VLBA IMAGING OF NGC 4261: SYMMETRIC PARSEC-SCALE JETS AND THE INNER ACCRETION REGION

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ABSTRACT

We observed the nuclear region of NGC 4261 (3C 270) with VLBI to determine the morphology of the central radio source on parsec scales and in particular to see whether the inner radio axis remained in the same direction as the kiloparsec-scale jets or whether it was aligned with the apparent rotation axis of the nuclear disk imaged by HST. The position angle of the radio axis in our Very Long Baseline Array (VLBA) images agrees, within the errors, with the position angle of the VLA-scale jet. Thus, there is no evidence for precession of the jets on timescales shorter than the material propagation time from the nucleus to the diffuse radio lobes. Our dual frequency observations also reveal basically symmetric radio structures at both 1.6 and 8.4 GHz. Analysis of these images shows that most of the central 10 pc of this source is not significantly affected by free-free absorption, even though HST images of the nucleus of the galaxy show it to contain a nearly edge-on disk of gas and dust on larger scales. The lack of detectable absorption over most of the central 10 pc implies that the density of ionized gas in this region is less than \( \sim 10^3 \) cm\(^{-3} \), assuming a temperature of \( \sim 10^4 \) K. Our highest angular resolution images show a very narrow absorption feature just east of the radio core, suggesting that there may be a small, dense inner accretion disk with a width of less than 0.1 pc. If the inclination of this inner disk is close to that of the larger scale HST disk, it becomes optically thin to 8.4 GHz radiation at a deprojected radius of about 0.8 pc. The brightness of the parsec-scale jets falls off very rapidly on both sides of the core, suggesting that the jets are rapidly expanding during the first several parsecs of their travel. The rate of jet expansion must slow when the internal pressure falls below that of the external medium. We suggest that this occurs between about 10 and 200 pc from the core because the rate of decrease in radio brightness is far slower at more than 200 pc from the core than it is within 10 pc of the core. It appears that there is a small, dense inner disk centered on the radio core (the base of the jets; less than 1 pc), a low-density, presumably hot “bubble” filling most of the inner several parsecs of the nucleus (within which the radio jets expand rapidly; \( \sim 10 \) pc), and a surrounding cool, higher density region (of which the HST absorption disk is part; \( > 10 \) pc) within which the transverse expansion of the radio jets, as implied by the rate of decrease in jet brightness, is nearly halted.

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

1. INTRODUCTION

The radio source 3C 270 (PKS 1216 + 06) associated with the E2 galaxy NGC 4261 is composed of two symmetric lobes of extended emission on opposite sides of the galaxy, connected by symmetric kiloparsec-scale jets to a compact radio source coincident with the optical nucleus of the galaxy. The compact radio core is a relatively weak VLBI source (180 mJy at 1.6 GHz; Jones, Sramek, & Terzian 1981). The radio jets extend out approximately \( \pm 4^\circ \), have opening angles of less than \( 5^\circ \), and are co-aligned to within \( 1^\circ \) along position angle \( 88^\circ \) (Birklinshaw & Davies 1985). The ratio of jet/counterjet surface brightness within a few arcseconds of the central compact source is only about 2:1, indicating that relativistic beaming effects are not strong on kiloparsec scales. The minor axis position angle of the galaxy remains \( 69^\circ \pm 2^\circ \) over a wide range of radii (van den Bosch et al. 1994; Ferrarese, Ford, & Jaffe 1996), \( 19^\circ \) from the radio axis, but the stellar rotation axis is along position angle \( 153^\circ \pm 4^\circ \) (Davies & Birklinshaw 1986), only \( 6^\circ \) from the projected major axis of the galaxy. Evidently NGC 4261 is a nearly prolate galaxy, the stellar rotation axis of which has no relationship with the direction of the radio jets.

