A search for molecular absorption in the tori of active galactic nuclei

M.J. Drinkwater¹, F. Combes², T. Wiklind³

¹ Anglo-Australian Observatory, Coonabarabran, NSW 2357, Australia
² DEMIRM, Observatoire de Paris, 61 Av. de l’Observatoire, F–75014 Paris, France
³ Onsala Space Observatory, S–43992 Onsala, Sweden

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Abstract. We describe a search for molecular absorption at millimetre wavelengths associated with dusty molecular tori in active galactic nuclei (AGN). The sample observed consists of 11 flat-spectrum radio sources known to have red optical to infra-red colours plus two steep-spectrum narrow-line radio galaxies. Spectra of the sources were obtained in the 3-, 2- and 1.3-millimetre bands at frequencies corresponding to common molecular transitions of CO, HCO⁺, HCN and CS at the AGN redshift. The observations were thus sensitive to absorption taking place either in dusty molecular tori surrounding the AGN nucleus, or in molecular clouds in the AGN host galaxy.

No absorptions were detected in any of the sources. We calculated upper limits to the column density in molecular absorption, using an excitation temperature of 10 K, to be \( N_{\text{CO}} < 10^{15} - 10^{16} \text{cm}^{-2} \), equivalent to hydrogen columns of order \( N_H < 10^{19} - 10^{20} \text{cm}^{-2} \). These limits are significantly lower than the values (\( N_H \approx (2 - 6) \times 10^{21} \text{cm}^{-2} \)) that might be expected if the red colours of these sources were due to dust absorption at the quasar redshift as suggested by Webster et al. (1995). Should the excitation temperature of the molecular transitions be higher than 100K, the upper limits to the \( H_2 \) column densities would be greater than those derived from the red colours.

To explain the lack of molecular absorption we conclude that either the optical extinction takes place outside the host galaxy (along the line of sight), or the excitation temperature of the molecular transitions is very high, or the obscuration is not associated with significant amounts of cold molecular gas. It is quite possible that the hard X-ray flux from the central source of these AGN is strong enough to photo-dissociate the molecules.

Key words: interstellar medium: molecules – galaxies: ISM, absorption lines, radio continuum

Send offprint requests to: M. Drinkwater, mjd@aoobsn.aao.gov.au

1. Introduction

In the unified models of active galactic nuclei (AGN), the central “engine” is surrounded by a parsec-scale geometrically and optically thick dust torus. The Broad Line Region (BLR) and a non–thermal continuum source are situated inside the torus, whereas the Narrow Line Region (NLR) is outside. Many observed characteristics and apparent differences of AGN can then be ascribed to orientation effects (see Antonucci 1993).

Although the unified model is hotly debated, it is clear that at least some AGN are surrounded by tori. That opaque tori can block the BLR from direct view has been demonstrated by spectropolarimetry, where the polarized flux spectra show broad permitted lines in AGN which normally are characterized by forbidden narrow lines only, i.e. a hidden BLR (cf. Antonucci & Miller 1985).

In nearby AGN there is evidence for the presence of molecular gas that may be associated with dusty tori. Very Long Baseline Array observations of \( H_2 \) maserspots in the nucleus of NGC 4258 (Miyoshi et al. 1995) strongly suggest a circumnuclear molecular torus with Keplerian rotation. However the extent of the maser emission region is only 0.13 pc and the disk is not geometrically thick. On much larger scales than proposed for tori, Planesas et al. (1991) found a circumnuclear molecular ring with a radius of 130 pc in NGC 1068, a prototypical Seyfert 2 galaxy, and in NGC 4945, Bergman et al. (1992) inferred a thick torus consisting of a large number of small but dense molecular clouds. A circumnuclear ring has also been seen in Centaurus A, with a radius of ~ 100 pc (Israel et al. 1990, Rydbeck et al. 1993).

