

# THE FIRST FEW PARSECS OF THE JETS IN NGC 4261

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**Abstract.** We have imaged the nucleus of the nearby radio galaxy NGC 4261 (3C270) with the VLBA at 1.6, 8.4, 22, and 43 GHz. At 8.4 GHz our image reveals a narrow gap in emission just east of the core, which we interpret as absorption by an inner accretion disk seen nearly edge-on. If correct, this interpretation implies that the radio jets are almost perpendicular to our line of sight. Thus, NGC 4261 provides an unusually good opportunity to measure component proper motions in both jet and counterjet, free from most relativistic beaming effects. Observations to do this are underway. This is one of the very few sources in which both jet and counterjet are detectable on parsec scales, and it is also one of the closest “classical” double-lobed radio galaxies. Consequently, NGC 4261 is a good laboratory for testing models of jets in low luminosity radio galaxies.

## 1. Introduction

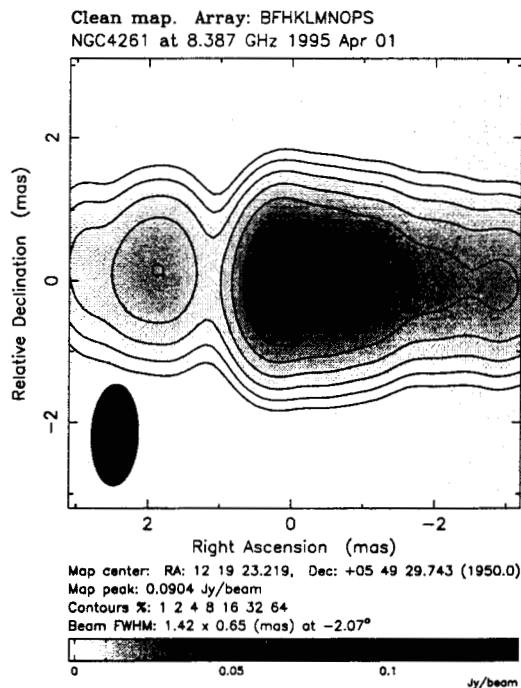
The structure of accretion disks in the inner parsecs of active galactic nuclei can be probed on sub-parsec scales through VLBI observations of free-free absorption of synchrotron radiation from the base of radio jets. The nearby radio galaxy NGC 4261 (3C270) contains a pair of highly symmetric kpc-scale jets (Birkinshaw and Davies 1985, [1]), and optical imaging with HST has revealed a large, nearly edge-on nuclear disk of gas and dust (Ferrarese, Ford, and Jaffe 1996, [2]). This suggests that the radio axis is close to the plane of the sky, and consequently relativistic beaming effects should be negligible. This orientation also precludes gravitational lensing by the central black hole from affecting the observed jet-to-counterjet brightness (Bao and Wiita 1997, [3]). In addition, the central milliarcsecond (mas) scale radio source is strong enough for detailed imaging with VLBI. Thus, NGC 4261 is a good system for the study of an edge-on accretion disk and intrinsic differences between a jet and counterjet.

Our previous 8.4 GHz VLBA image of NGC 4261 (see figure 4 in Jones and Wehrle 1997, [4]; hereafter JW) shows the inner parsec of the jet and counterjet, including a 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 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) [5]. We report here 22 and 43 GHz VLBA† observations which were made to map this gap with higher resolution. The combination of high angular resolution provided by the VLBA at 43 GHz and the relative closeness of NGC 4261 (41 Mpc; Faber et al. 1989 [6]) give us a very high linear resolution, approximately  $0.02 \text{ pc} \approx 4000 \text{ AU} \approx 400$  Schwarzschild radii for a  $5 \times 10^8 M_{\odot}$  black hole.

## 2. Observations and Results

We observed NGC 4261 with the 10-station VLBA on 7 September 1997, alternating 22-minute scans between 22.2 and 43.2 GHz. 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 3C273 and 1308+326. The data were calibrated and fringe-fit using standard routines in AIPS‡ and imaging, deconvolution, and self-calibration were carried out in Difmap (Shepherd, Pearson, and Taylor 1994 [7]). An 8.4 GHz image of NGC 4261, made in a similar manner from VLBA data obtained in April 1995, is shown in figure 1 for comparison with our newer, higher frequency images.



**Figure 1.** 8.4 GHz VLBA image of NGC 4261 showing the rapid decline in brightness just east (left) of the brightest peak.

‡ The Very Long Baseline Array (VLBA) is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., for the National Science Foundation.

