H I AND CO IN THE NUCLEAR DISK OF NGC 4261

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ABSTRACT

We detect radio absorption from neutral gas in the nuclear disk of NGC 4261 seen in front of the nuclear radio source. The gas surface density is consistent with that inferred from the dust optical depth and a gas/dust ratio near the Galactic value. The moderately high velocity dispersion of the gas suggests that the disk orbits would decay rapidly unless the disk is in essentially solid body rotation. The absorption seen in NGC 4261 is consistent with that expected in dust torus “unified models” of radio galaxies, but similar absorption is only seen in a relatively small fraction of radio galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 4261) — galaxies: ISM — galaxies: nuclei

1. DISCUSSION

The discovery of a nuclear dust disk in NGC 4261 (Jaffe et al. 1993; Kormendy & Stauffer 1987); Mollenhoff & Bender 1987) led us to investigate the kinematic and physical state of neutral gas there using emission/absorption of H I 21 cm radiation (for atomic gas) and CO (2 → 1) 1.3 mm radiation (for molecular gas). In a broad-band 5550 Å image taken with the Planetary Camera on the Hubble Space Telescope, the dust appears as a smooth ellipse with axes of 171 ± 0:74 whose major axis has a position angle of −16°, and whose optical depth is of order unity (Jaffe et al. 1993). The H I observations were carried out at the Very Large Array (VLA) in its C-array configuration, with a maximum baseline of 3.5 km. The CO observations were carried out at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea. The parameters of both observing runs are given in Table 1. The effective resolution of the VLA mapping measurements was 18′ : 1 × 19′ : 7, the beam size of the JCMT spectrum (measured only at the nucleus) was 21″.

NGC 4261, the radio galaxy, 3C 270, is a copious source of radio continuum emission. This provides an opportunity for detecting gas in absorption as well as in emission, but can complicate the interpretation of any measurements. The VLA data provide a map of the 1.4 GHz continuum emission, shown in Figure 1. The total VLA flux density measured is 16.4 ± 0.2 Jy. This is slightly lower than the value of 17.8 ± 0.4 measured both by Pauliny-Toth, Wade & Heeschan (1966) with the Green Bank 300 foot (91 m) telescope and Kotanyi (1980) at the same frequency. The difference may be due to a slight difference in flux scale between data sets. The flux density is ~6% of the flux density of 3C 274 = M87. For an assumed distance to the Virgo cluster of 15 Mpc, the luminosity of 3C 270 is 4.4 × 10^{23} W Hz^{-1}, which classifies it as a weak radio galaxy. The structures seen in our map are similar to those seen at 4.8 GHz (Birkinshaw & Davies 1985). The radio structure is that of a two sided jet with an unresolved nuclear component; this is typical of weak radio galaxies. It is possible that NGC 4261 is actually in the “Virgo West” cluster at about twice the distance of the main Virgo Cluster (de Vaucouleurs 1961; Binggeli, Sandage & Tammann 1985). In this case the luminosity would be 4 times as high as just calculated, and all physical sizes would be twice those used here. These changes do not affect the further interpretation of these measurements significantly.

The nuclear position is α(1950) = 12h 16m 49′ 98″ ± 0′′.4, δ(1950) = +06° 06′ 10″ 1 ± 2″. The accuracy is limited by the low resolution of the VLA at this frequency in its small C-array configuration, and by confusion from the extended emission. In 1993 May, Chris O’Dea kindly reobserved the nucleus at 8.4 GHz in the larger A-array, where these problems are less important. He reports the nuclear position to be α = 12h 16m 50′ 00″, δ = +06° 08′ 65″ with a flux of 241 mJy. The error in the position estimate is dominated by the systematic error in the VLA calibrator coordinate system, which is of order 0′′.2. This position is 2′′.5 south of the optical nuclear position of NGC 4261 (Jaffe et al. 1994). This difference is unlikely to be physical, but rather to be due to an error in the HST guide star positions near NGC 4261. The position of NGC 4261 at the edge of the Palomar Sky Survey plates on which the guide star position were measured makes an error of this magnitude plausible (P. Hemenway, private communication).