These observational data clearly show the existence of molecular gas close to the central engine of AGN, but the dimensions are rather extreme and the masses are quite small. The rather large torus in Centaurus A only contains
The physical conditions in the molecular tori, such as density and temperature, are largely unknown. The small molecular mass combined with the low beam filling factor of nuclear tori means that observations of CO emission from more distant sources will be beyond the capacity of present and future millimetre-wave telescopes.

Molecular absorption, however, is much easier to detect and can be observed at any distance as long as the background source remains unresolved and has a reasonably strong continuum flux at millimeter wavelengths. The utility of mm–wave molecular absorption lines in deriving detailed properties of molecular gas at large distances has been demonstrated by the observations of 38 different molecular transitions in four absorption systems at redshifts $z = 0.25 - 0.89$ (Wiklind & Combes 1994, 1995, 1996a, 1996b). The high sensitivity of molecular absorption line observations means that molecular species much rarer than CO can be observed. For instance, HCO$^+$, HCN, HNC, CS and CN have been observed, as well as the isotopic variants $^{13}$CO and C$^{18}$O (Combes & Wiklind 1995) as well as H$^{13}$CO$^+$ (Wiklind & Combes 1996a).

Hence we have the tools to derive detailed physical and chemical properties of the molecular component of the interstellar medium at high redshifts, something which is impossible by other means. Molecular absorption lines can therefore be used to search for molecular tori very close to the presumed black holes in distant AGN.

The main problem in observing molecular gas close to the centre of AGN is to select the best candidates. Many quasi-stellar object (QSO) surveys have selection criteria which favour objects which do not suffer substantial extinction (blue colours, UV–excess, etc). A better approach is to use surveys compiled at wavelengths which are unbiased concerning extinction. Radio surveys are suitable; indeed several radio–loud QSOs (i.e. quasars) are known to be optically faint, but are bright in the near–infrared. These sources are most likely “optically quiet” because of extinction. Webster et al. (1995) have recently discovered a population of radio–loud quasars that are 2–4 magnitudes redder in optical to infra-red $B_J - K_n$ colours than samples of optically selected QSO samples. The distribution of emission line equivalent widths indicates that the red colours are not due to an intrinsically red spectrum from the central continuum source, so they conclude that the red colours are caused by dust absorption. There are three possible sources of the extinction:

1. An intervening galaxy (which seems to be the case for B0218+357 and PKS 1830–211).
2. Molecular clouds in the AGN host galaxy (PKS 1413+135 and B31504+377).
3. A molecular torus obscuring the line of sight to the nucleus.

In this paper we present data from a search of molecular absorption directly associated with the AGN themselves, i.e. cases 2 and 3, concentrating on sources from Webster et al. (1995) that are known to be optically red. We did not detect any absorption. This does not necessarily imply that the first case is correct, but it does put very stringent limits to the amount of molecular material in the AGN host galaxy or torus along the line of sight. In Section 2 we describe the sources observed and in Section 3 we present the results of our observations: high signal-to-noise spectra which did not reveal absorption in any of the sources. In Section 4 we derive upper limits to the molecular absorption columns in our sources and compare these to estimates of the absorption required by the optical reddening. A discussion of possible scenarios for explaining the lack of molecular gas along the line of sight to heavily obscured AGN and the consequences for the unified model are discussed in Section 5.

2. The Sample

As our intention was to observe objects known to be obscured, we selected 11 red ($B_J - K_n \geq 4$) sources from the Webster et al. (1995) sample. The sample is fully listed and defined in Drinkwater et al. (1996); basically it consists of flat-spectrum radio sources brighter than 0.5 Jy at 2.7 GHz. In the unified model, flat-spectrum sources are most likely seen with the torus “face-on” giving an unobstructed view of the central source of the AGN. This would tend to select against cases where we might expect to have significant absorption by the torus. This is to some degree borne out by the fact that broad permitted emission lines are seen in many of the optical spectra (see Table 1). There is probably some range of orientations in the sample however, e.g. the radio–galaxy PKS 0521–365 which is an intermediate case with a spectral index of $-0.49$ (at the steep limit of our sample), and a radio morphology of two lobes plus a compact core.

