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Molecular tori in AGN: a search using excited states of OH

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One of the fundamental concepts in the unified scheme of active galactic nuclei is that both Seyfert 1 and Seyfert 2 galaxies harbour supermassive nuclear engines blocked from direct view by an optically and geometrically thick torus. If the pressure is sufficiently high, the content of the torus should mostly be molecular. Although molecular rings with diameters of a few hundred parsecs are common, the expected small scale tori (<10 pc) have been difficult to detect. Searches for absorption lines of common molecules like CO and OH have mostly resulted in non-detections. Before concluding that tori are not molecular, radiative excitation effects, in which coupling to the nonthermal continuum can suppress the opacity in the lowest transitions, deserve some attention and influence our selection of the most favourable transitions to observe. To explore these effects, we modified the search strategy by looking for the higher excited rotational states of OH and by selecting a sample of 31 Seyfert 2 galaxies which are known to have a high X-ray absorbing column. We present here the results of single dish observations of the transitions at 6031 MHz and 6035 MHz, yielding detections in five sources. We also present a spectral line VLBI observation carried out at 13.4 GHz towards the core of Cygnus A, yielding a tentative detection.

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1. Molecular tori in AGN

Active galactic nuclei (AGN) come in two main types: those with and those without broad optical line emission (type 1 and type 2 AGN, respectively). In the unified scheme of active galactic nuclei, all AGN are intrinsically similar; in type 2 objects our view of the central continuum source and the broad line region (BLR) is blocked by an obscuring material of significant column density [1]. The obscuring material is expected to be an approximately parsec-scale torus of molecular gas, whose structure was predicted by, e.g., Krolik & Begelman [3]. Despite many efforts to detect the expected molecular absorption or emission in a number of surveys, only in very few cases could molecular absorption be confirmed (e.g. Schmelz et al. 1986, Baan et al. 1992, Staveley-Smith et al. 1992 [4], [5], [6]). The unified scheme accounts for many observed properties, but evidence for the existence of a molecular torus remains somewhat indirect and the structure and extent of the obscuring material are still poorly understood.

As the nearest (z = 0.0565) powerful FR II radio galaxy, Cygnus A has been the subject of a number of studies aimed at testing the predictions of the unified scheme. Several lines of evidence suggest that Cygnus A harbours a quasar nucleus hidden from direct view in the visible and soft X-rays emission by a dusty obscuring torus [7]. An X-ray absorbing column of $N_{\rm H} = (3.75 \pm 0.73) \times 10^{23}\,{\rm cm}^{-2}$ is consistent with the notion of a buried quasar in Cygnus A [8]. Searches for 18-cm OH and 6-cm H_2CO by Conway & Blanco [9] yielded non-detections at 1% optical depth [9]. Also, Barvainis & Antonucci [10] failed to detect CO J=0-1 and CO J=1-2 absorption, challenging the torus model for Cygnus A. The authors suggested three possible solutions. First, it may be that there is no such torus. Second, the sizes of the molecular clouds in the torus may be smaller than the size of the background continuum source. Alternatively, the radio continuum emission from the nucleus may radiatively excite the CO, increasing the excitation temperature of the lower rotational levels and suppressing the absorption optical depths in the lower transitions [2]. Interestingly, Fuente et al. [11] report 118-GHz CO+ absorption, supporting CO excitation from radiative excitation effects. Given the abundances of OH predicted in some molecular torus models, the non-detection of OH absorption is hard to explain unless this, too, is radiatively excited. Radiative excitation effects have been predicted by Black (1997) also for the 18-cm OH transitions [12], suggesting that the rotationally-excited doublets at 6 GHz and 13.4 GHz, so far neglected, could be more profitable targets than the 1.6-GHz lines.

