H I Absorption in Cygnus A

By **Philip R. Blanco**[1] & **John E. Conway**[2]

[1]Center for Astrophysics & Space Sciences, University of California, San Diego, USA

[2]Onsala Space Observatory, Onsala, S-43992, Sweden.

Using the VLA in A- and B-array configurations we have searched for spectral absorption towards the radio nucleus of Cygnus A due to neutral gas as a signature of a circumnuclear obscuring torus. The HI 21 cm line was detected in absorption with two velocity components, while similar observations of OH and H_2CO yielded upper limits.

The A-array's spatial resolution at the HI transition of 1.3 arcsec ($\simeq$1 kpc) is insufficient to resolve Cygnus A's pc-scale core-jet structure. However, we have been able to combine our results with X-ray and radio continuum observations, and recent modeling of atomic and molecular tori, to place constraints on the density and size of the HI obscuring region in Cygnus A. One possibility is that the majority of the gas is in a hot (5000–10000 K) mainly atomic phase. Alternatively, the HI absorption might be due to the small fraction (e.g. 10%) of atomic gas within a warm ($\sim$1000 K) molecular torus. In this case the non-detection of molecular absorption might be explained by radiative excitation of OH, CO and NH_3 due to the central radio source. We discuss the implications of these results for future observations of neutral gas and dust in Cygnus A.

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1. Introduction

One of the fundamental concepts in the unified scheme of AGN is that narrow line galaxies harbor a quasar nucleus, which is obscured from our direct view at optical and soft X-ray frequencies by an optically and geometrically thick circumnuclear "torus" of gas and dust. An essential step in testing this hypothesis is to search for direct evidence of this obscuring torus. In Cygnus A, X-ray observations by *Ginga* [1] and now *Asca* [2] have provided strong evidence for a quasar-like nucleus behind a large foreground column $N_H = 3.75 \pm 0.73 \times 10^{23}\,\mathrm{cm}^{-2}$ (90% errors). While providing our best estimate for the total column, however, these X-ray observations can neither constrain the location (e.g. from a pc-scale circumnuclear torus up to a kpc-scale dust lane) nor the physical state (molecular or atomic, neutral or ionized) of the absorbing gas.

Therefore, in March 1994 we used the VLA in A-array configuration to search for the spectral signatures of HI, OH and H_2CO towards the compact radio nucleus of Cygnus A [3]. Follow up B-array observations were conducted in July 1994 to confirm our detection of HI absorption. Further details can be found in [4].

2. Data reduction

Amongst the difficulties with reducing these spectral observations were the overall brightness of the continuum emission from the lobes (1600 Jy for the HI and OH observations) relative to the core (<900 mJy), and the extent and complexity of the lobe structure. The overall brightness causes problems primarily because small residual bandpass errors can generate large errors in the channel maps at the position of the hotspots and lobes; sidelobes from these errors can then mask spectral absorption at the core position. The bright continuum also significantly increases the system temperature at each antenna contributing of order 160 K for the HI and OH observations which increases the map noise by a factor of 5 from its nominal value (or by a factor of 2 for H_2CO). Finally the size and complexity of the source combines with the large continuum flux density to increase the difficulty of carrying out continuum subtraction.

Data reduction proceeded by (i) interactively editing to remove the sporadic effects of radio interference, (ii) amplitude- and phase-calibrating the data, (iii) making continuum images by averaging together several frequency channels, and then iteratively deconvolving and self-calibrating. For the A-array observations, in which two overlapping IF channels were used, these continuum images were then used to self-calibrate the spectral line data. This procedure aligned the phases and amplitudes of the edge channels prior to combining the data from the two IFs together in the visibility domain.

2.1. *Bandpass calibration and limits on absorption against the lobes*

Bandpass effects were then solved for using the Cygnus A data themselves—this was necessary because no sufficiently bright external calibrator exists. Only short baselines with continuum flux density > 70 Jy (> 10 Jy for H_2CO) were used in making bandpass solutions. Since these short baselines were dominated by lobe emission and not emission from the 0.8 Jy core, this procedure is therefore valid, provided there is no spectral emission or absorption from the lobes. This was checked by by applying the solutions obtained to calibrator data, BL Lacertae. The resulting calibrator spectra only show thermal noise, in the case of the A-array observations the spectral dynamic range (continuum flux density divided by RMS noise per channel) achieved is about 550:1, showing that residual bandpass effects are much less than the observed absorption toward the Cygnus A nucleus. This procedure also rules out significant absorption towards Cygnus A's radio lobes and hotspots; the 550:1 dynamic range corresponds to a HI opacity limit of 0.0018 per 11.5 $\mathrm{km\,s^{-1}}$ channel for a uniform foreground screen covering the whole of Cygnus A (cf. [5]). Any greater absorption would show up as apparent HI *emission* in the calibrator spectrum.