 Möllenhoff & Bender (1987) discovered a small dust lane in the center of NGC 4261 that is oriented perpendicular to the radio jets. More recent HST observations have revealed that the optical nucleus is surrounded by a disk of gas and dust \( 1.7 \) in diameter with a projected rotation axis aligned within several degrees of the radio jets (Jaffe et al. 1993, 1996; Ferrarese et al. 1996). At a distance of \( 41 \) Mpc (Faber et al. 1989) the HST disk diameter is \( 340 \) pc. Some authors give distance estimates up to 3 times smaller than this, which of course would reduce the calculated physical size of the HST disk by the same factor. The rotation axis of the HST disk is inclined \( 69^\circ \) from our line of sight based on HST FOS spectral data, or \( 64^\circ \) based on isophote fitting.
The apparent inclination of the HST absorption disk and the larger scale (Möllenhof & Bender's 1987 dust lane) disk differ by about 10°. It is likely that the HST disk and the larger scale dust lane are both part of a single warped disk structure (Mahabal et al. 1996). Since the minor axis of the HST disk is at a position angle of 63° ± 2° (Ferrarese et al. 1996), which is not parallel to the position angle of the radio jets (88° ± 1°; Birkinshaw & Davies 1985), the presumed warp continues in the region close to the central black hole. Jaffe et al. (1996) point out that the apparent center of the HST disk is displaced from the optical center of the galaxy (based on isophote fitting) by at least 5 pc (see also Ferrarese et al. 1996).

Neutral hydrogen and CO have been detected in absorption against the radio core by Jaffe & McNamara (1994). Their measurements indicate that the total mass of gas in the HST disk is \( \sim 10^5 \, M_\odot \), which is sufficient to power the radio source for \( \sim 10^8 \) yr. All of the above evidence suggests that the radio source is powered by material accreting in from the large-scale dust disk through the HST dust disk and eventually onto the (unseen) inner accretion disk where the radio jet formation takes place within a few Schwarzschild radii of a central, massive black hole. The accreting material probably came from a merger between NGC 4261 and a smaller gas-rich galaxy. This would explain the apparently unrelated dynamics between the gas and dust in the nuclear disks and the overall stellar dynamics of the galaxy.

We observed the nuclear region of NGC 4261 with VLBI to determine the morphology of the central radio source on parsec scales and, in particular, to see if the inner radio axis remained in the same direction as the kiloparsec-scale jets (position angle = 88°) or whether it was aligned with the apparent rotation axis of the HST disk.

2. OBSERVATIONS AND RESULTS

We observed NGC 4261 for 8.5 hr on 1995 April 1 using all 10 antennas of the NRAO Very Long Baseline Array (VLBA). Individual scans, typically of 26 minutes duration, were alternated between 1.6 and 8.4 GHz. We recorded a bandwidth of 64 MHz with single polarization, and the data were cross-correlated on the VLBA correlator.

After cross-correlation the data were read into AIPS\(^1\), where standard programs were used for editing, amplitude calibration, and fringe fitting. Prior to fringe fitting the strong compact radio source 1308 + 326 was used to derive corrections for phase slopes across the frequency channels at both 1.6 and 8.4 GHz. After fringe fitting the data were averaged over frequency and exported to the Caltech program DIFMAP (Shepherd, Pearson, & Taylor 1994) for additional editing, self-calibration, imaging, and deconvolution. Only marginal detections were obtained on the longest VLBA baselines (to the antennas at Saint Croix and Mauna Kea) at 1.6 GHz, but good fringes were found to all 10 antennas at 8.4 GHz.

\(^1\) The Astronomical Image Processing System was developed by the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
FIG. 3.—Full resolution VLBA image of NGC 4261 at 8.387 GHz. The contour levels are $\left[0.5\%, 0.5\%, 1\%, 2\%, 4\%, 8\%, 16\%, 32\%, 70\%, 70\%, \text{and } 95\%\right]$ of the peak surface brightness (101 mJy beam$^{-1}$). The restoring beam is 1.84 × 0.80 mas with the major axis along position angle $-1.1^\circ$.

FIG. 4.—Gray-scale representation of the full-resolution 8.387 GHz image, showing the narrow gap in emission just east of the brightest peak (core).
is perhaps surprising that an even larger absorption feature is not seen in our 1.6 GHz images. To investigate this, we simulated the one-dimensional brightness distribution of an intrinsically symmetric source with a narrow gap on one side and convolved this profile with Gaussian beams of different widths. We found that it is possible for the simulated absorption feature to be easily visible with the VLBA 8.4 GHz beam but invisible with the 1.6 GHz beam, which is more than 5 times as wide. In fact, the actual beam used at 1.6 GHz is nearly 10 times as wide as the full-resolution 8.4 GHz beam because we downweighted the low signal-to-noise ratio data on the longest baselines at 1.6 GHz to improve the dynamic range.

Figure 5 is an image at 8.4 GHz that was made by applying a Gaussian taper to the visibility data to match the angular resolution available at 1.6 GHz. The same field of view and restoring beam has been used for Figures 1 and 5 to allow easy comparison.