We observed two additional sources which are much more likely to have edge–on configuration: the powerful narrow–line radio galaxies Cygnus A and Hydra A. We do not have such complete information about these sources, but Cygnus A is red in $B_J - K_n$ and Hydra A is steep-spectrum by our definition, and both have extended radio structure indicative of edge-on configurations (e.g. Carilli et al. 1994 for Cygnus A and Morganti et al. 1993 for Hydra A).

The sources we observed, which are listed in Table 1, display a range of properties relating to their orientation, ranging from the compact core-dominated flat-spectrum quasars to more extended steep–spectrum radio–galaxies.
3. Observations

The observations were made with the IRAM 30–m telescope at Pico Veleta in Spain, during the period 1995 June 10–16 and on the SEST 15–m telescope at La Silla in Chile on a number of runs in 1993 January and 1995 June–July. We used the 3–, 2– and 1.3–mm SIS receivers, tuned to the redshifted frequencies of the molecular transitions in question (see Table 2). The data for most of the sources were presented previously by Wiklind & Combes (1996b) where full details of the observing setup are given, although we note in particular that the bandpass of the spectra was 500 MHz for the IRAM data and 1000 MHz for the SEST data. In this paper we present new measurements of PKS 0438–436, PKS 2223–052, Cyg A and Hydra A.

No absorption was detected in any of the spectra. The sources were bright at millimetre-wavelengths so high signal-to-noise spectra were obtained (see the spectra of Cygnus A in Figure 1) which allowed us to place upper limits on the molecular absorption columns. Details of the spectra and the derived upper limits are given in Table 2. Before discussing the absorption limits in the next section it is necessary to confirm that the observations sampled a large enough range in redshift to include the emission redshift of each source. Note that this is not guaranteed for two of the sources: PKS 0422+004 has no published reference and for PKS 1555+001 the measurement is not precise (Baldwin et al. 1981). In Table 2 we list the best available optical redshift for each source along with an error if available. The cases where no error is given are all of reasonable quality so we can assume an error of $\Delta z = 0.002$. Then for each of the transitions involved we have calculated the range of redshifts ($z_{\text{observed}}$) covered on the basis of the central frequency observed and the appropriate bandpass. Note that in some cases a second overlapping frequency range was also observed. We find that in all cases except the two mentioned above, the spectral range is sufficient to have included the emission redshift.

4. Analysis of Absorption Limits

4.1. Molecular Absorption Upper Limits

We used the non-detection of absorption in our data to place upper limits on the column density in the various molecules. These are shown in Table 2. The calculations were made in the same way as in Wiklind & Combes (1996b), except that we have taken a slightly less conservative limit of 2–sigma, based on the noise in a single spectral element of width $\delta v$ (indicated in column 8 of Table 2) and assuming an excitation temperature of 10 K.

The upper limits on absorption at $z = z_{\text{em}}$ in the various sources were of the order $N_{CO} < 10^{15} – 10^{16}$ cm$^{-2}$ (similar results were obtained for the other molecular species using the relative abundances e.g. $N_{CO}/N_{HCN} \approx N_{CO}/N_{HCO} \approx 10^3$). These column densities were derived assuming an excitation temperature of 10 K. This is a value typical for molecular gas in a variety of different