2.2. *Baseline subtraction and continuum estimation*

The final step was to remove continuum baselines from the data. First the effects of the bright hotspots were removed using the AIPS task UVSUB, then continuum baselines were removed from the residual data using the AIPS task UVLIN [6,7]. The data were then Fourier-inverted to obtain spectra at the core position (e.g. see Figure 1).

Depending on the deconvolution algorithm and imaging parameters used we obtained estimates of the core continuum flux density of between 654 mJy and 902 mJy (the large uncertainty is related to the lack of short spacings in the A-array observation and the poor B-array *uv* coverage).

3. Results

3.1. *H I absorption*

HI absorption toward the nucleus of Cygnus A was detected in both the original A-array data (see Figure 1) and confirmed in the follow-up B-array observations (see [4]).

The best fitting single Gaussian model for the A-array data requires FWHM$= 276 \pm 26\,\mathrm{km\,s^{-1}}$($\chi^2 = 124.1/84$ d.o.f.). However, the A-array spectrum shows strong evidence that the absorption is split into two components; a two-Gaussian fit yields centroid velocities of $+40 \pm 6$ and $-149 \pm 8\,\mathrm{km\,s^{-1}}$ for these components, with FWHM$= 151 \pm 16\,\mathrm{km\,s^{-1}}$ and $102 \pm 20\,\mathrm{km\,s^{-1}}$ respectively ($\chi^2 = 83.7/81$ d.o.f.).

Other models are not supported by our data. In particular, models invoking a gaussian HI *emission* line superposed on a single, broader absorption line cannot reproduce the observed A-array line profile for plausible values of line luminosity at Cygnus A's distance.

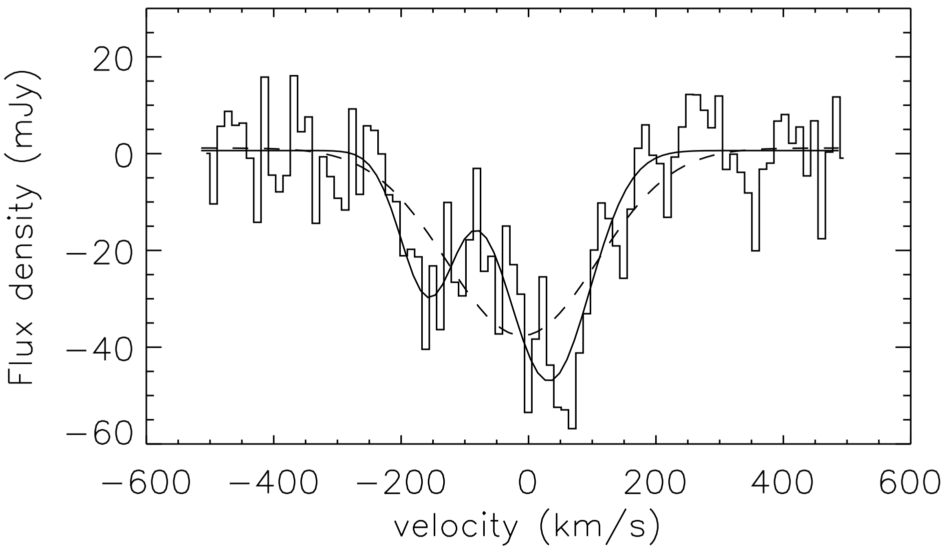

FIGURE 1. VLA HI spectrum of the core of Cygnus A, taken in A-array configuration. The velocity scale is centered on a heliocentric redshift of 0.0565, spectral sampling is $11.5\,\mathrm{km\,s^{-1}}$, and the synthesized beam is 1.3 arcsec. Dashed and solid lines show the one- and two-gaussian fits to the data, respectively.

Nor can we identify either component of the absorption line with the observed profile of [OI]6300Å at the position of the radio nucleus [8]. Note though that the HI absorption components' redshifts are in closer accord with those of the optical emission lines, than with the smaller value recently determined from stellar Mg b absorption [9].