Although the degree of symmetry depends on both frequency and angular resolution, the source appears basically two-sided in all of the above figures. The more symmetric appearance at 1.6 GHz is partially caused by the greater extent of the jets at 1.6 GHz resulting from spectral index effects, and also suggests that the cause of the "gap" in Figures 3 and 4 is confined to an angular scale much smaller than the 1.6 GHz or tapered 8.4 GHz beams.

Attempts were made to detect more distant emission at both 1.6 and 8.4 GHz using larger image sizes and tapering the visibility data to favor short baselines. In no case did we find any emission significantly more extended than that shown in Figures 1 and 5, although the range of VLBA baselines would allow more extended radio structure to be detected. We conclude that the brightness of the two parsec-scale radio jets does drop below our noise level very rapidly at both frequencies, and that this is not an artifact of the imaging procedure.

In referring to the images in Figures 1–5 as symmetric or two-sided, we are implicitly assuming that the central brightness peak is the "core" of the source (the base of the radio jets). Is there any evidence to support this assumption? We have compared the images in Figures 1 and 5 to determine spectral index distributions for a range of position offsets between the two images. Figure 6 shows the spectral index distribution along the east-west axis of the source when the central peaks at both frequencies are aligned. Not surprisingly, the spectral index distribution is also quite symmetric with an inverted spectrum near the center and increasingly steep spectra with increasing distance from the center. It is possible to offset the 8.4 GHz peak up to 10–12 mas from the 1.6 GHz peak without making the spectral index $\alpha = +2.5$ (using $S \propto \nu^\alpha$), but in this case the spectral index more than $\approx 30$ mas from the center becomes extremely steep ($\alpha < -2$). We therefore favor a registration in which the brightest peaks in Figures 1 and 5 are nearly co-aligned, giving a spectral index distribution close to that shown in Figure 6.

The inverted spectrum at the center of the source could be caused by synchrotron self-absorption or by free-free absorption. In the case of free-free absorption, the ionized gas responsible for the inverted spectrum at the center of the source would have to cover only the inner 0.2–0.3 pc and/or have a filling factor substantially less than unity to account for the fact that $\alpha < 1$. Free-free absorption by thermal gas uniformly covering a source gives an inverted spectrum with $\alpha \approx 2$. Synchrotron self-absorption is seen in the cores of many compact extragalactic radio sources, and, by analogy, we might expect to see this effect in the core of NGC 4261. Our brightness temperatures (see below) are lower limits, and therefore they do not rule out synchrotron self-absorption, which can produce inverted spectra with $\alpha \leq 2.5$ depending on the turnover frequency and homogeneity of the source. We can not exclude a combination of both effects in the center of NGC 4261. In both morphology and spectral index distribution NGC 4261 is very similar to the parsec-scale source in Hydra A (Taylor 1996).

The brightness of both the east and west jets drops off rapidly at both frequencies. To quantify this, we found that
three of the four brightness profiles could be reasonably well fit with a power law of the form (surface brightness) \( \propto (\text{distance from peak})^x \). At 1.6 GHz the exponent \( x = -1.9 \) for the jet extending to the west and \( -2.0 \) for the jet extending to the east. The linear brightness profile fits for 1.6 GHz are shown in Figure 7.

Although the western jet fades slightly more slowly with distance from the core, these values are very similar. At 8.4 GHz the corresponding exponents are \( x = -1.2 \) for the western jet and \( -2.0 \) for the eastern jet. Again, the eastern jet fades more rapidly. The eastern jet at 8.4 GHz is not very well fit by a single exponential law, although the western jet is. The 8.4 GHz brightness profile fits are shown in Figure 8.

In all cases we used measurements of the flux density per unit length (Jy mas\(^{-1}\)) starting near 50% of the peak value and extending out in steps of 0.7–0.8 times the half-power beamwidth (6.5 mas steps at 1.6 GHz and 1.2 mas steps at 8.4 GHz). This represents a compromise between having truly independent measurements and having an adequate number of points for the least-squares fit.

The total flux density of the VLBI structure shown in Figures 1 and 3 is 0.20 Jy at 1.6 GHz and 0.34 Jy at 8.4 GHz. The peak (core) surface brightness is 0.10 Jy beam\(^{-1}\) at both 1.6 and 8.4 GHz. This corresponds to a brightness temperature of \( 3.3 \times 10^8 \) K at 1.6 GHz and \( 1.2 \times 10^9 \) K at 8.4 GHz; these values are lower limits to the true brightness temperature of the core, which is angularly unresolved at both frequencies.

