Photon-photon absorption above a molecular cloud torus in blazars

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Abstract

Gamma rays have been observed from two blazars at TeV energies. One of these, Markarian 421, has been observed also at GeV energies and has roughly equal luminosity per decade at GeV and TeV energies. Photon-photon pair production on the infrared background radiation is expected to prevent observation above $\sim 1$ TeV. However, the infrared background is not well known and it may be possible to observe the nearest blazars up to energies somewhat below $\sim 100$ TeV where absorption on the cosmic microwave background will give a sharp cut-off.

Blazars are commonly believed to correspond to low power radio galaxies, seen down along a relativistic jet; as such they are all expected to have the nuclear activity encircled by a dusty molecular torus, which subtends an angle of 90 degrees or more in width as seen from the central source. Photon-photon pair production can also take place on the infrared radiation produced at the AGN by this molecular torus and surrounding outer disk. We calculate the optical depth for escaping $\gamma$-rays produced near the central black hole and at various points along the jet axis for the case of blazars where the radiation is observed in a direction closely aligned with the jet.

We find that the TeV emission site must be well above the top of the torus. For example, if the torus has an inner radius of 0.1 pc and an outer radius of 0.2 pc, then the emission site in Mrk 421 would have to be at least 0.25 pc above the upper surface of the torus, and if Mrk 421 is observed above 50 TeV in the future, the emission site would have to be at least 0.5 pc above the upper surface. This has important implications for models of $\gamma$-ray emission in active galactic nuclei.
1 Introduction

The second EGRET catalog of high-energy γ-ray sources [4] contains 40 high confidence identifications of AGN, and a further 11 AGN identifications with lower confidence. They show spectra where the luminosity is of similar order of magnitude across the entire electromagnetic wavelength range, from far infrared/mm wavelengths to GeV gamma photon energies, with at times the gamma luminosity exceeding all other wavelengths substantially. The variability of blazars in all wavelengths, including the range explored by EGRET on board the Compton Gamma Ray Observatory, is known to be extreme. The variability both in the radio and in the gamma range can reach time scales as short as hours. Several of the AGN detected by EGRET have shown variability with time scales of a few days for factors of ~ 2 changes in flux [2, 3, 4]. One of the EGRET blazars, Markarian 421, has been observed at TeV energies [5, 6, 7, 8], as has Markarian 501 [9] which was not detected by EGRET. At TeV energies Markarian 421 is extremely variable, and very recently outbursts of TeV photons from Markarian 421 [10] have been observed with flux increases by a factor of 2 in one hour. Such rapid variability indicates that the emission is produced in the jet where relativistic effects can lead naturally to the short timescales. Furthermore, all of the active galactic nuclei (AGN) observed by EGRET are blazars, objects in which the jet moving relativistically is pointing approximately towards the observer. It is therefore natural to suppose that the γ-ray emission is produced in the jet as a result of particle acceleration and interaction with ambient medium, radiation or magnetic field.

There are two basic approaches to interpreting and modelling the spectral energy distributions of these blazars. The first approach involves the acceleration of electrons and subsequent inverse Compton interactions of electrons with ambient radiation to produce the γ-rays. The ambient radiation may be radiation coming directly from the accretion disk [11, 12, 13, 14, 15], or reprocessed by clouds or in an accretion disk corona [16, 17, 18]. These models have been quite successful in fitting the observational data.

The second approach is to accelerate protons instead of, or as well as, electrons. Generally, the electron models have the emission region in the jet rather closer to the central object than the models involving proton acceleration. In the proton models, energetic protons interact with radiation by pion photoproduction. Again, this radiation may be reprocessed or direct accretion disk radiation [19], or may be produced locally, for example, by synchrotron radiation by electrons accelerated along with the protons [20, 21, 22, 23]. Pair synchrotron cascades initiated by photons and electrons resulting from pion decay give rise to the emerging spectra, and this also leads to quite acceptable fits to the observed spectra. This second approach has the obvious advantage of leading to potentially much higher photon energies, because protons have a much lower synchrotron energy loss rate than electrons for a given magnetic environment. In both classes of model, shock acceleration has been suggested as the likely acceleration mechanism (see refs. [24, 25, 26, 27] for reviews of shock acceleration), and maximum energies were obtained and discussed in some detail in ref. [28].
The observations clearly indicate that blazars are fairly low luminosity radio galaxies seen along a line of sight rather close to the symmetry axis of the bulk relativistic motion. These radio galaxies are well known to enshroud the central source in a dusty torus, which may cover a large fraction of $4\pi$, as seen from the central source. The role of this dust torus has been the object of many investigations \cite{29,30,31,32}, and has been discussed at some length in \cite{31}, where many earlier references are given (see also \cite{33,34}).