Independent of the model, the integrated absorption from -400 to $+200\,\mathrm{km\,s^{-1}}$ is $-10.64 \pm 0.64\,\mathrm{Jy\,km\,s^{-1}}$. The corresponding HI column density depends on the flux density of the VLA core and what fraction of this core (which is resolved on parsec scales) is covered by the absorbing HI screen. Assuming that the 1.34 GHz continuum flux is distributed on a similar scale ($15h^{-1}$ pc) to the 5 GHz VLBI structure [10], it follows that if the absorbing screen has size $> 15h^{-1}$pc then all the continuum emission is covered. From our estimate of 778 ± 128 mJy for the VLA core flux density, the observed HI absorption then implies a HI column of $2.54{\pm}0.44{\times}10^{19}\,T_{spin}\,\mathrm{cm^{-2}}$ where T_{spin} is the spin temperature averaged along or line-of-sight; if the screen is smaller then the column must be larger.

3.2. *Limits on molecular absorption*

Our OH and H_2CO observations show no evidence for significant absorption or emission. The OH observations, which were somewhat affected by radio interference generally had a noise per channel only slightly larger than thermal, i.e. $12\,\mathrm{mJy\,beam^{-1}}$ (though several channels had an RMS noise of $18\,\mathrm{mJy\,beam^{-1}}$). The corresponding 3σ limit on the opacity of OH absorption is 0.065 per $8.3\,\mathrm{km\,s^{-1}}$ channel. The core spectra for formaldehyde showed features above the noise, but no convincing signature of absorption. Taking the ratio of the continuum core flux density (0.8 Jy) to the highest channel residual (8 mJy) we obtain an opacity limit of 0.01 per $54\,\mathrm{km\,s^{-1}}$ channel.

4. The location of the H I obscuring gas

Measurements of the Paschen and Balmer lines imply a foreground extinction of A_V =1.2 mag towards the Narrow Line Region (NLR) in Cygnus A [11]. For a normal dust-to-gas ratio, the associated neutral gas (if entirely atomic with $T_{spin} \simeq$100 K) could easily account for the observed integrated H I opacity.

However, a serious problem with this interpretation is the large velocity width of the absorption feature (FWHM= 276 km s^{-1}). In known cases of dust lane ellipticals with associated H I absorption, the absorption occurs within multiple narrow components, quite different to what we see in Cygnus A [12,13,14,15].

Conversely, in those objects which have broader (> 150 km s^{-1}) H I absorption profiles there is increasing evidence that the absorption occurs close to the nucleus (NGC4151: r <50 pc [16]; NGC4261: $r \approx$100 pc [17]; NGC3079: $r \approx$90 pc [18]). Although an origin in the NLR cannot be ruled out (and we shall return to this point later), the broad velocity width of Cygnus A's H I absorption is more clearly consistent with theoretical predictions for circumnuclear tori [19], since in order for such tori to be geometrically thick the cloud dispersion velocity within the torus must approximately equal the orbital velocity, i.e. typically a few hundred km s^{-1}. Torus models could also give a natural explanation of the apparently split line seen in Cygnus A, if the torus gas rotates around a parsec scale radio jet which is somewhat edge-brightened and orientated close to the sky plane. This hypothesis will be tested by upcoming H I VLBI observations.

An important result of recent physical modelling of circumnuclear tori [20] is that the constituent gas can be either atomic or molecular depending on the value of the effective ionization parameter $\xi_{eff} = 4\pi F_X {N_{22}}^{-0.9}/n = L_X {N_{22}}^{-0.9}/nr^2$ [20]. If $\xi_{eff} > 10^{-3}$ (in Maloney *et al.*'s units) the gas must be largely atomic, otherwise it is mainly molecular; we discuss these two possibilities below.

4.1. *An atomic obscuring torus*

Support for a largely atomic obscuring column in Cygnus A comes from the absence of detectable CO [21], NH_3 [22], OH or formaldehyde absorption. Although other explanations are possible, the simplest is that this absorption does not occur because most of the gas along the line of sight is atomic. [20] find that an atomic torus results if $\xi_{eff} > 0.001$; using the hard X-ray luminosity reported by [1] this implies that the torus will be largely atomic provided that its outer radius $r_{outer} < 32h^{-1}n_6^{-1/2}$ pc where n_6 is the H I number density in the torus clouds in units of 10^6 cm^{-3}.