Table 1. Parameters of the Sources Observed

| Source        | RA(B1950) hours | Dec(B1950) degrees | $\alpha$ | ID  | $z_{\text{c}}$ | $\Delta v^{(a)}$ km s$^{-1}$ | $B_{J}$ mag | $B_{J} – k_{n}^{(b)}$ mag | $N_{H, \text{Gal}}^{(c)}$ $10^{20}$ cm$^{-2}$ | $N_{H, \text{X-ray}}^{(d)}$ $10^{20}$ cm$^{-2}$ |
|---------------|-----------------|-------------------|---------|-----|-------------|-----------------------------|-------------|---------------------------|---------------------------------|---------------------------------|
| PKS 0113−118  | 1:13:43.22      | −11:52:04.5       | 0.09    | Q   | 0.672       | 5200                        | 19.42       | 4.1                       | 3.1                             | -                               |
| PKS 0422+004  | 4:22:12.52      | 0.29:16.7         | 0.35    | BL  | 0.310       | -                           | 16.19       | 3.7                       | 8.7                             | -                               |
| PKS 0438−436  | 4:38:43.18      | −43:38:53.1       | 0.12    | Q   | 2.852       | 1700                        | 19.08       | 2.7                       | 1.8                             | 6.5, 86$^{(e)}$                 |
| PKS 0521−365  | 5:21:12.99      | −36:30:16.0       | 0.49    | G   | 0.0552      | 1800                        | 16.74       | -                         | 2.7                             | 4.5$^{(e)}$                     |
| PKS 0537−441  | 5:37:21.00      | −44:06:46.8       | −0.02   | Q   | 0.894       | 2400                        | 15.45       | 3.9                       | 3.1                             | (3.1)$^{(e)}$                   |
| Hydra A       | 9:15:41.45      | −11:53:08.3       | −0.95   | G   | 0.0538      | <1500                       | 13.7        | -                         | 4.6                             | -                               |
| PKS 1213−172  | 12:13:11.67     | −17:15:05.3       | −0.06   | X   | -           | -                           | -           | -                         | 4.4                             | -                               |
| PKS 1548+056  | 15:48:06.93     | 5:36:11.3         | 0.28    | Q   | 1.422       | 4400                        | 18.45       | 4.3                       | 4.7                             | -                               |
| PKS 1555+001  | 15:55:17.69     | 0:06:43.5         | 0.21    | Q   | 1.77        | 4700                        | 22.12       | 6.6                       | 6.9                             | -                               |
| PKS 1725+044  | 17:25:56.34     | 4:29:27.9         | 0.71    | Q   | 0.296       | 4500                        | 18.20       | 4.4                       | 7.3                             | (21)$^{(d)}$                    |
| Cygnus A      | 19:57:44.45     | 40:35:46.1        | -       | G   | 0.0561      | <1500                       | 17.0        | 4.4                       | 41.                             | 820$^{(f)}$                     |
| PKS 2223−052  | 22:23:11.08     | −5:12:17.8        | −0.14   | Q   | 1.404       | -                           | 17.12       | 3.7                       | 5.1                             | (6.2)$^{(d)}$                   |
| PKS 2329−162  | 23:29:02.40     | −16:13:30.8       | 0.08    | Q   | 1.155       | 2900                        | 20.87       | 4.3                       | 3.6                             | -                               |

Note: The following data are from Drinkwater et al. (1996) (except Cygnus A and Hydra A from NED): RA and Dec are the accurate radio source positions; $\alpha$ is the spectral index $(S_{\nu} \propto \nu^{\alpha})$ measured from 2.7 to 5.0 GHz; ID identifies the source as Quasar, BLac, Galaxy or X-near a bright star; $z_{\text{c}}$ is the redshift. a) Line widths (FWHM) of permitted lines estimated from the spectra cited in Drinkwater et al. (1996). b) $k_{n}$ magnitudes from Webster (private communication) except for 0438–436, Elston (private communication). c) Galactic $N_{H}$ column density estimated from Stark et al. (1992). d) X-ray $N_{H}$ column density estimated from ROSAT hardness ratios; sources with no significant excess in parentheses (Brinkmann, private communication). e) X-ray $N_{H}$ column density from Elvis et al. (1994a), two values at rest and quasar redshifts respectively. f) X-ray $N_{H}$ column density from Arnaud et al. (1987).
Table 2. Molecular tori not detected in absorption