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

The full resolution (uniform weighting, no taper) images at 43 and 22 GHz are shown in figures 2 and 3, respectively. In both cases no detectable emission was found outside of the area shown.

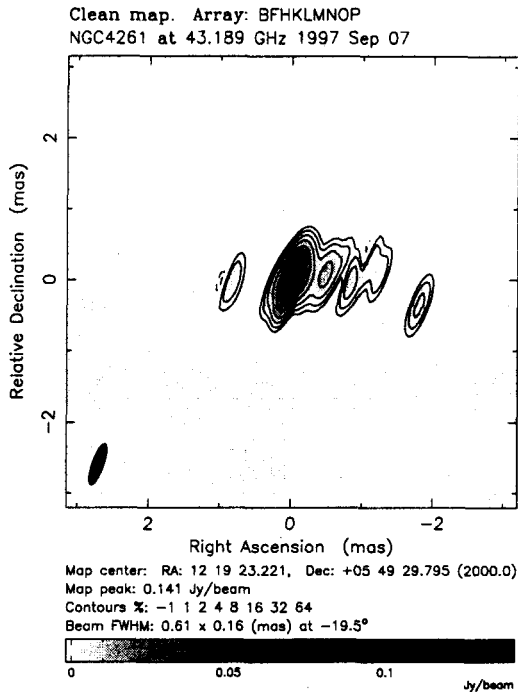


Figure 2. Full resolutions VLBA image of NGC 4261 at 43 GHz.

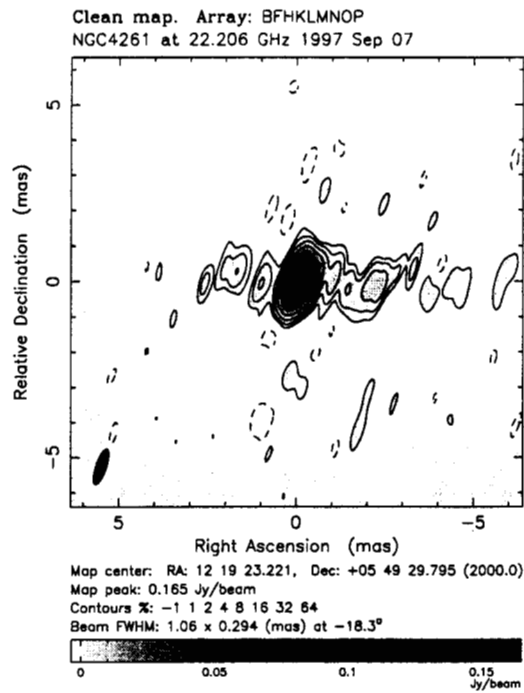
In addition, figure 4 shows the 43 GHz image after convolution with the same restoring beam as used in figure 3 to allow spectral index measurements. Although only the innermost parts of the jet and counterjet are detectable at 43 GHz, it is clear that the brightness ratio near the core is closer to unity than it is at lower frequencies.

A comparison of our 8, 22, and 43 GHz VLBA images indicates that the region just east of the core, including the first parsec of the counterjet, has a highly inverted spectrum ( $\alpha > 0$ , where  $S_\nu \propto \nu^\alpha$ ). Indeed, the most inverted spectral slope occurs at the position of the presumed accretion disk and not at the position of the bright core. 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 this model is correct, the most inverted spectrum may not be located at the position of the true core (the “central engine”).

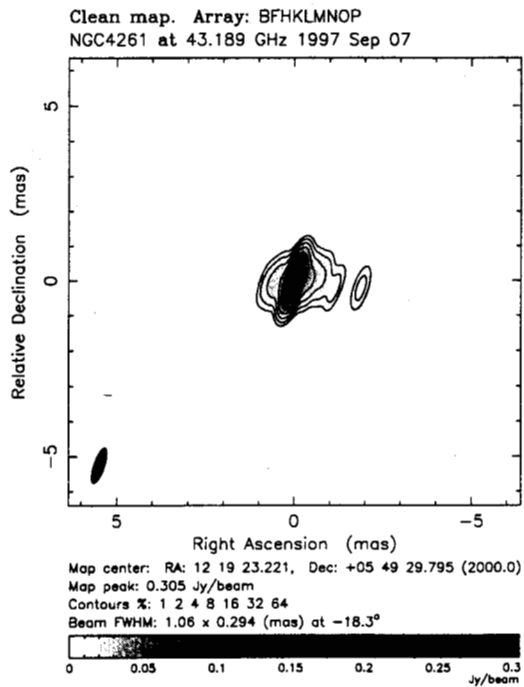
We find that the orientation of the radio jet axis is the same on pc and kpc scales, indicating that the spin axis of the inner accretion disk and black hole has remained unchanged for at least  $10^6$  (and more likely  $> 10^7$ ) years.