We determine the 1.4 GHz nuclear flux $S_{1.4}$ to be 164 ± 10 mJy. This is consistent with a VLBI value at 18 cm of $S_{1.6} = 180$ mJy (Jones, Sramek, & Terzian 1981) for an unresolved component less than 0′′01 (<0.7 pc) in size, and the flux of 171 mJy found by van Gorkom et al. (1989) with the VLA in the larger A-array. Both values are much smaller than the value of $S_{1.6}$ of 315 mJy found by Birkinshaw & Davies (1985) at 4.8 GHz. Either the nuclear spectrum is rising very rapidly with frequency, or is variable on year timescales. In either case, we may expect measurable millimeter continuum emission from the nucleus. Our JCMT data were not calibrated for point

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TABLE 1

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VLA</td>
</tr>
<tr>
<td>Technique</td>
<td>27 element interferometer</td>
</tr>
<tr>
<td>Back end</td>
<td>Digital cross correlator</td>
</tr>
<tr>
<td>Line (rest freq.)</td>
<td>H I (1420 MHz)</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>42 km s(^{-1})</td>
</tr>
<tr>
<td>Velocity coverage(^a)</td>
<td>800 → 3200 km s(^{-1})</td>
</tr>
<tr>
<td>Flux calibrator</td>
<td>3C 286</td>
</tr>
<tr>
<td>Integration time</td>
<td>27 minutes</td>
</tr>
<tr>
<td>Single channel rms</td>
<td>1.4 mJy</td>
</tr>
<tr>
<td>Nuclear continuum</td>
<td>164 ± 10 mJy</td>
</tr>
</tbody>
</table>

\(^{a}\) The VLA measurements were made with two slightly overlapping 6.25 MHz IF channels. The area of overlap can be seen in Fig. 1.

Sources, but from the average baseline of the 1.3 mm spectrum, we estimate a continuum brightness temperature \( T_{\text{b}} \) of 19 mK, which for the JCMT (15 m diameter) corresponds to a flux of 200 mJy. There is an uncertainty of \( \sim 50\% \) in this estimate.

The single-channel VLA maps show significant absorption or signal only at the position of the nucleus. The nuclear spectrum is shown in Figure 2, where the 230 GHz JCMT spectrum is also displayed. The VLA backend contains two separate cross-correlation spectrometers which were tuned to adjacent, slightly overlapping spectral regions; these two segments can be seen in Figure 2 at velocity near 1900 km s\(^{-1}\). Most of the noise in VLA observations arises in the telescope frontends. Since the same frontends feed both backends, the noise functions in the two backends will be almost 100\% correlated. For this reason the two spectral segments in the plot are practically identical in the overlap region, and the uncertainty of the flux determination inside the overlap region is no better than outside.

In both the VLA and JCMT spectra a zero order (constant) baseline has been subtracted. Both spectra show significant absorption near 2200 km s\(^{-1}\) and possible, but not statistically significant, emission on both wings of the absorption. The derived absorption-line parameters are given in Table 2. The velocity centroid is consistent with the optical systemic velocity of 2227 km s\(^{-1}\) (Jaffe et al. 1993). Since the lines are only partially resolved in velocity, it is possible that they are in fact somewhat deeper and narrower than we have estimated, or that they are composed of a number of unresolved lines.

The H I line is similar in its depth, width, and low relative velocity to those seen in \( \sim 10\% \) of radio galaxies measured with similar velocity resolution (van Gorkom et al. 1989), while the CO absorption is similar, but somewhat broader than that seen in Cen A = NGC 5128 (Israel et al. 1991). We know of no systematic search for CO absorption toward radio galaxies, but an incomplete compendium of published and unpublished results known to us indicates NGC 5128 as the only positive absorption detection among a larger number of negative results (M87, NGC 1275: Jaffe 1987; 4C 12.50, Cyg A: Mirabel, Sanders, & Kazes 1989; Fornax A: T. de Graauw, private communication). It is curious that only 10\% of radio galaxies

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**Fig. 1.—** VLA 1414 MHz continuum map of NGC 4261 = 3C 270. Synthesized beam size is 19\'\'7 by 18\'\'1 at P.A. = 52°.
show this type of H I absorption (although another 20% show absorption from infalling material) and \( \sim 30\% (\hat{\gamma}) \) show CO absorption. In the context of those “unified models” of AGNs that invoke a dusty torus with large visual optical depth to hide the nuclei of radio galaxies, all galaxies should show either H I or CO absorption, providing their nuclear radio flux is high enough to permit observation and the dust/gas ratio is similar to that in our Galaxy.