2. Observations

To explore the effects of radiative excitation we modified the search strategy for molecular absorption, starting with a survey with the 100-metre telescope in Effelsberg to search for OH in the the higher-order transitions at 6031 MHz and 6035 MHz in 31 type 2 AGN (see Table 1) selected for having a known high X-ray absorbing column ($\geq 10^{22}\,{\rm cm}^{-2}$) and for having $S_{6\,{\rm GHz}} > 50$ mJy to ensure sufficient continuum core strength. We included some AGN with polarized broad-line emission, indicating an obscured BLR, and some additional sources with known OH absorption at 1.6 GHz. The observations were carried out between August 2003 and February 2004 with an average integration time of 3 h per source and 40-MHz bandwidth. Twenty of the stronger sources

Source	Redshift z	S_{6cm} mJy	$N_{\rm H}$ X-ray cm^{-2}	Int. time min	Det	Source	Redshift	S_{6cm}	$N_{\rm H}$ X-ray	Int. time	Det
Hydra A	0.055	154	-	-		NGC 5135	0.014	598	$> 10^{24}$	120	-
Cygnus A	0.056	1400	$10^{23.5}$	-	-	NGC 5506	0.006	160	3.4×10^{23}	230	-
NGC 1052	0.005	1500	$> 10^{22}$	-	-	NGC 5793	0.011	96		230	abs
NGC 1068	0.004	1090	$>10^{25}$	-	-	NGC 6240	0.024	131	2.2×10^{25}	103	-
NGC 1167	0.002	243	$<2\times10^{23}$	154	-	NGC 7130	0.016	62	$> 10^{24}$	180	-
NGC 1275	0.017	16623	1.5×10^{23}	-	-	NGC 7674 .	0.029	66.5	$> 10^{24}$	205	-
NGC 1365	0.006	191	2×10^{24}	180	-	Mrk 3	0.014	361	1.1×10^{25}	205	-
NGC 1808	0.003	207	3×10^{23}	180	-	Mrk 231	0.042	414	-	†	abs
NGC 2110	0.007	175	2.9×10^{23}	180	-	Mrk 273	0.037	103	-	†	abs
NGC 2639	0.040	54.5	-	154	-	Mrk 348	0.015	254	10^{24}	211	-
NGC 2992	0.008	77	6.9×10^{22}	185	-	Mrk 463	0.050	100	1.6×10^{24}	180	-
NGC 3079	0.004	145	1.6×10^{23}	65	abs	Mrk 1210	0.014	45	10^{25}	180	-
NGC 4151	0.003	125	2.2×10^{22}	255	-	Mrk 1073	0.024	44	-	358	-
NGC 4261	0.007	80	-	180	abs	F 01475-0740	0.177	127	-	103	-
NGC 4388	0.008	76	4.2×10^{24}	205	-	IRAS 05414+5840	0.015	55	-	180	-
			-			IRAS 1345+1232	0.121	2160	-	180	-

Table 1: List of sources observed at 6 GHz with the 100-m telescope in Effelsberg. † sources observed by Henkel et al. (priv. comm.)

were followed up in the 4.7-GHz transitions with Effelsberg telescope between June 2004 and August 2004.

Four of our top candidates: Cygnus A, Hydra A, NGC 1052 and NGC 1275, were too strong for single-dish spectroscopy, and so demanding unachievably high spectral dynamic range and for two of these we thus proposed an interferometric study. We looked for excited OH at 13.4 GHz in Cygnus A and NGC 1052 with the VLBA, omitting Hydra A since its core was too weak at 13.4 GHz. The observations were made with two IFs of 16-MHz bandwidth (corresponding to 357 km/s per IF). The IFs were centred at 13.434 GHz and 13.441 GHz, respectively, with 256 channels per IF, yielding a spectral line resolution of 1.4 km/s per channel. The data were calibrated using standard phase and amplitude calibration procedure, using 2005+403 and 2013+370 for bandpass calibration of Cygnus A, and 0423-01 and 3C84 for NGC 1052.

