, consistent with the observed luminosity. A more realistic disk model with thickness increasing with radius and density decreasing with radius is described in Appendix. This model predicts a lower total mass of ionized gas within 1 pc, which implies that material must migrate through the disk from radii greater than 1 pc during the source lifetime. It is interesting to note that the electron number density we derive at 0.1 pc is comparable to that in the solar corona at $\sim 2 R_\odot$. That is, the disk is tenuous and optically thin to visible light.

Equating the thermal gas pressure in the disk with the local magnetic field ($B^2 = 8\pi\alpha n_e kT$, where $\alpha \approx 0.01$ is the usual viscosity parameter; Shakura & Sunyaev 1973) gives a disk magnetic field of $\sim 10^{-2}$ to 10^{-4} gauss at 0.1 pc. General expressions for estimating physical parameters in an optically thin, gas-pressure-dominated accretion disk at radii of ~ 0.1 – 1 pc are derived in Appendix. Table 1 compares these parameter values with those for other galaxies in which there is evidence for an inner accretion disk. Of the five nearby (< 100 Mpc) radio galaxies for which some inner accretion disk characteristics are known, only two (NGC 4261 and NGC 4258) have well-determined central black hole masses (see Table 1).

4. DISCUSSION

A geometrically thin inner disk that would not completely obscure optical emission from the core is a plausible model, given the very high percentage of low-luminosity 3CR radio galaxies that have bright, unresolved optical continuum sources visible in *HST* Wide Field and Planetary Camera 2 (WFPC2) images (Chiaberge, Capetti, & Celotti 1998). This includes NGC 4261. A geometrically and optically thick dusty torus would obscure the central optical continuum source in many low-luminosity objects with FR I radio morphology, since these sources are expected to be oriented at large angles to our line of sight. A nearly edge-on disk orientation may also explain the low bolometric luminosity of the NGC 4261 nucleus and lack of an ultraviolet excess in its spectral energy distribution (Ho 1999). Additional constraints on the inclination and density of the inner disk could come from observations of free-free radio emission from ionized disk gas or radio emission from the central jets scattered by electrons in the far inner edge of the accretion disk (Gallimore, Baum, & O’Dea 1997). However, the dynamic range of our VLBA images is not adequate to detect this emission in the presence of the bright parsec-scale radio jets. Another way to constrain the radio axis orientation, and thus the inner disk orientation, would be measurement of proper motions in both the jet and the counterjet (e.g., Taylor, Wrobel, & Vermeulen 1998). VLBA observations to attempt this are underway.

The above analysis makes use of the fact that the observed jet/counterjet brightness ratio in NGC 4261, and in some other galaxies that are well observed with VLBI, peaks at intermediate frequencies and falls to nearly unity at

both low frequencies (where the beam is much larger than the angular size of the absorbing material) and high frequencies (where the free-free optical depth becomes very small). See, for example, Figure 15 in Krichbaum et al. (1998). At low frequencies the brightness ratio R should decrease approximately linearly with frequency ($\theta_{\text{beam}} \propto \nu^{-1}$), while at high frequencies the falloff of R should be more rapid ($\tau_{f-f} \propto \nu^{-2}$). With VLBA images at four frequencies we cannot confirm this behavior in detail, but it is clear that near the core the brightness ratio R is greater at 8.4 GHz than at 1.6, 22, or 43 GHz.

The mass of the central black hole in NGC 4261 is $(5 \pm 1) \times 10^8 M_{\odot}$ (Ferrarese, Ford, & Jaffe 1996). Thus, the mass of material in the inner accretion disk is negligible compared with the black hole mass, and the orbital period of material in the inner accretion disk at a radius r (in pc) is $\approx 4 \times 10^9 (r/0.1)^{3/2}$ s ($\approx 10^2$ yr for $r = 0.1$ pc). The spin rate of the central black hole is unknown but is predicted to be small to moderate by the model of Meier (1999). A lower limit on the spin of the black hole can be derived from the known mass of the hole, the assumed accretion rate ($10^{-3} M_{\odot} \text{ yr}^{-1}$), and the spin axis alignment timescale ($> 10^6$ yr) implied by the colinear kiloparsec-scale jets. The resulting dimensionless spin parameter (see Misner, Thorne, & Wheeler 1973) is greater than 2×10^{-4} , which allows either high or low black hole spin rates.

The angular momentum of gas in the inner accretion disk is expected to be aligned with the spin axis of the black hole (Bardeen & Petterson 1975). If the black hole is spinning slowly, its spin axis will eventually become aligned with the angular momentum of the accreting gas at large radii (Natarajan & Pringle 1998). However, the long-term directional stability of the radio jets in NGC 4261 implies that the gas falling into the central region of the galaxy and supplying the central engine has had a constant angular momentum direction for most of the life of the radio source. This in turn implies that a single merger event may be responsible for the supply of gas in the nucleus of NGC 4261.