The most interesting quantities in Table 2 are the derived surface density and the velocity dispersion. The surface density estimated from the CO absorption, \( N_{HI} \sim 7 \times 10^{21} \) for \( T_e \sim 30 \) K, corresponds to several magnitudes of visual absorption for material with a Galactic gas/dust ratio. This is in fact consistent with our own optical data suggesting \( \tau \sim 1 \) (Jaffe et al. 1993). Note that the radio value refers to the surface density along a single line of sight to the nucleus, while the visual absorption is an average over the whole disk. The total amount of gas in the disk, \( \pi R_d^2 N_{HI} \), is \( \sim 2 \times 10^8 M_\odot \).

The estimated rms velocity dispersion of the H I profile, \( \sim 44 \) km s\(^{-1}\), is larger than would be estimated from the FWHM velocity spread because the profile is non-Gaussian, with a narrow core, and broad wings. This suggests that it is composed of several unresolved components.

In both spectra there is a slight excess of positive fluctuations in the regions plus or minus 200 km s\(^{-1}\) from the absorption line center. This might indicate weak emission, although the signal/noise ratio is too low to consider this as a detection.

We can calculate the expected ratio of emission to absorption temperature from a gas disk of given size and temperature as

\[
\frac{T_e}{T_v} = \frac{2k T_e \Omega_v V_v}{S_v \lambda^2 V_e}
\]

where \( T_e \) is the temperature of the disk gas, \( \Omega_v \) is the disk solid angle, \( S_v \) is the continuum source flux, \( \lambda \) the wavelength, and \( V_v/V_e \) the ratio of the velocity widths seen in absorption and emission. If we take \( T_e(\text{HI}) \sim 100 \) K, \( T_e(\text{CO}) \sim 30 \) K, \( S_v \sim 200 \) mJy in both cases, \( V_v/V_e \sim 0.25 \) and further the disk dimensions quoted in Jaffe et al. (1993), we find \( T_e/T_v(\text{HI}) \sim 10^{-4} \) and \( T_e/T_v(\text{CO}) \sim 1.3 \). Thus H I emission at a potentially detectable level could only arise from gas in a much larger region than the dust disk. The observations limit the CO emission temperature to at most \( \sim 30\% \) of the absorption temperature; consistency

\begin{table}[h]
\centering
\caption{Absorption-Line Analysis}
\begin{tabular}{lcc}
\hline
Parameter & VLA & JCMT	tabularnewline
\hline
Channels per bin & 1 & 64	tabularnewline
Binned channel rms & 1.4 mJy & 4 mK	tabularnewline
Peak absorption & 7.0 mJy & 14.2 mK	tabularnewline
Peak optical depth & 0.042 & 0.7	tabularnewline
Centroid & \( 2237 \pm 15 \text{ km s}^{-1} \) & \( 2235 \pm 15 \text{ km s}^{-1} \)	tabularnewline
Full width half-power & 65 km s\(^{-1}\) & 65 km s\(^{-1}\)	tabularnewline
Velocity dispersion & 44 km s\(^{-1}\) & 30 km s\(^{-1}\)	tabularnewline
\( \int \delta V \) & 4.0 km s\(^{-1}\) & 50 km s\(^{-1}\)	tabularnewline
Surface density \( N_{HI} \star \) & \( 7.2 \times 10^{19} \text{ cm}^{-2} \) & \( 2 \times 10^{20} \text{ cm}^{-2} \)	tabularnewline
\hline
\end{tabular}
\end{table}

* Surface densities computed from \( N_{HI} = 1.8 \times 10^{19} \text{ cm}^{-2} \int T_{HI} dV \) and \( N_{HI} = 5 \times 10^{20} \text{ cm}^{-2} \int T_{CO} dV \).
then demands $T_\nu \sim 10$ K, or that the CO emission come from a smaller region than the dust disk. Slightly more sensitive CO measurements should detect the emission easily.