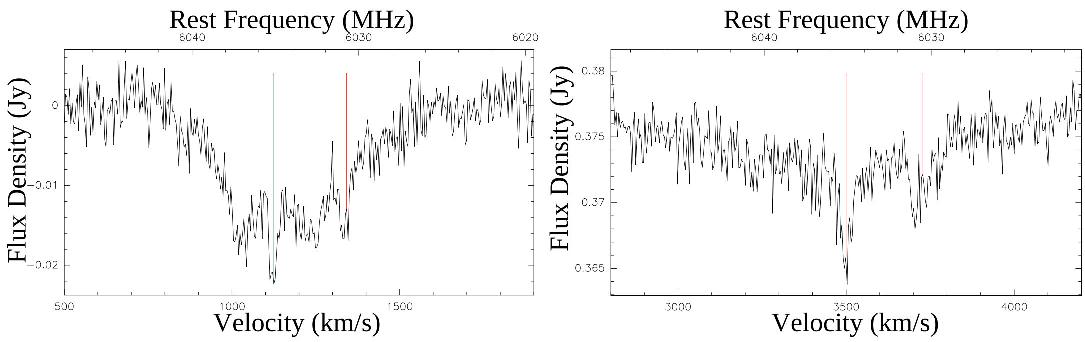

Figure 1: Absorption spectra of NGC 3079 (left) and NGC 5793 (right). The red lines mark the position of the two main lines at 6031 MHz and 6035 MHz at the systemic velocity. The velocity scales refer to the 6035-MHz line.

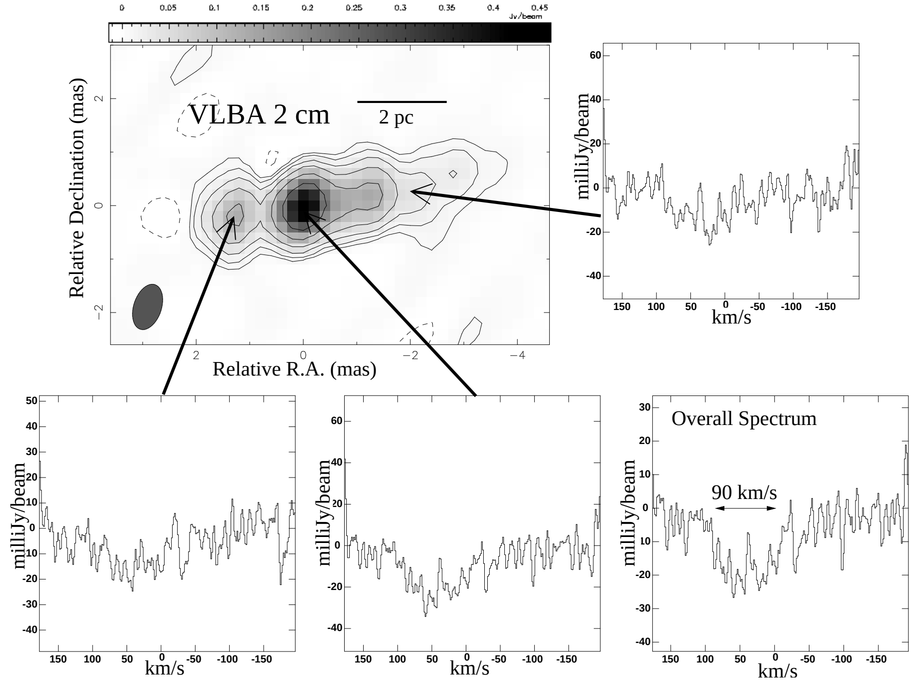

Figure 2: VLBA image of Cygnus A at 2 cm. The synthesized beam is (0.879×0.52) mas^2. The image is contoured at -1.5, 1.5, 3, 6, 12, 24, 48, 96 percent of the map peak at 0.453 Jy/beam. The panels show a montage with selected OH absorption spectra. The bottom right panel shows the absorption spectrum integrated over the whole source.