Energetic photons may interact with low energy photons by photon photon pair production if the centre of momentum frame energy is above threshold, i.e. $\sqrt{s} > 2m_e c^2$. Such interactions with the cosmic microwave background severely limit the distance $\gamma$-rays above $\sim 100$ TeV can travel from sources \cite{35,36}. At lower energies interactions on the infrared and optical backgrounds limit the transparency at TeV energies (e.g. \cite{37,38}). Within the central regions of the AGN, interactions with photons directly from the accretion disk are important \cite{39,40} (See Bednarek \cite{41} for an earlier discussion of $\gamma$-ray escape from the radiation field of an accretion disk surrounding a neutron star in an X–ray binary source). In the present paper we wish to present new calculations which give the photon photon opacity of gamma photons produced in the jet, in the photon bath of the infrared torus which surrounds the accretion disk. We will demonstrate that the origin of the high energy gamma photons can only be above the infrared torus by a factor of a few. This excludes many of the published models for $\gamma$-ray emission and variability.

2 The basic geometry of the torus and calculation of the opacity

From early on, there were attempts to unify and simplify the various classes of active galactic nuclei \cite{12}. The most successful has been those models which unify the radio-loud AGN, where the two main parameters are only the aspect angle and the total power of the source \cite{13}. Attempts to include also the radio-weak AGN into such a scheme, have become more complicated \cite{14,29,45}. The aspect angle is the angle between the line of sight to the observer, and the symmetry axis of the AGN itself, presumably the axis of the powerful jet, which in turn is usually taken to be perpendicular to the compact accretion disk around a black hole. The total power of the source is the electromagnetic luminosity, integrated over all wavelengths (sometimes dominated by GeV $\gamma$-rays), plus the power flowing along the jet, in thermal particles, in magnetic energy, in relativistic particles such as cosmic rays, and in kinetic luminosity, plus any other power channel, such as energetic particles coming out directly (e.g. neutrinos, neutrons, cosmic ray particles independent of the jet energetics).

It was recognized very early that the aspect angle plays a crucial role in our observations of AGN, on the one side with respect to the relativistic boosting possible for small angles between jet and the line of sight \cite{12,43,40,47}, and on the other side, with respect to absorption and scattering by surrounding material, nowadays usually referred as the torus \cite{48,49,16}.
Since the far infrared emission of quasars was realized as arising from molecular material by Chini et al. \cite{50, 51} the far infrared emission of AGN has also become a favorite topic in these attempts to model the structure and emission region of AGN \cite{52, 53, 54}. It now appears possible to begin mapping at least some part of the molecular cloud distribution with H$_2$O-maser lines such as in the galaxy NGC4258 and NGC1068 \cite{55, 56, 57}. As a result we now have a fairly well established model that suggests \cite{58, 59} that the blazars are the low power end of a distribution of intrinsic luminosities, seen under various aspect angles; however, due to relativistic boosting, they belong to the most luminous sources observed. Key in such a picture is the inferred property of the molecular cloud tori to cover a larger fraction of 4$\pi$ with decreasing luminosity of the source \cite{31}.

The model by Pier & Krolik \cite{53} is a very good starting point to investigate the consequences of the radiation field given by the molecular cloud torus, and we model the molecular torus following in the same way. The torus is of height $h$, symmetrical about the plane of reference, and centred on the basic AGN source. The cross section of the torus is approximated by a rectangle, and the inner and outer radii are $a$ and $b$. Typically, $a \sim 1$ pc, $b \sim 2a$, and $h \sim a$ to 10$a$. For simplicity we model the torus with a single black body temperature of 1000 K \cite{53}, and surround the torus with a disk emitting black body radiation at a lower temperature which decreases from 1000 K to 30 K between radius $r = b$ and $r = 100$ pc using a local power-law approximation, i.e. $T(r) = 1000(r/b)^{-\alpha}$ K, where $\alpha = 1.52/\log(100\text{ pc}/b)$. Fig. 1 shows the location of the emission region in relation to the torus and outer disk. The figure also illustrates the interaction of a $\gamma$-ray emitted at point A interacting at point B with a photon emitted from the upper surface of the torus.