The theory of accretion disks (e.g., Pringle 1981) predicts certain relations between the disk turbulent velocity, its circular velocity, $V_c$, and the other quantities. For instance, the ratio of disk thickness $H$ to radius $R$ is approximately $H/R \approx V_c / V_t$. Here we assume that the turbulent velocity is isotropic so that $V_t \sim V_c$, where $V_t$ is the velocity perpendicular to the plane of the disk. Our line of sight, inclined at an angle $i \sim 60^\circ$ (e.g. Jaffe et al. 1993) from the normal to the disk, passes through the gas at some radius $R$, not necessarily the outer edge. This implies that $H/R > \cos i = 0.5$ at $R$. Thus $V_t / V_c \gtrsim 0.5$ if gas can rise $30^\circ$ above the disk plane, or $V_t \sim 80$ km s$^{-1}$ at the radius where the line of sight cuts into the disk. Emission-line spectra of NGC 4261 in fact indicate rotation velocities of order 150 km s$^{-1}$ at radii of $\sim 0.2$ (Jaffe et al. 1994). On the other hand, an accretion disk decays from viscous transfer of angular momentum at a rate of order $\Gamma \sim \Omega (V_t / V_c)^2 (d \ln \Omega / d \ln R)$ where $\Omega = V_c / R$ is the angular velocity of rotation. Thus we estimate $\Gamma / \Omega \approx 0.25 (d \ln \Omega / d \ln R)$ is very small, i.e., the disk is in essentially solid body rotation. This is the case if the rotation curve is generated by a stellar core of nearly constant density, but not if the gravity is dominated by a point mass. The sharp outer edge of the disk may represent the point where the core density begins to drop from its central value and $(d \ln \Omega / d \ln R)$ becomes of order unity. Alternatively, the absorption we see, and the turbulent velocity we estimate, may originate within a few parsecs of the nucleus and not be representative of the disk as a whole. Confirmation of broad CO emission would exclude this possibility.

We note that of order $\sim 10^{-3} M_\odot$ yr$^{-1}$ falling into a black hole is sufficient to power the radio source. The above total disk mass estimate of $10^7 M_\odot$ could therefore power the source for $10^8$ years. The net inward velocity necessary to sustain this fueling, once the material has settled into a viscous accretion disk, is only $\sim 1$ km s$^{-1}$, which is not distinguishable from the systemic velocity.

2. CONCLUSIONS

1. We detect CO(2–1) and $\text{H} \alpha$ absorption in NGC 4261 arising from gas with surface density of $\sim 10^{21}$ cm$^{-2}$. The gas probably lies in the 100 pc sized “large accretion disk” seen in $HST$ images of NGC 4261.

2. The gas velocity is near the systemic velocity, and thus the gas is probably in near circular rotation. It has sufficient velocity perpendicular to the rotation plane to rise at least $30^\circ$ out the plane. From the upper limit on CO emission, this gas is physically cool.

3. Absorption from neutral gas in a cool accretion disk, or circumnuclear torus, is only seen in $\lesssim 30\%$ of radio galaxies. This is a puzzle in the context of unified theories of active galaxies that require optical obscuration of the nuclei of radio galaxies.

It is now urgent that these measurements be improved so that the detailed kinematics of the absorption can be determined, and the possible emission verified. Mapping of such CO emission at subarcsecond resolution would directly yield a rotation curve in the innermost few parsecs of the disk, leading to an unambiguous estimate of the mass distribution there.

We thank Dan Harris and Mark Birkinshaw for helpful comments.

REFERENCES


Note added in proof.—Barvainis & Antonucci (AJ, 107, 1291 [1994]) discuss in detail the above noted lack of CO absorption lines in radio galaxies for the case of Cygnus A. They quote a suggestion by M. Rees that the CO spin temperature is so much increased by the nuclear continuum emission that the absorption is not detectable.