The VLBI position angles are at 1.6 GHz and \( 86^\circ \pm 1^\circ \) at 8.4 GHz. At both frequencies the VLBI position angles are consistent (within the combined errors) with the \( 88^\circ \pm 1^\circ \) position angle of the VLA jets, although the 8.4 GHz value may suggest a small curvature of the jets very close to the core. If real, this curvature makes the inner jet orientation slightly closer to the minor axis of the \( HST \) disk \( (73^\circ \pm 2^\circ ; \text{Ferrarese et al. 1996}) \). Higher frequency VLBI observations will be needed to determine the reality of any jet curvature in the central few parsecs of this source.

### 3. DISCUSSION

It is clear from VLA images that both the east and west jet in NGC 4261 extend far beyond the scale of our VLBA images. Therefore, the disappearance of both jets within a few tens of mas of the core is not caused by their disruption.
or “smothering” by a dense interstellar medium. It is possible that the jets are fading because of expansion close to the core. This implies that the external pressure is less than the internal jet pressure. At some point the internal pressure in the expanding jets will become lower than the external pressure (which should fall more slowly than $d^{-2}$ at large distances), causing the opening angle of the jets to be reduced and possibly creating shocks that could reaccelerate the relativistic electrons. The result will be a much slower decrease in jet brightness on kiloparsec scales. Our angular resolution is insufficient to measure the opening angle of the parsec-scale jets, but from Figure 2 we can get an upper limit of approximately $10^\circ$ for the east jet, compared with less than $5^\circ$ on kiloparsec scales.

We can set an upper limit on the free electron density in the inner $\sim 10$ pc of NGC 4261 from the apparent lack of free-free absorption of either jet at 1.6 GHz. If absorption by a 10 pc scale disk or torus of ionized gas were significant, we would expect to see a much more asymmetric radio morphology in Figures 1 and 2 (cf. 3C 84; Vermeulen, Readhead, & Backer 1994; Walker, Romney, & Benson 1994). Since both east and west jets in NGC 4261 are visible out to $\sim 10$ pc with similar brightness, the optical depth from free-free absorption must be much less than unity. Assuming a gas temperature of $\sim 10^4$ K and a path length of 10 pc gives an electron density $< 10^3$ cm$^{-3}$. Note however that our limit applies to the inner few parsecs of NGC 4261 as a whole; the apparent absorption on a subparsec scale in Figures 3 and 4 would be undetectable at lower angular resolutions. Thus, we are not ruling out free-free absorption by a high electron density gas within the central parsec. If the path length through the inner disk suggested by Figures 3 and 4 is assumed to be $\sim 0.1$ pc, the resulting lower limit for $n_e$ is $\sim 10^5$ cm$^{-3}$.

For NGC 4261 the total mass of ionized gas implied in the inner 10 pc, neglecting the possible subparsec inner disk, is less than $5 \times M_\odot$. It appears that we have a low-density, presumably hot, inner “bubble” filling the inner several parsecs of the nucleus (within which the radio jets expand rapidly) surrounded by a cool, higher density region (of which the HST absorption disk is part), within which the transverse expansion of the radio jets is nearly halted. Higher electron densities have been estimated from optical observations (Jaffe et al. 1996; Ferrarese et al. 1996), but the angular resolution of these measurements is no better than 0′′1, and, consequently, they may be partially sampling a higher density region surrounding the region in which we see the VLBI radio jets. Another possibility is that much of the optical emission comes from within the central parsec, in which case a small region of higher density gas could dominate the optical measurements.

As Bridle & Perley (1984) point out, the central brightness of an expanding synchrotron jet decreases as a different power of distance (or radius) $d$ depending on whether the jet is dominated by a parallel or transverse magnetic field, or if equipartition is assumed. Our VLBI images do not resolve the jets in the transverse direction, so we measure the brightness per unit length rather than the surface brightness. For an optically thin jet with $x = -0.65$ the brightness per unit length falls off as $d^{-2.2}$ for a parallel magnetic field, $d^{-2.5}$ for a transverse magnetic field, and $d^{-3.1}$ if equipartition is assumed. All of these exponents are more negative than the observed fall-off of brightness per unit length in the parsec-scale jets of NGC 4261. This is a common result for many radio jets (e.g., Perley, Bridle, & Willis 1984), and it implies that magnetic field amplification and/or particle reacceleration (or a dramatic reduction in jet velocity) must take place as the jet expands. Based on Figure 5, the jets in NGC 4261 appear to be optically thin only at distances greater than 10–15 mas from the core. This complicates the interpretation of the brightness profiles at 8.4 GHz, but at 1.6 GHz the jet profiles with their $d^{-2.0}$ fall-off extend well beyond this region.