If the torus is large enough to cover most of the compact radio jet at 1.34 GHz (i.e. has outer radius $> 15h^{-1}$ pc) then the observed H I opacity requires a column density of H I of $2.54\pm0.44\times10^{19}\,T_{spin}$ cm^{-2}. Atomic gas irradiated by hard X-rays is predicted to have a stable equilibrium state at a temperature of $\approx$8000 K, almost independent of density [23,24]. It can be shown that the increase in line-of-sight-averaged spin temperature due to radiative excitation effects [25] will be less than a factor of 2 provided that $r_{outer} > 4.4n_6^{-1/2}$ pc, where r_{outer}, the torus outer radius, is assumed to be much larger than the inner radius. Assuming a spin temperature in the range 8000–16000 K the required H I column density to give our observed H I absorption is then in the range 2.0–4.0×10^{23} cm^{-2}, in excellent agreement with the total column density derived from X-ray observations.

Since an atomic torus contains a significant fraction (i.e. 0.01) of free electrons [24], there is an additional constraint on torus properties due to the lack of observable free-free absorption effects. The fact that the observed VLA core spectrum is flat (in F_ν) down to at least 1.34 GHz suggests that the free-free opacity at 1.34 GHz is less than about 0.5. Assuming electron fractions of 0.01, electron temperatures of 8000 K, and a

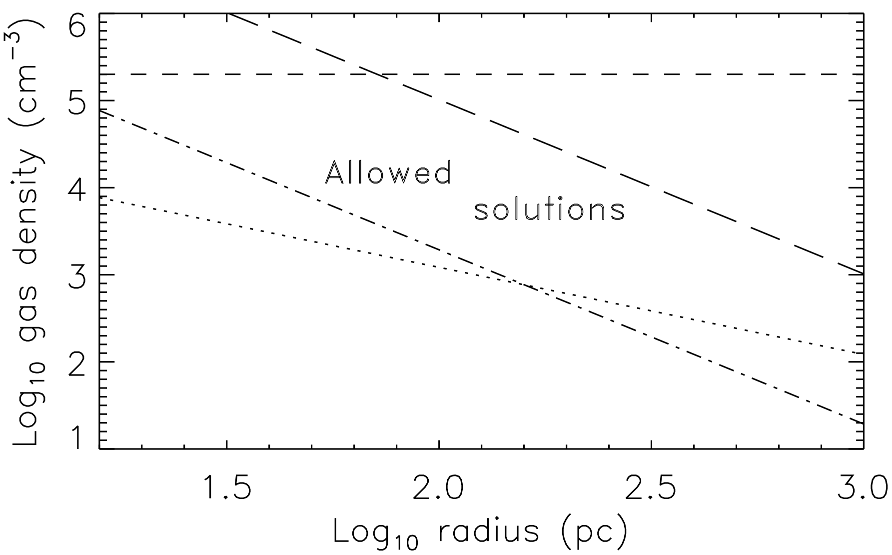

FIGURE 2. Constraints on the size and density of an atomic obscuring torus in Cygnus A. As discussed in the text, we assume that the torus is larger than 15 pc ($H_0 = 100$) and all the gas along the line of sight is atomic with a column density of $N_H = 3.7\times10^{23}\,\mathrm{cm}^{-2}$ [1]. The gas thermal temperature is assumed to be 8000 K and the free electron fraction 0.01. For a given distance from the nucleus the region of allowed gas density is bounded below by the requirement that the filling factor is less than unity (dotted line) and constraints on radiative excitation of the gas spin temperature (dot-dashed line) such that the column remains consistent with the observed HI absorption. The region of allowed parameters is constrained from above by the requirement that the effective X-ray ionization parameter is high enough to keep the torus atomic (long-dashed line) and by constraints due to the lack of free-free absorption (short-dashed line).

total column density $N_H = 3.7\times10^{23}\,\mathrm{cm}^{-2}$ [1], this implies gas densities $n < 2\times10^5\,\mathrm{cm}^{-3}$. Substituting this density limit into the radiative excitation limit discussed above we find that an atomic torus of radius 15 pc or greater is able to satisfy the radiative excitation and free-free constraints simultaneously.

In contrast, a smaller atomic torus would have difficulty fitting all the constraints. Such a torus would only cover part of the continuum structure, increasing the column densities required to explain the observed HI absorption. Furthermore, the high densities within such a torus would increase the effects of free-free absorption while the proximity to the nucleus would increase radiative excitation.

While a detailed analysis is not possible without maps of the 1.34 GHz parsec scale continuum emission (and is complicated by the uncertainty in H_0 and the large errors on the X-ray estimate of N_H), it appears that these arguments already rule out a very compact torus with $r_{outer} < 5$ pc which only covers the "core" component visible in the 5 GHz VLBI maps [10].

