SEARCH FOR FREE-FREE ABSORPTION CUTOFFS FROM TORI IN THREE TYPE 2 ACTIVE GALACTIC NUCLEI

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ABSTRACT

We have observed three type 2 radio-loud active galactic nuclei using the Very Large Baseline Array at five frequencies between 1.6 and 15 GHz in a search for the free-free absorption cutoff predicted by some models for optically obscuring dusty molecular tori. We find no evidence for sharp cutoffs toward low frequencies in any of the sources. However, one source, OW 637, has VLBI components that fall steeply toward high frequencies ($S \propto \nu^{-2}$).

Key words: galaxies: active

1. INTRODUCTION

By now the standard dusty molecular torus scenario for unifying type 1 (broad-line) and type 2 (narrow-line) active galactic nuclei via obscuration/orientation effects will be familiar to most readers (otherwise, see Antonucci 1993 for a comprehensive review). The physics of the hypothesized torus was modeled in detail in a series of papers by Krolik and collaborators (Krolik & Begelman 1986, 1988; Krolik & Lepp 1989, hereafter KL). They present a general picture of a torus composed of small, dusty molecular clouds lying roughly 1 pc from the central engine. They are unusual molecular clouds, according to KL, having electron fractions $\sim 10^{-3}$ and temperatures $\sim 10^3$ K.

To date, the torus model has not been satisfactorily tested. Barvainis & Antonucci (1994) searched unsuccessfully for CO absorption from a torus against the compact radio nucleus of the type 2 radio galaxy Cygnus A. The result, while unexpected at the time, was subsequently rationalized within the torus framework by Maloney, Begelman, & Rees (1994).

One testable prediction from torus models is that the torus should free-free absorb radio photons below a certain frequency as a result of the relatively high electron densities—provided, of course, that the central radio source is compact enough to be blocked by the torus. The inner edge of the torus is at a radius of about 1 pc, for a central UV luminosity of $10^{44}$ ergs s$^{-1}$ (scaling as $L^{1/2}$). The height of the torus material varies roughly as $h \approx 0.7r$. According to the KL model, the cutoff frequency is about 5–10 GHz. However, Neufeld, Maloney, & Conger (1994, hereafter NMC) found a much lower electron fraction in the torus relative to that of KL ($10^{-5}$ vs. $10^{-3}$), with the discrepancy arising because KL underestimated the destruction rate of the molecular ion $H_2^+$. NMC predict instead a warm atomic region lying near the inner edge of the torus, having an electron fraction $\sim 10^{-2}$ (see also Maloney 1996). Coincidentally, however, the resulting free-free absorption is the same as for KL: the cutoff frequency is predicted in the range from a few to 10 GHz.

In a search for this predicted cutoff, we observed the radio cores of three narrow-line radio galaxies at a range of frequencies between 1.6 and 15 GHz, using the NRAO\textsuperscript{2} Very Long Baseline Array (VLBA). We report the results below.

2. SOURCE SELECTION AND OBSERVATIONS

The ideal source for this search would be a type 2 active galactic nucleus (AGN), i.e., one in which the nucleus (central optical continuum source, broad-line region) is obscured by the torus. It would be reasonably strong in the radio regime and sufficiently compact to have significant flux on VLBI scales. To further select for compactness, the radio spectrum would be flat or inverted, indicating a partially self-absorbed synchrotron source.

Markarian 348 (NGC 262; $z = 0.014$) was chosen as our top-rated object for its strong, inverted VLBI core source (Neef & de Bruyn 1983) and its nearness (providing good linear resolution). It has a Seyfert 2 optical spectrum in unpolarized light, with clear broad emission lines in polarized (reflected) light, indicating the presence of a hidden Seyfert 1 nucleus (Miller & Goodrich 1990). Additional evidence for the presence of a dusty torus has been offered by Simpson et al. (1996). Its host galaxy is an early-type spiral.