| Source       | $z_e$  | Transition          | $v_{\text{obs}}$ | $z_{\text{obs}}$ | $T_{\text{cont}}$ | $t^a$ | $\sigma_{\text{rms}}$ | $\int v_{\text{cut}}^2 dv$ | $N_{\text{tot}}$ |
|--------------|--------|---------------------|------------------|------------------|------------------|------|------------------|-------------------|----------------|
| PKS 0113−118| 0.672  | HCO+(2−1)           | 106.68           | 0.672±0.004      | 0.090            | I    | 2.8              | 5.6               | < $2 \times 10^{12}$ |
|              |        | CO(2−1)             | 137.88           | 0.672±0.003      | 0.090            | I    | 2.2              | 8.9               | < $1 \times 10^{15}$ |
|              |        | CO(3−2)             | 206.81           | 0.672±0.002      | 0.040            | I    | 1.8              | 13.8              | < $1 \times 10^{16}$ |
| PKS 0422+004 | 0.310  | CO(1−0)             | 87.993           | 0.310±0.008      | 0.035            | S    | 12.6             | 5.2               | < $2 \times 10^{16}$ |
|              |        | HCN(2−1)            | 135.31           | 0.310±0.005      | 0.030            | S    | 9.6              | 6.9               | < $3 \times 10^{14}$ |
|              |        | HCO+(2−1)           | 136.16           | 0.310±0.005      | 0.030            | S    | 9.6              | 6.9               | < $3 \times 10^{14}$ |
|              |        | HNC(2−1)            | 138.41           | 0.310±0.005      | 0.030            | S    | 9.6              | 6.9               | < $4 \times 10^{14}$ |
| PKS 0438−436 | 2.852  | CO(3−2)             | 89.770           | 2.852±0.021      | 0.045            | S    | 2.3              | 3.9               | < $2 \times 10^{15}$ |
| PKS 0521−365 | 0.055  | HCO+(1−0)           | 84.538           | 0.055±0.006      | 0.200            | S    | 9.6              | 5.8               | < $6 \times 10^{12}$ |
| WC96         |        | HCN(2−1)            | 93.591           | 0.89±0.010       | 0.250            | S    | 12.1             | 10.0              | < $6 \times 10^{12}$ |
|              |        | HCO+(2−1)           | 94.179           | 0.89±0.010       | 0.250            | S    | 12.1             | 10.0              | < $5 \times 10^{12}$ |
|              |        | HNC(2−1)            | 95.765           | 0.89±0.010       | 0.250            | S    | 12.1             | 10.0              | < $7 \times 10^{12}$ |
|              |        | CS(4−3)             | 103.46           | 0.89±0.009       | 0.250            | S    | 12.1             | 10.0              | < $3 \times 10^{14}$ |
|              |        | CS(5−4)             | 129.32           | 0.89±0.007       | 0.170            | S    | 15.6             | 6.5               | < $6 \times 10^{14}$ |
| Hydra A      | 0.0538 | CO(1−0)             | 109.39           | 0.053±0.002      | 0.060            | I    | 2.7              | 9.4               | < $6 \times 10^{15}$ |
|              |        | HCO+(2−1)           | 169.27           | 0.053±0.002      | 0.050            | I    | 7.2              | 13.3              | < $2 \times 10^{14}$ |
|              |        | CO(2−1)             | 218.77           | 0.053±0.001      | 0.040            | I    | 6.8              | 10.0              | < $1 \times 10^{16}$ |
| PKS 1213−172 |        |                      |                  |                  |                  |      |                  |                  |                  |
| WC96         |        |                      |                  |                  |                  |      |                  |                  |                  |
|              |        |                      |                  |                  |                  |      |                  |                  |                  |
|              |        |                      |                  |                  |                  |      |                  |                  |                  |
| PKS 1548+056 | 1.422  | CO(2−1)             | 95.185           | 1.423±0.006      | 0.250            | I    | 3.1              | 1.0               | < $8 \times 10^{14}$ |
|              |        | CO(3−2)             | 142.77           | 1.422±0.006      | 0.160            | I    | 2.1              | 10.0              | < $1 \times 10^{15}$ |
| PKS 1555+001 | 1.77   | CO(3−2)             | 96.591           | 1.770±0.007      | 0.110            | I    | 3.1              | 9.1               | < $3 \times 10^{12}$ |
|              |        | CO(4−3)             | 166.44           | 1.770±0.004      | 0.100            | I    | 1.8              | 25.5              | < $2 \times 10^{16}$ |
| PKS 1725+044 | 0.296  | CO(2−1)             | 88.943           | 0.296±0.004      | 0.120            | I    | 3.4              | 11.0              | < $4 \times 10^{15}$ |
|              |        | HCO+(2−1)           | 137.63           | 0.296±0.002      | 0.100            | I    | 2.2              | 12.0              | < $3 \times 10^{12}$ |
| Cygnus A     | 0.0561 | CO(1−0)             | 109.10           | 0.056±0.002      | 0.120            | I    | 2.7              | 4.9               | < $1 \times 10^{15}$ |
|              |        | HCO+(2−1)           | 168.82           | 0.056±0.002      | 0.080            | I    | 1.8              | 9.3               | < $2 \times 10^{12}$ |
|              |        | CO(2−1)             | 218.19           | 0.056±0.001      | 0.070            | I    | 1.7              | 6.5               | < $1 \times 10^{15}$ |
| PKS 2223−052 | 1.404  | CO(2−1)             | 95.897           | 1.404±0.004      | 0.285            | I    | 3.1              | 4.2               | < $3 \times 10^{14}$ |
| WC95d        |        |                      |                  |                  |                  |      |                  |                  |                  |
| PKS 2329−162 | 1.155  | CO(2−1)             | 106.98           | 1.155±0.015      | 0.080            | I    | 2.8              | 6.6               | < $2 \times 10^{15}$ |
|              |        | CO(3−2)             | 160.46           | 1.155±0.003      | 0.060            | I    | 1.9              | 12.0              | < $5 \times 10^{15}$ |