3. Results

3.1 The Effelsberg survey

Of the originally selected 31 Seyfert 2 galaxies listed in Table 1, 27 sources were observed at 6 GHz and 20 sources were observed at 4.7 GHz with the 100-m Effelsberg telescope. We detected absorption at 6 GHz towards five sources. The spectra of two of them, NGC 3079 and NGC 5793, are shown in Fig. 1. Absorption was detected towards the centre of each source, with wide velocity components and narrow troughs at the systemic velocities of the two lines. In NGC 3079 (Fig 1, left panel), the absorption width is 800 km/s, with two deeper components corresponding to the two transitions (6031 MHz and 6035 MHz) at the systemic velocity. The maximum line opacity is $\tau = 0.05$. Two further lines corresponding to the two transitions were also observed blueshifted relative to the systemic velocity by 100 km/s, indicating the presence of some outflowing gas. Alternatively, these two troughs, symmetric around the 6035-MHz line, might suggest the presence of gas rotating around a central source. The VLBI jets in this source, a Seyfert 2 galaxy 16 Mpc away, extend to 1.5 pc from the central engine [14]; the 1.6-GHz absorption in this source has been found to come from nuclear region [15] and in addition to the broad velocity width, suggest that the 6-GHz absorption was also likely to come from the central region, where the torus is expected to be. No absorption was observed in the 4.7-GHz transition.

The absorption spectrum in NGC 5793 also shows a very broad line width, which ranges up to 1000 km/s (Fig.1, right panel). Two narrow troughs, corresponding to the two transitions at the systemic velocity and corresponding to a maximum line opacity of $\tau \sim 0.034$, were observed. Both these sources show previously detected OH in absorption in the lower state transitions at 1.6 GHz [16], [17].

3.2 Cygnus A

The 2-cm continuum image of Cygnus A (Fig. 2) shows a compact radio source, extending east–west up to 4 pc from the core, with a peak flux density of 453 mJy/beam. The noise in the map is 5 mJy/beam. Fig. 2 shows the spectra for different positions at the source. We report a tentative detection of the rotationally-excited OH transition at 13.434 GHz towards the centre of Cygnus A. The apparent optical depth derived from the ratios of intensities of peak absorption and adjacent continuum is $\tau = 0.125$ with a line FWHM corresponding to $\sim$ 90 km/s. The absorption profile towards the lobes is suggestive that part of the gas is diffuse and is surrounding the inner jets, whereas a deeper and broader absorption profile is seen towards the core. The profile is strongest when integrated over the entire area containing continuum emission, and again seems to indicate that the gas is spread over the whole source, with prevalence towards the central region. Further tests are needed to confirm this result and to rule out a spurious feature due to low-level instrumental effects only detectable after long integration times.

4. Conclusions

We have detected rotationally-excited, broad OH lines in absorption towards five of the 27 sources observed with the 100-m telescope in Effelsberg. This yields a detection rate of 19 %, which is higher than the detection rates achieved in previous surveys. Those previous studies mainly targeted red quasars, where an infrared excess is indicative of large columns of dust towards the line of sight (e.g. [18], [19]). The source selection in our study was based on X-ray column densities. This is the first time this has been done. The observed line widths range from a few 100 km/s to 2000 km/s, suggesting that the gas in all sources is close to the central region, either rotating around the central engine, or infalling/outflowing. We have found that the new 6-GHz detections have absorption in the ground state transition at 1.6 GHz. This does not support the hypothesis of radiative excitation models alone to explain the previous lack of molecular detections. However, given the high X-ray absorbing columns in our systems, the non-detections still need to be explained. Since the nature of the absorbing material is unknown, one possibility is that it may be non-molecular in most galaxies.

We have found that in the five systems with detections the lines are strong and were visible after short integration times, whereas in the non-detections no lines were visible even after longer integration times. This bimodal distribution of absorptions could be explained assuming the presence of compact clouds crossing the line of sight in a few sources.

We also report a tentative OH detection at 13.4 GHz towards the powerful, nearby galaxy Cygnus A. This result needs further study to be confirmed. The compactness of the radio source at this frequency indicates that the absorbing material lies within 4 pc along the line of sight to the central engine. This is consistent with most recent results based on high-resolution IR observations of NGC 1068, which show a torus size that is no more than a few parsecs, e.g. [20], [21].

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