Two other sources were selected for observation because of their availability during the observing time allocated for Mrk 348. These are OW 637 and 3C 99, both of which are narrow-line radio galaxies. OW 637 ($z = 0.227$) has a strong, flat-spectrum core that dominates the radio emission; 3C 99 ($z = 0.426$) is a lobe-dominated radio galaxy with very asymmetric lobe fluxes, having a VLBI core at 1.6 GHz with peak flux density 60 mJy. The core is steep-spectrum, making this source less than ideal for observation of a very compact structure that is likely to be contained within a torus.

The observations were conducted during a 12.5 hr period on 1995 April 5/6 under VLBA project code BB21. The usefulness of this project’s results depended heavily on image fidelity, and an observing strategy was chosen that optimized the $(u,v)$-coverage. We used the frequency agility of the VLBA to switch rapidly between the five observing frequencies: 1630, 2270, 4990, 8420, and 15360 MHz. The

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observing frequency was switched typically every 2 minutes, and combined with interleaving of target sources in time, all 15 source/frequency combinations received good \((u, v)\)-coverage, with no major holes. In addition to the program sources, 3C 84 and 1739 + 522 were observed as fringe finders.

The data were correlated in Socorro and were calibrated in the normal manner using the VLBA log data. The data were edited, fringe-fitted, and imaged in AIPS with no significant problems, except that 3C 99 at 15 GHz was too weak for fringe fitting and had to be abandoned. The rms noise levels on the images are generally in the range 0.2–0.5 mJy beam\(^{-1}\), except for OW 637, for which dynamic range limits of 200–500 result in rms fluctuations at the 3 mJy beam\(^{-1}\) level. Component flux densities are reported in Table 1. At 8.4 and 15 GHz, the fluxes are taken from maps convolved to the same beam size as those in the 5 GHz maps in order to avoid resolution effects and to facilitate measurement of spectral indices.

We obtained additional X-band data on OW 637 from the US Naval Observatory (USNO) Radio Reference Frame Image Database (courtesy A. L. Fey). These observations are of longer duration and higher quality than our own X-band measurements (for a contour image see Fey, Clegg, & Fomalont 1996). The observing date was 1994 July 8. Four separate observing frequencies within the X band were used. See Table 1 for details.

### 3. RESULTS AND DISCUSSION

#### 3.1. Low-Frequency Cutoffs

The angular resolutions differ by a factor of order 10 from the L band to the U band, limiting the range of component sizes and separations for which reliable five-point spectra can be derived. Only compact, well-separated components are analyzed below. While high-frequency spectral information at a higher resolution exists in our data set, no dramatic spectral gradients were evident, and no detailed analysis was performed.

Source 3C 99 shows double structure in the VLBI core that is resolvable at all frequencies, with a separation of 14 mas. A weak third component is also visible in some of the maps of 3C 99. OW 637 has four VLBI components (see below). Mrk 348 was resolved into two components only in the highest resolution map (15 GHz), with a component separation of 1 mas. While for Mrk 348 the components are not separable at the lower frequencies and we plot only the total flux (Fig. 1), for 3C 99 and OW 637 we plot radio continuum spectra of all components that could be well resolved (Figs. 2 and 3).

None of the spectra show the sharp low-frequency cutoff expected for free-free absorption. Component B in OW 637 rolls over from 5 to 2.3 GHz, but the spectral index of +1 is not high enough to eliminate other possibilities such as synchrotron self-absorption (it is worth bearing in mind, however, that this represents a lower limit to the spectral index because of the finite sampling of the spectrum). Therefore, we have not found any new evidence for the existence of a torus. The possible explanations of this result include the following:

1. The torus is not present in these objects. Given the growing body of direct evidence for anisotropic obscuration, combined with persuasive arguments on which orientation-related unified schemes are based, it seems probable that something akin to a torus does in fact exist, and we regard this possibility as unlikely.

