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

C. M. Violette Impellizzeri
Max-Planck-Institut für Radioastronomie, Bonn, Germany
E-mail: violette@mpifr-bonn.mpg.de

Alan L. Roy, Christian Henkel
Max-Planck-Institut für Radioastronomie, Bonn, Germany
E-mail: aroy@mpifr-bonn.mpg.de, chenkel@mpifr-bonn.mpg.de

One of the fundamental concepts in the unified scheme of AGN 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 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 yielded 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.

The 8th European VLBI Network Symposium on New Developments in VLBI Science and Technology and EVN Users Meeting
September 26-29 2006
Torun, Poland

*Speaker.
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 the type 2 objects our view of the central continuum source and the broad line region is blocked by a significant column density of obscuring material \[1\]. 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 has been somewhat indirect and the structure and extent of the obscuring material are still poorly understood. As the nearest powerful FR II radio galaxy (\(z = 0.0565\)), Cygnus A has been the subject of a number of studies that test 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 by a dusty obscuring torus \[7\]. An X-ray absorbing column of \(N_{\text{H}} = (3.75 \pm 0.73) \times 10^{23} \text{cm}^{-2}\) is consistent with the notion of a buried quasar in Cygnus A \[8\]. Searches for 18 cm OH and 6 cm H2CO by Conway & Blanco \[9\] yielded non-detections at 1% optical depth \[9\]. In 1994, Barvainis & Antonucci failed to detect CO J=0-1 and CO J=1-2 absorption, challenging the torus model for Cygnus A \[10\]. 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 \[3\]. Interestingly, Fuente et al. \[11\] report 118 GHz CO+ absorption, supporting CO excitation from radiative excitation effects \[11\]. 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 (\(\geq 10^{22} \text{cm}^{-2}\)) and for having \(S_{6\text{GHz}} > 50 \text{mJy}\) to ensure sufficient continuum core strength. We included some AGN with polarized broad-line emission, which indicates an obscured broad line region, 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 were followed up in the 4.7 GHz transitions with Effelsberg between June 2004 and August 2004.
Table 1: List of sources observed at 6 GHz with the 100-m telescope in Effelsberg. † sources observed by Henkel et al. (priv. comm.)

Four of our top candidates, Cygnus A, Hydra A, NGC 1052 and NGC 1275, were too strong for single-dish spectroscopy, 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, 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.

3. Results
3.1 An 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 100m telescope at Effelsberg. We detect absorption at 6 GHz towards five sources. The spectra of two of them, NGC 3079 and NGC 5793, are shown in Fig. 1. Absorption is detected towards the centre of the sources, with wide velocity components and narrow troughs at the systemic velocity 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 are also observed corresponding to the two transitions 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 is also likely to come from the central region, where the torus is expected to be. No absorption is 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 are observed corresponding to the two transitions at the systemic velocity and corresponding to a maximum line opacity of $\tau \sim 0.034$.

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 detect rotationally excited, broad OH lines in absorption towards five of the 27 sources observed with the 100m telescope in Effelsberg. This yields a detection rate of 19 %, which is higher than the detection rates achieved in previous surveys in the literature. These 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]). In our study, source selection was for the first time based on X-ray column densities. 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 find 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 find 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 in the case of compact clouds crossing the line of sight in a few of the 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 is within 4 pc along the line of sight to the central engine, consistent with most recent results based on high resolution IR observations, showing torus sizes which are no more than a few parsecs, e.g. [21]. [21].

References

[1] R. Antonucci, Unified models for active galactic nuclei and quasars, ARA&A (1993) 31 473
[2] P. Maloney; M. C. Begelman; M. J. Rees, Radiative excitation of molecules near powerful compact radio sources, ApJ (1994) 432 606

[3] J.H. Krolik; M.C. Begelman, Molecular tori in Seyfert galaxies - Feeding the monster and hiding it, ApJ (1988) 329 70

[4] J.T. Schmelz; W.A. Baan; A.D. Haschick et al., An Arecibo survey for extragalactic hydroxyl absorption. I - Presentation of results, AJ (1986) 92 1291

[5] W.A. Baan, Willem; A. Haschick et al. Hydroxyl in galaxies. I - Surveys with the NRAO 300 FT telescope, AJ (1992) 103 728

[6] L. Staveley-Smith; R.P. Norris; J.M. Chapman et al. A southern OH megamaser survey, MNRAS (1992) 258 725

[7] R. Antonucci; T. Hurt; A. Kinney, Evidence for a Quasar in the Radio Galaxy Cygnus-A from Observation of Broadline Emission, Nature (1994) 371 313

[8] S. Ueno; K. Koyama; M. Nishida et al. X-ray observations of Cygnus A using the GINGA satellite, ApJ (1994) 431 1

[9] J.E. Conway; P.R. Blanco, HI Absorption Toward the Nucleus of the Powerful Radio Galaxy Cygnus A: Evidence for an Atomic Obscuring Torus?, ApJ (1995) 449 131

[10] R. Barvainis; R. Antonucci, Search for CO absorption from a molecular torus in Cygnus A, AJ (1994) 107 1291

[11] A. Fuente; J.H. Black; J. Martín-Pintado et al. Tentative Detection of CO+ toward Cygnus A, ApJ (2000) 545 113

[12] J. Black, The Molecular Astrophysics of Stars and Galaxies (1997), 469

[13] U. Bach; T.P. Krichbaum; E. Middelberg et al. Spectral Properties of the Core and the VLBI-Jets of Cygnus A, evn.conf (2004) 155

[14] A.S. Trotter; L.J. Greenhill; J.M. Moran et al. Water Maser Emission and the Parsec-Scale Jet in NGC 3079, ApJ (1998) 495 740

[15] Y., Hagiwara; H.R. Klückner; W. Baan VLBI imaging of OH absorption: the puzzle of the nuclear region of NGC3079, MNRAS (2004) 353 1055

[16] W.A. Baan; J.A. Irwin, The Nuclear Structure of NGC 3079, ApJ (1995) 446 602

[17] Y. Hagiwara; P.J. Diamond; N. Nakai et al. Probing circumnuclear molecular gas in NGC 5793 with OH absorption, A&A (2000) 360 49

[18] S.J. Curran; M.T. Whiting; M.T. Murphy et al. A survey for redshifted molecular and atomic absorption lines - I. The Parkes half-Jansky flat-spectrum red quasar sample, MNRAS (2006) 371 431

[19] M.J. Drinkwater; F. Combes; T. Wiklind, A search for molecular absorption in the tori of active galactic nuclei, A&A (1996) 312 771

[20] W. Jaffe; K. Meisenheimer; H. Röttgering et al, The central dusty torus in the active nucleus of NGC 1068, nature (2004) 02 531

[21] A. Poncelet; G. Perrin; H. Sol A new analysis of the nucleus of NGC 1068 with MIDI observations, A&A (2006) 450 483