5. CONCLUSIONS

We have imaged the nuclear radio source in NGC 4261 with the VLBA at four frequencies. We find that the jet/counterjet brightness ratio near the core is larger at 8.4 GHz than at lower frequencies. This can be explained by a com-

TABLE 1
CHARACTERISTICS OF ACCRETION DISKS

Source Name	Distance ^a (Mpc)	S_{jet}^b (Jy)	Height (pc)	Radius (pc)	n_e (cm^{-3})	Disk Magnetic Field (G)	M_{BH} (M_{\odot})	Assumed Temperature (K)	Reference
NGC 5128.....	3.5	7.0	< 1	> 1	$> 10^5$	$> 2 \times 10^{-3}$	...	10^4	1
NGC 4258.....	6.4	0.003	< 0.1	~ 0.3	...	$\leq 3 \times 10^{-1}$	3.5×10^7	N/A	2
NGC 1052.....	17	1.0	~ 0.1	> 1	$\sim 10^5$	3×10^{-3}	...	10^4	3
NGC 4261.....	41	0.5	~ 0.01	~ 0.1	$\sim 10^6$	10^{-4} to 10^{-2}	5×10^8	10^4	4
Mrk 348.....	56	0.5 v	~ 0.1	~ 1	10^5 – 10^7	$\approx 6 \times 10^{-4}$	...	8×10^3	5
Mrk 231.....	168	0.03 v	~ 0.1	~ 1	10^5 – 10^7	$\approx 6 \times 10^{-4}$	...	8×10^3	5
Cygnus A.....	225	1. v	< 0.3	< 15	$> 7 \times 10^3$	$> 4 \times 10^{-4}$	...	$> 3 \times 10^3$	6
1946+708.....	400	0.3	< 20	< 50	$> 2 \times 10^2$	$> 10^{-5}$	...	8×10^3	7
NGC 1275.....	700	30. v	~ 0.1	> 25.0	$\sim 7 \times 10^4$	8×10^{-4}	$\sim 10^8$	10^4	8

^a Using $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for distances given as redshifts. The four nearest galaxies have published distances that do not depend on H_0 .

^b The letter “v” indicates variability.

REFERENCES.—(1) Jones et al. 1996, Tingay et al. 1998; (2) Herrnstein et al. 1997, 1998; (3) Braatz et al. 1999, Kellermann et al. 1999; (4) This paper; (5) Ulvestad et al. 1999; (6) Krichbaum et al. 1998; (7) Peck, Taylor, & Conway 1999; (8) Dhawan, Kellermann, & Romney 1998.

bination of two effects: low angular resolution at 1.6 GHz, which masks small-scale brightness variations, and low absorption by ionized thermal gas at 22 and 43 GHz. The brightness asymmetry at 8.4 GHz could be caused by a nearly edge-on inner accretion disk. If so, the (model-dependent) electron density in the inner 0.1 pc of the disk has an average value between 3×10^3 and 10^8 cm^{-3} . Future observations to measure proper motions in the jet and counterjet will better define the orientation of the radio axis and thus the inclination of the inner accretion disk. This will determine the path length L through the disk and consequently reduce the allowable range of electron number density averaged over the path length.

The optically thin, uniform-temperature model disk described in the Appendix, derived only from accretion physics and values of the black hole mass and accretion rate consistent with NGC 4261, is remarkably similar to the disk

that we observe in free-free absorption against the radio jet. We therefore believe that these observations have detected the subparsec accretion disk powering the active nucleus in NGC 4261.

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APPENDIX

ISOTHERMAL, OPTICALLY THIN ACCRETION DISKS FAR FROM BLACK HOLES

In this appendix we describe a simple accretion disk model, suitable for optically thin gas-pressure-dominated flow far from the black hole, in which the plasma temperature is a very slowly varying function of distance from the hole. The canonical temperature is assumed to be 10^4 K for the range of interest in this model. (Such a temperature is typical of an optically thin, warm plasma undergoing moderate heating to keep it mostly ionized.) Following Shakura & Sunyaev (1973), and ignoring the factor of $(1 - r^{-1/2}) \approx 1$ (since at 0.1–1.0 pc, $r = R/3R_{\text{Sch}} = 3400\text{--}34,000$ for a $10^8 M_{\odot}$ black hole), we obtain the following equations for the disk structure, expressed in units of $M_8 \equiv M_{\text{BH}}/10^8 M_{\odot}$ for the black hole mass: $\dot{M}_{-3} \equiv \dot{M}/(10^{-3} M_{\odot} \text{ yr}^{-1}) = \dot{M}/(6.3 \times 10^{22} \text{ g s}^{-1})$ for the accretion rate, and $R_{18} \equiv R/10^{18} \text{ cm}$ for the distance from the black hole.