2. The torus is there, but its parameters are such that the cutoff occurs below our lowest observing frequency of 1.6 GHz or above our highest observing frequency of 15 GHz (so that the true core is never observed). It may be worthwhile to investigate possible torus conditions that would...
give rise to free electron densities significantly lower (or higher) than the models of KL or NMC. If the inner edge of the torus resides for some reason outside the \( \sim 1 \text{ pc} \) inner radius of these models, the free-free optical depth will be lower because of a reduction in radiation pressure (upon which \( \tau_{ff} \) depends linearly). Maloney (1996) invoked this effect as a possible explanation for the absence of free-free absorption at gigahertz frequencies in Cyg A (see Maloney 1996 for expressions relating to \( \tau_{ff} \) and various physical parameters of the torus).

3. The test is not applicable because the bulk of the radio emission lies outside the torus and therefore cannot be absorbed by it, or the torus orientation is not "side-on." The former could occur if the jet material we observe lies more than 1 pc or so from the true central engine. This seems plausible for 3C 99, which has no strong self-absorbed component identifiable as a "core," but less so for Mrk 348 and OW 637, which do. The "core" component would then have to be a standing shock or similar feature in the flow some distance downstream from the center. Hints of such a phenomenon may have been seen in other sources (Marscher 1997). Orientation may be more of an issue for Mrk 348 and OW 637, despite our optical selection for torus obscuration of the inner regions. Both objects have strong, variable (see Neff & De Bruyn 1983 for Mrk 348, and below for OW 637) cores and weak or nonexistent lobes. These properties suggest that our line of sight may be near the axis of a relativistic jet and, therefore, in the unified picture, perpendicular to the plane of the torus. Future experiments, perhaps using phase referencing to enhance sensitivity, might profitably target weak, quiescent cores of lobe-dominated narrow-line radio galaxies.

Free-free absorption on small scales has been discussed recently for several radio galaxies. Probably the most convincing case known to us is that of Centaurus A, where Jones et al. (1996) found that the spectrum of the milliarcsecond core is probably highly inverted, \( \alpha \sim 4 \) (\( S \propto v^\alpha \)) between 2.3 and 8.4 GHz, with the main uncertainty being a possible misregistration of the images at the two frequencies. Another good case is that of NGC 1275 (3C 84), where the northern jet (the counterjet) is resolved, yet has an inverted spectrum (Vermeulen, Readhead, & Backer 1994; Walker, Romney, & Benson 1994; Levinson, Laor, & Vermeulen 1995). The inferred size of the free-free absorbing screen, or torus, is less than 1 pc for Cen A and a few parsecs for NGC 1275. Hydra A and NGC 4261 may also possess components that are free-free absorbed (Taylor 1996; Jones & Wehrle 1997).
Our strategy was to look for the most direct evidence of free-free absorption, that being a spectrum well sampled over a range of frequencies exhibiting a clear and sharp cutoff toward low frequencies. Such a cutoff was not seen in the three type 2 AGNs observed. The most probable explanation is that the emission measure through the torus is lower than current models suggest, at least in these objects, though it is possible that our observations failed to probe the torus because of geometric considerations.

3.2. Unusually Steep Components in OW 637

The maps of OW 637 show several components, arranged roughly along a line (four components are resolvable at C and X bands; see Fig. 4). Components A, B, and D (same convention as used by Bartel et al. 1984) appear to be unresolved at all frequencies. Component C is extended at C, X, and U bands, making its spectrum difficult to determine (we do not report flux values for component C for this reason). Therefore we only show spectra of components A, B, and D in Figure 3. Component D is relatively flat over the limited frequency range where it is not blended with component C. However, components A and B both have spectra that are unusually steep (i.e., steeply falling toward high frequencies), at least over part of the spectral range. Component D appears to have varied since the measurements of et al. Bartel 1984. We find a flux density of 1950 ± 100 mJy at 8.4 GHz, compared with their 850 ± 70 mJy at 8.3 GHz.