a) Telescope: I=IRAM; S=SEST.
b) $\tau_v = -\ln(1 - 2\sigma_{\text{rms}}/T_{\text{cont}})$.
c) This source is next to a very bright star for which reason the emission redshift is unknown; a particular effort was made to search a large part of 2- and 3-mm bands for any absorption features; none were detected.
d) WC96: Wiklind & Combes 1996b
e) WC95: Wiklind & Combes 1995

4.2. Expected Absorption from Optical Data

We now consider what hydrogen column we might expect from the optical reddening proposed by Webster et al. (1995). They find a mean colour of $B_J - K_J \approx 2.5$ mag for the optical Large Bright QSO Survey (LBQS) compared to the redder colours of flat–spectrum radio quasars. For the sample observed here the colour range is $B_J - K_J =$
the metallicity
of CO(J=1−0), HCO+(J=2−1) and CO(J=2−1) towards
Cygnus A. The velocity scale is heliocentric and centered at
z_e = 0.0566.

3.7 − 6.6 mag. If we assume all the difference is due to
absorption in B_J, then A_B ≈ 1−4 mag. If the absorption
follows a 1/λ dust law then A_B/A_V ≈ 1.33, so A_V =
1 − 3 mag. We can use the Bohlin et al. (1978) results
for the Solar neighbourhood to convert this absorption
to a hydrogen column density (E(B − V) ≈ A_V/3 and
N(HI + H2) ≈ E(B − V) × 5.8 × 10^{21}cm^{-2}). This gives
N_H ≈ (2−6) × 10^{21}cm^{-2}.

If all the reddening is dust at the quasar redshift it
implies a hydrogen column density 2 orders of magnitude
larger than the upper limit implied by the CO data. This
could imply that the absorption is not taking place in the
AGN host galaxy or that the excitation temperature is at
least an order of magnitude higher than what is normally
found in molecular gas; alternatively the dust may not
have any associated molecular absorption: see the discus-
sion in Section 5.