### 3. Discussion

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



**Figure 3.** 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  $\pm 1$  mas from the core is smaller at 22 GHz than at 8.4 GHz.



**Figure 4.** 43 GHz VLBA image convolved with the same restoring beam as the 22-GHz image in figure 3.

the absorption 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  $\pm 25$  mas. Using  $\pm 10$  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  $\sim 0.1$  pc. We now use the HI and CO column densities measured by Jaffe and McNamara (1994)[8],  $\approx 10^{21} \text{cm}^{-2}$ , to estimate an electron density of  $n_e \geq 3 \times 10^3 (0.1/L) \text{cm}^{-3}$ , where  $L$  is the path length in pc. 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 and Birkinshaw (1994)[9]. 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 pc of the disk should be fully ionized. The inclination of the disk is needed to further constrain  $L$  and thus  $n_e$ .

To get an upper limit for  $n_e$ , we note that the jet/counterjet brightness ratio near with core in figure 4 is also small ( $\approx 2$ ). This implies a low optical depth at 43 GHz. Assuming that the inner disk thickness is  $< 0.01$  times its radius in the inner pc, the temperature at 0.1 pc will be approximately  $10^8$  K. At this electron temperature, an optical depth  $\tau < 1$  at 43 GHz requires  $n_e < 4 \times 10^8 \sqrt{0.1/L} \text{cm}^{-3}$ . Thus, the electron density of the inner accretion disk, averaged over the line of sight, is

$$3 \times 10^3 (0.1/L) < n_e < 4 \times 10^8 \sqrt{0.1/L} \text{cm}^{-3}. \quad (1)$$

Assuming a thin inner disk with a radius of 1 pc and a thickness of 0.01 pc, an average electron density of  $10^6 \text{cm}^{-3}$ , and one proton per electron, the mass of ionized gas in the disk is  $\sim 10^3 M_\odot$ . Of course, a larger assumed radius would lead to a larger inner disk mass. Even  $10^3 M_\odot$  is sufficient to fuel the central engine for  $10^6$  years at an accretion rate of  $10^{-3} M_\odot$  per year, consistent with the observed luminosity. 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 and Sunyaev 1973, [10]) gives a disk magnetic field of  $\sim 0.1$  gauss at 0.1 pc.

A geometrically thin inner disk is a plausible model given the very high percentage of low luminosity 3CR radio galaxies which have bright, unresolved optical continuum sources visible on HST/WFPC2 images (Chiaberge et al. 1998, [11]). This includes NGC 4261. A geometrically 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, [12]). 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 inner disk (Gallimore, Baum, and O'Dea 1997, [13]). 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, and thus the inner disk, orientation would be measurement of proper motions in both the jet and counterjet (*e.g.*, Taylor, Wrobel, and Vermeulen 1999, [14]). 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 which 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) [15]. At low frequencies the brightness ratio  $R$  should decrease approximately linearly with frequency ( $\theta_{\text{beam}} \propto \nu^{-1}$ ), while at high frequencies the fall-off of  $R$  should be more rapid ( $\tau_{\text{r-f}} \propto \nu^{-2}$ ). With VLBA images at four frequencies we can not confirm this behaviour in detail, but it is clear that near the core  $R$  is greater at 8.4 GHz than at 1.6, 22, or 43 GHz. The similar jet and counterjet brightness near the core at 43 GHz implies minimal absorption, so the more gradual decrease in brightness of the jet compared with the counterjet may reflect intrinsic asymmetry in the brightness or the ambient medium on opposite sides of the core.

The mass of the central black hole in NGC 4261 is  $(5 \pm 1) \times 10^8 M_{\odot}$  (Ferrarese, Ford, and Jaffe 1996, [2]). Thus, the mass of material in the disk is negligible compared to the black hole mass, and the orbital period of material in the disk at a radius  $R$  (in pc) is  $\approx 4 \times 10^9 (R/0.1)^{3/2}$  seconds ( $\approx 10^2$  years for  $R = 0.1$  pc). The spin rate of the central black hole is unknown, but is predicted to be small by the model of Meier (1999) [16]. The angular momentum of gas in the inner accretion disk is expected to be aligned with the spin axis of the black hole (Bardeen and Petterson 1975, [17]). 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 and Pringle 1998, [18]). 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.

#### 4. Conclusions

Since emission from both the jet and 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 residual relativistic beaming effects on the jet/counterjet brightness accounted for. 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.

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