Component A appears to be steep throughout the measured range, with the segment between C and X bands having spectral index \(\alpha_{CX} = -2.05 \pm 0.14\). The steep slope is apparent even within the closely spaced X-band measurements (see inset to Fig. 3). Component B has a spectral peak at 5 GHz and steepens rapidly toward high frequencies, with \(\alpha_{BX} = -2.22 \pm 0.11\) between 8.4 and 15.4 GHz. Such steeply falling spectra appear to be quite unusual. Among the 518 total flux density (i.e., large-beam) spectra of extragalactic radio sources assembled by et al. Kuhr et al. 1981, none have spectra approaching this steepness. However, summing all the components in OW 637 will produce a fairly flat spectrum, so it is possible that very steep components like A and B may only be observable with VLBI.

Typical spectral indices for extended structures in extragalactic radio sources are in the range \(-1.3 \leq \alpha \leq -0.5\), with the steepest observed index having a value of about \(-2\) (Kellerman & Owen 1988). For a sample of ultrasteep radio sources compiled by Röttgering et al. (1994), the steepest have spectral indices around \(-1.6\). Steep spectra in diffuse sources are generally thought to be due to synchrotron aging of electrons that have drifted far from any source of reacceleration. Spectra of VLBI components typically run from inverted (\(\alpha \sim -1\), due to synchrotron self-absorption and component superposition) to moderately steep (\(\alpha \sim -1\)). We know of no VLBI components previously reported with slopes as steep as \(-2\). Synchrotron lifetimes for electrons in luminous, compact components like those seen in OW 637 can be on the order of years. However, current thinking holds that VLBI components are the sites of shocks in jets, with attendant continuous reacceleration of particles. It is conceivable that in OW 637 a shock has suddenly turned off, allowing the decay of electron energies through synchrotron losses. However, this would have to have happened at nearly the same time in components A and B to produce the observed steep spectra in both and therefore seems unlikely.

A nonrelativistic, adiabatic, strong shock will have a compression factor \(3 \leq r \leq 4\), and electrons accelerated by the Fermi mechanism in such a shock will have an electron energy power-law index \(-2.5 < s < -2\) [\(N(E) \propto E^s\), with \(s = -(r+2)/(r-1)\) (see Begelman, Blandford, & Rees 1984). This produces the canonical range \(-0.75 < \alpha < -0.5\) for the radiation spectral index via \(\alpha = (s+1)/2\). The case of \(s \leq -2\) found for OW 637 requires \(s = -5\) and \(r = 1.75\). Again, for a nonrelativistic shock, the Mach number is given by \(M = [(s+2)/(s+3)]^{1/2}\). For \(s = -5\), \(M = 1.53\), which corresponds to a weak shock. In the relativistic case, the result becomes \(M = [(2s-4)/(2s+3)]^{1.41}\), again a weak shock.

Another possibility for producing a steep spectrum is synchrotron emission from a relativistic Maxwellian electron distribution at frequencies well above \(v_F\), the characteristic synchrotron frequency for electrons of energy \(T_m c^2\). At \(v/v_F \sim 100\), the spectrum is steep and slightly curved (convex), with \(\alpha \sim -2\) (using eq. [6] of Jones & Hardee 1979). This could account for the shape of component A, but not B, which is too sharply peaked to be fitted by a relativistic Maxwellian distribution.

Pulsars produce radio spectra that are very steep \((-1 < \alpha < -4\) via coherent radiation, but quasar radio emission is thought to be incoherent synchrotron emission and differs observationally from that of pulsars in several ways (e.g., much lower levels of polarization, lower brightness temperatures, normally much flatter spectra). However, because of its two steep-spectrum components, OW 637 is an unusual case among quasars and should be studied more thoroughly. The present observations were set up only for total intensity measurements; we plan to measure the polarization properties and extend the spectral coverage of OW 637 in a future experiment.

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