4.3. X-ray Absorption
An independent measure of the N_H absorption column
for some of our sources is given by detections of X-ray
absorption. Elvis et al. (1994a) report a significant X-ray
absorption for the source PKS 0438−436, well in excess of
foreground Galactic N_H. They measure excess X-ray ab-
sorption equivalent to a column of N_H = 6.5 × 10^{20}cm^{-2},

but the column needed to produce the required absorption
increases with the absorption redshift because the
photons gain energy according to E ∝ (1 + z) (see Elvis
et al. 1994a). In the case of this source, the absorption
becomes much larger at z = 2.8 giving
N_H = 8.6 × 10^{21}cm^{-2}.

We searched the ROSAT public sky survey catalogue
for detections of other sources in our sample: 4 were found
(including PKS 0438−436) that had good enough data
to estimate the total absorption column using the hardness
ratio method (see Schartel et al. 1992). These estimates
were made by Brinkmann (private communication) and are shown in Table 1. In two of the four cases
(PKS 0438−436 and 0521−365) the values were signifi-
cantly in excess of that expected from the Galaxy. We also
note that a very large amount of absorption was re-
ported for Cygnus A by Arnaud et al. (1987), although
that is a rather special case because of the complex cluster
environment of the source as well as the large Galactic
column density.

Although we only have X-ray data for a very small
number of our sample, the inferred absorption columns are
consistent with the large amounts of absorption we obtain
for the optical reddening hypothesis. (Note that a similar
absorption column of N_H = 9 × 10^{21}cm^{-2} was obtained
for the steep-spectrum “red quasar” 3C 212 by Elvis et al.
1994b.) These values are in excess of the upper limits we
infer above from the millimetre data of N_H < 10^{15}cm^{-2},
but are not inconsistent with the lack of absorption at the
quasar redshift because the redshift of the X-ray absorp-
tion is not known.

5. Discussion
A previous attempt to detect CO absorption towards
cygnus A failed (Barvainis & Antonucci 1994) and our
results put even stronger limits on this non-detection. If
we consider 3σ upper limits within channels of 6km s^{-1},
we find that the optical depth in CO \tau_CO is lower than 0.08,
while Barvainis & Antonucci found a limit of \tau_CO < 0.6. If
broader lines are considered, the limits are even stronger,
evolving as the square root of the line-width. This result
is somewhat disappointing since the nucleus of Cygnus A
exhibits strong extinction at optical wavelengths as well
as a significant column density of hydrogen as show by
the X-ray results. Indeed, there is an appreciable HI col-
umn density, as observed through HI absorption (Conway
& Blanco 1995): 2.54 × 10^{22}cm^{-2}, if T_{spin} ≈ 1000K. The
absorption appears to come from nearby the nucleus,
because of its broad width (280km s^{-1}), but not closer than
≈40 pc as deduced from the lack of free–free absorption
at 1.4 GHz (Conway & Blanco 1995; Maloney 1996). None
of our other sources revealed any molecular absorption ei-
ther, even PKS 0438−436 which also has significant X-ray
absorption.
There are several possible causes for the non-detections. The most reasonable are:

1. The material causing the optical and X-ray absorption may not have any molecular gas associated with it because of photo-dissociation by the ionizing flux from the AGN nucleus. This is supported by the fact that appreciable HI column density is detected in absorption in Cygnus A. This effect was considered by Maloney et al. (1994), who showed that for CO to be present in significant amounts the “effective” X-ray ionization parameter

\[ \xi_{\text{eff}} = 1.1 \times 10^{-2} L_{44}/(n_9 r_{pc}^2 \Lambda_{22}^{0.9}) \]

must satisfy the condition \( \xi_{\text{eff}} \leq 5 \times 10^{-3} \), where \( L_{44} \) is the hard (2–10keV) X-ray luminosity in units of \( 10^{44}\text{ergs}^{-1} \), \( n_9 \) is the density in units of \( 10^9\text{cm}^{-3} \), \( r_{pc} \) is the distance from the nucleus in pc, and \( \Lambda_{22} \) is the hydrogen column density from the source. In the case of Cygnus A with an X-ray luminosity of \( 10^{44}\text{ergs}^{-1} \) and radii of order 1pc, Maloney et al. find that the condition can be satisfied if the density is as high as order \( 10^9\text{cm}^{-3} \). This is “not implausible” so photodissociation might not be important at small radii. If so, it would not be important at larger radii as well, since the condition for non-photodissociation is satisfied for radii larger than a critical one, given the column density imposed by the extinction and HI absorption. In the case of an isobaric model, considered by Maloney (1996), the medium would be molecular only above a critical pressure, depending on the radiation pressure, and could be atomic at all radii.