Taylor (1996) presents VLBA images and spectral index maps of the central radio source in Hydra A that look remarkably similar to those presented in this paper. Taylor finds evidence for significant ($\tau > 1$) free-free absorption of the radio core in Hydra A at 1.3 GHz and deduces a value of $n_e^2$ that is equal to the upper limit we find for NGC 4261. At our lowest frequency of 1.6 GHz the free-free absorption deduced by Taylor would have an optical depth less than 1. If the thermal gas density in the nucleus of NGC 4261 is somewhat smaller than in Hydra A, the effects of free-free absorption would be quite small at our observing frequencies. The neutral hydrogen column density in front of the radio core in NGC 4261 is approximately 20 times smaller than in Hydra A (Jaffe & McNamara 1994; Taylor 1996).

Another method for estimating hydrogen column density is through X-ray absorption. NGC 4261 contains an X-ray source with an angular extent similar to that of the optical galaxy (Fabbiano, Kim, & Trinchieri 1992; Worrall & Birkinshaw 1996), as well as fainter emission on larger scales (Worrall & Birkinshaw 1994; Davis et al. 1995) and a strong component that is angularly unresolved by ROSAT (Worrall & Birkinshaw 1994; 1996). Birkinshaw & Worrall (1996) concluded that the extended X-ray gas confines the kiloparsec-scale radio jets, and that the jets terminate (flare into the two diffuse lobes) at the point where the external pressure falls below the internal pressure in the jets. This implies that the flow in the jets is subsonic. Einstein IPC spectra can be fit with a power law (Kim, Fabbiano, & Trinchieri 1992), but a thermal plus power law spectrum provides the best fit to ROSAT data (Worrall & Birkinshaw 1994). In the thermal plus power law model the derived neutral hydrogen column density in NGC 4261 is quite small ($N_H < 4 \times 10^{20}$ atoms cm$^{-2}$), and the cooling time for gas within the core radius is estimated to be $3.4 \times 10^9$ yr. The low hydrogen column density derived from the X-ray data is difficult to reconcile with the higher H I densities derived from the radio absorption measurements of Jaffe & McNamara (1994). Worrall & Birkinshaw (1994) discuss several possible reasons for this difference. One explanation is that the radio emission comes to us directly from the core and inner regions of the jets and, consequently, at least partly through the suggested dense inner accretion disk, while the X-ray emission (the nonthermal power law component) is initially directly in the same general direction as the radio jets and is scattered into our line of sight by plasma within the jet or surrounding the inner nuclear region. If this proposed X-ray scattering occurs far enough from the radio core, the gas density along the mean X-ray line of sight could be substantially smaller than along the mean radio line of sight. This model predicts that future very high angular resolution X-ray images of the NGC 4261 nucleus will find a position offset between the radio and X-ray peaks, and that this offset will be approximately along the direction of the radio jets. An alternative possi-
bility is that the X-ray emission comes from an angularly larger region than the bright central radio source; this would have the same effect of allowing most of the X-ray emission to avoid the presumed inner accretion disk.

The position angle of the radio axis in our VLBA images agrees, within the combined errors, with the position angle of the VLA-scale jets. Thus there is no evidence for precession of the jets on timescales shorter than the material propagation time from the nucleus to the diffuse radio lobes. This long-term stability implies that the central compact object has a very large angular momentum.

If the central black hole in NGC 4261 is $10^8-10^9 M_\odot$, it is unlikely that it would have any detectable orbital motion about a presumably less massive secondary nucleus from a merger (which could be the cause of the positional offset between the apparent center of the HST dust disk and the radio core). In this case the secondary nucleus (and perhaps parts of the nuclear gas disk) would show almost all of the orbital motion. This could also explain the small but significant difference between the radio jet position angle and the position angle of the HST disk rotation axis.

4. CONCLUSIONS

We have found that the parsec-scale radio source in the nucleus of NGC 4261 is unusually symmetric and aligned along the same position angle as the larger scale radio structure imaged with the VLA. The morphology and spectral index distribution of the parsec-scale source indicates that free-free absorption is not significant within several parsecs of the radio core, except possibly within the central parsec. The brightness of both radio jets decreases very rapidly in both directions from the core, which we interpret as evidence for a large initial opening angle (rapid expansion). At some distance between about 50 and 500 pc the jet opening angles decrease to the $<5^\circ$ value seen on kiloparsec scales. This should occur when the internal jet pressure falls below that of the external medium.

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