4.2. *A molecular obscuring torus*

It is still possible that the majority of the obscuring column towards Cygnus A is in a molecular state. Various explanations are possible for the lack of detectable molecular absorption in any of the species CO, OH, H_2CO, NH_3. The models of [26] predict clouds with temperatures of order 1000 K, and depending on conditions a wide range of HI fractions from 0.05 to about 0.5. If the torus is large ($> 15h^{-1}$pc) and covers the whole VLBI radio jet then adopting T_{spin} = 1000K the required N_{HI} is $\approx 2.5\times10^{22}\,\mathrm{cm}^{-2}$, which is consistent with the total column density given by [1] if the HI abundance is 0.07. Conversely, if the torus is small ($< 5h^{-1}$pc) and just covers the radio core, which is predicted to have flux density of ≈100 mJy at 1.34 GHz, then the required HI abundance is 0.5. While these calculations assume no radiative excitation of the HI, this can easily be realised even in the compact torus case, by having low cloud filling factors and high cloud densities. In contrast to a hot, atomic torus there are no constraints due to free-free absorption because the free electron fraction is negligible [24].

As noted by [21], CO(J=1–0) absorption might have escaped detection if the molecular clouds are smaller than the background source, have a covering factor of about unity (as expected), and a large velocity dispersion. If the clouds were hot ($T \approx$1000 K) and were distributed over a velocity range similar to that of the detected HI absorption, they would indeed be below the detection level of previous searches.

The other possible explanation for the non-detection of CO is radiative excitation via millimeter-wave continuum emission from the nucleus [20]. Note that it is quite possible for the cloud density to be such that CO is radiatively excited but HI is not. Assuming a flat spectrum continuum source, then at any given distance from the nucleus, CO radiative excitation is still significant at densities 30 times larger than those for which it ceases to be important for HI [25].

Given the abundances of OH predicted in some molecular torus models (e.g. [26]), our non-detection of OH absorption is hard to explain unless this too is radiatively excited. However, more recent modelling [20,24] predicts that at least in high pressure ($10^{11}\,\mathrm{K\,cm^{-3}}$) warm (500–1000 K) molecular tori, OH is efficiently converted to H_2O; this is one possible explanation of the lack of detectable OH absorption. Alternatively, OH might be radiatively excited; unfortunately, published calculations for OH and other molecules [27] do not deal with the pressures and temperatures expected in circumnuclear tori; more work is required in this area to understand our non-detection of OH absorption.

5. Implications

5.1. *Associated dust absorption*

We note that despite the high temperatures predicted for atomic tori (≈8000 K), this gas could still contain enough dust to explain the derived optical/IR obscuration of A_V =50–100 mag [11,28]. Dust grains are in thermal equilibrium with the local radiation field, and so they can be much cooler than the gas. Given the hard X-ray luminosity derived for Cygnus A [1], from [24] we find that grain temperatures in Cygnus A should only exceed their sublimation temperature of ≈1000 K within a radius $0.4h^{-1/2}$ pc.

An atomic torus could therefore still produce a strong 9.7 μm silicate absorption feature, unless such grains are destroyed by shocks or altered in composition close to the nucleus (see [29], and references therein). For further discussion of dust extinction and attempts to measure silicate dust absorption in Cygnus A, see [30].

5.2. *Future observations*

An upcoming XTE observation should provide an improved estimate of N_H and may even detect variability in this column. Planned VLBI observations may be able to constrain the location of the HI absorbing gas more effectively than the VLA observations presented here, though their spatial resolution will be limited to about 15 milli-arcsec by Galactic scattering. Radio continuum imaging at low frequency would improve the rather crude limits on free-free absorption arising in a putative atomic torus.

It is interesting to note that our joint constraints on gas density and size of an atomic torus overlap with values derived for the [OI] line-emitting warm neutral zone of classical NLR clouds, which however are generally believed to possess lower column densities (cf. [31], and references therein). Similarly, higher spatial resolution observations of the excited H_2 detected by [11] (which remains the only detection of molecular gas in Cygnus A to date) may establish a connection between the hot molecular gas and the HI absorbing medium, perhaps in a photodissociation region (cf. [18])..

Finally, the detection of an H_2O megamaser would support a compact, molecular torus [24]. The non-detections of other molecules may then be due to radiative excitation effects referred to above, though more sensitive searches and detailed modelling of these species are still required.

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