From the equation for hydrostatic equilibrium in the direction perpendicular to the disk, the disk half-thickness is

$$H = 0.0026 \text{ pc } M_8^{-1/2} R_{18}^{3/2}. \quad (\text{A1})$$

For NGC 4261, with $M_8 = 5$, the full disk thickness at a radius of 1 pc ($R_{18} = 3$) is 0.012 pc, very close to the 0.01 pc thickness assumed for the simple uniform thickness disk in § 3.2. Adopting a radiative cooling rate of $\sim 3 \times 10^{-23} n^2 \text{ ergs cm}^{-3}$ at 10^4 K (Krolik 1999) and setting it equal to the energy generated locally by viscous (accretion) heating, we obtain the particle density

$$n = 1.5 \times 10^4 \text{ cm}^{-3} M_8^{3/4} \dot{M}_{-3}^{1/2} R_{18}^{-9/4}. \quad (\text{A2})$$

The approximate optical depth of the disk in a direction perpendicular to it, caused by the inverse absorption processes (at $\nu \sim kT/h \approx$ optical frequencies), is

$$\tau_{\text{abs}} = 1.4 \times 10^{-11} M_8 \dot{M}_{-3} R_{18}^{-3}, \quad (\text{A3})$$

and that caused by electron scattering is

$$\tau_{\text{es}} \leq 1.5 \times 10^{-4} M_8^{1/4} \dot{M}_{-3}^{1/2} R_{18}^{-3/4} \quad (\text{A4})$$

(an upper limit, since the gas is not fully ionized). At IR-optical-UV wavelengths, therefore, the disk is very optically thin. It becomes optically thick to free-free absorption in the perpendicular direction ($\kappa_{\nu} m_p n 2H \geq 1$) only below the frequency

$$\nu_{\text{perp}} = 250 \text{ MHz } M_8^{1/2} \dot{M}_{-3}^{1/2} R_{18}^{-3/2}. \quad (\text{A5})$$

However, if viewed nearly edge-on, with the line-of-sight passing roughly from $R_{18}/3$ to $3R_{18}$ (i.e., 0.1–1.0 pc), the disk will be optically thick to free-free ($\int \kappa_{\nu} m_p n dR \geq 1$) below the frequency

$$\nu_{\text{edge-on}} = 8 \text{ GHz } M_8^{3/4} \dot{M}_{-3}^{1/2} R_{18}^{-7/4}. \quad (\text{A6})$$

For $M_8 = 5$, we get

$$\nu_{\text{edge-on}} = 27 \text{ GHz } \dot{M}_{-3}^{1/2} R_{18}^{-7/4}. \quad (\text{A7})$$

The mass of the disk within this radius range, and flow timescale (R/v_R), is

$$M_{\text{disk}} = 3.9 M_{\odot} M_8^{1/4} \dot{M}_{-3}^{1/2} R_{18}^{5/4}, \quad (\text{A8})$$

$$t_{\text{acc}} = 1200 \text{ yr } M_8^{1/4} \dot{M}_{-3}^{-1/2} R_{18}^{5/4}. \quad (\text{A9})$$

Three consistency checks on the model are the ratio of the half-thickness to disk radius at a given point, the ratio of the accretion (inflow) velocity to the Keplerian velocity, and the ratio of inward heat advection to radiative cooling, all of which

should be small, given the assumptions of the model. We find that

$$\frac{H}{R} = 0.008 M_8^{-1/2} R_{18}^{1/2} \quad (\text{A10})$$

for the disk height,

$$\frac{-v_R}{v_K} = 0.23 M_8^{-3/4} \dot{M}_{-3}^{1/2} R_{18}^{1/4} \quad (\text{A11})$$

for the inflow velocity, and

$$\frac{\dot{\epsilon}_{\text{adv}}}{\dot{\epsilon}_{\text{rad}}} = 2.5 \times 10^{-4} M_8^{-1} R_{18} \quad (\text{A12})$$

for the magnitude of the advection of thermal energy. Each of these three ratios will be even smaller if $M_8 = 5$, the value appropriate for NGC 4261, is used. (Note that, because of the low optical depth, the photon distribution is not a blackbody and has an even lower energy density than the thermal gas.) The assumption of a thin, radiating, 10^4 K, Keplerian accretion disk, therefore, is consistent with the model calculations, as well as with our observational results for the absorbing disk in NGC 4261.

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