In the case of four of our sources which have X-ray fluxes from the Einstein survey listed by Wilkes et al. (1994) (PKS 0438−436, 0537−441, 1725+044, and 2223−052) the above condition may not be satisfied. These sources have X-ray luminosities in the range \( 5 \times 10^{44} - 2 \times 10^{47}\text{ergs}^{-1} \) in the 0.2–4.5 keV band (for an assumed spectral slope \( \alpha = 1 \); Wilkes et al. 1994) which largely overlaps the hard X-ray band after allowing for the source redshifts. Using similar values as Maloney et al. for the other variables, these X-ray luminosities imply that the ionization parameters may be high enough to dissociate the CO. This is even more likely if we use the lower values of the density \( (10^8 - 10^9\text{cm}^{-3}) \) used in the models of Seyfert AGN tori by Krolik & Lepp (1989).

2. There could also be CO present, but with a very low optical depth in the lower transitions because of high excitation temperatures. The upper limits in Table 2 were obtained using a temperature of 10K, but the column densities derived vary as \( T_{xx}^2 \), and could be \( 10^4 \) times higher if the excitation temperature of the molecular gas is \( \sim 1000\text{K} \). Close to the transition point between warm atomic and cool molecular gas in a torus, the kinetic temperature of of the molecular gas is \( \sim 700\text{K} \) (Maloney 1996). The high density, required for the existence of the molecular phase (see above), ensures that the rotational transitions will be thermalized. The excitation temperature will therefore be similar to the kinetic temperature. The limits to the hydrogen column density derived from our data, would then be higher than those derived from the optical reddening.

3. Maloney et al. (1994) showed how the CO molecules could be radiatively coupled to the strong radio continuum source, increasing the rotation temperature and lowering the fractional population at low J–levels and, hence, its optical depth. This effect may cause the lack of molecular absorption in Cygnus A with its exceptionally luminous radio emission, but is not likely to be generally important in radio galaxies (Maloney 1996).

4. The absorption may not take place at the AGN redshift, but in intervening systems at lower redshifts. Whilst this possibility is perhaps the most consistent with our non-detection of molecular absorption, Webster et al. (1995) argue that intrinsic absorption is more likely because of the lack of dependence with redshift.

5. We should mention the possibility that the reddening is not real, but the result of continuum emission that is intrinsically red. Radio galaxies are known to have red optical to infra-red colours, so the red colours might be due to light from the quasar host galaxies. However at the redshifts we are considering, typical radio galaxies are too faint \( (K > 18 \text{ for } z > 0.5) \) to have any significant contribution to the colours (see Lilly & Longair 1984). In a recent comparison with X-ray selected and optically-selected quasar samples, Boyle & di Matteo (1996) conclude that most of the spread in the colours is due to effects other than dust obscuration.

In summary, we found no evidence for molecular absorption at the emission redshift of the 13 AGN in our sample. Several of the sources have significant X-ray absorption or are optically reddened, implying a high column density of absorbing gas. Our results imply that either the absorption takes place along the line-of-sight to the AGN outside the host galaxy, or that the absorbing material is hot or not associated with molecular species like CO. In the model where the absorbing material is concentrated in a parsec-scale dusty torus, we suggest that the molecular gas is dissociated by the X-ray flux from the nucleus. This in principle allows us to put upper limits on the density of the torus, although we defer a detailed analysis until we can measure a larger sample of sources.

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