We then ask the following question: What is the optical depth to gamma-gamma opacity from pair creation of a gamma-photon in the bath of the surrounding infrared light. Using the top of the torus as our reference level, i.e. $z = 0$ corresponds to height $h/2$ above the midplane in which the central source lies, we inject a $\gamma$-ray on the axis at height $z = \ell$ (negative $\ell$ corresponds to injection inside the tunnel surrounded by the torus) and calculate the optical depth out along the axis to infinity.

Consider a $\gamma$-ray photon of energy $E$ propagating out along the axis from $z = \ell$ to $z = \infty$ in the radiation field of the upper surface of the torus. The interaction probability depends on the angle, $\theta$, between the directions of the $\gamma$-ray and infrared photon. When the photon is at height $z$ above the surface, the maximum and minimum values of $\cos \theta$ are

\begin{align*}
(\cos \theta)_\text{min} &= \frac{z}{(b^2 + z^2)^{1/2}}, \\
(\cos \theta)_\text{max} &= \frac{z}{(a^2 + z^2)^{1/2}}.
\end{align*}

The optical depth of the path from $z$ to $(z + dz)$ is

\begin{align*}
d\tau(E) &= dz \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon n(\epsilon) \int_{(\cos \theta)_\text{min}}^{(\cos \theta)_\text{max}} d \cos \theta \frac{1}{2} (1 - \cos \theta) \sigma_{\gamma\gamma}(s) \tag{3}
\end{align*}
where
\[ \varepsilon_{th} = s_{th}/2E(1 - \cos \theta_{\min}), \]  
(4)

\( n(\varepsilon)d\varepsilon \) is the number density of photons of energy \( \varepsilon \) to \((\varepsilon + d\varepsilon)\) of black body radiation at the temperature of the torus,

\[ s = 2E\varepsilon(1 - \cos \theta) \]  
(5)
is the square of the centre of momentum frame energy, \( s_{th} = (2m_e c^2)^2 \), and \( \sigma_{\gamma\gamma} \) is the cross section for photon-photon pair production [60] (see ref. [61], and references therein, for a discussion of cascading in the radiation field along the axis of a luminous disk). After a change of variables, we can write

\[ d\tau(E) = \frac{dz}{8E^2} \int_{\varepsilon_{th}}^{\infty} d\varepsilon \frac{n(\varepsilon)}{\varepsilon^2} \int_{s_0}^{s_{\max}} ds s\sigma_{\gamma\gamma}(s) \]  
(6)

where

\[ s_{\min} = 2E\varepsilon[1 - (\cos \theta)_{\max}], \]  
(7)

\[ s_{\max} = 2E\varepsilon[1 - (\cos \theta)_{\min}], \]  
(8)

and \( s_0 \) is the larger of \( s_{\min} \) and \( s_{\th} \). Integrating over \( z \) from \( \ell \) to \( \infty \) we obtain the contribution to the optical depth due to the top surface of the torus. With slight modifications to the procedure described above, we can easily obtain the contributions from the inner surface of the torus, and the outer disk (for computational reasons this is split into many annular rings each with a different temperature decreasing appropriately with radius).

3 The results

In Fig. 2 we show the optical depth for \( \gamma \)-rays produced at the central point of symmetry, i.e. centre of the torus \( \ell = -h/2 \), where by construction the AGN should be. Results are given for \( a = 1 \) pc, \( b = 2a \), for the cases \( h = a \) (bottom solid curve), \( 2a, ..., 10a \) (top solid curve), and because \( \tau_{\gamma\gamma} \) scales with \( a \) we show the optical depth in units of \( \tau_{\gamma\gamma}/a \). The dotted curve shows the contribution to \( \tau_{\gamma\gamma} \) from \( z > 0 \). These curves demonstrate already that for photon energies above about 300 GeV the opacity is so large that no appreciable radiation can emerge if the source of \( \gamma \)-rays is near the centre of the torus.

Fig. 3 shows how far above the top of the torus we need to be in order to be able to receive high energy photons. These curves, now from top to bottom, give the cases \( \ell = -a, 0, a, ..., 10a \) for \( b = 2a \) and \( a/h = 0.3 \). This means that this sequence supplements the sequence in Fig. 2. Fig. 4 shows the height of the emission region such that the optical depth is \( \tau_{\gamma\gamma} = 1 \) for the case \( b = 2a \) and \( a/h = 0.3 \) (as in Fig. 3), and for a range of inner torus radius, \( a \). It is plotted in this way to show more clearly how high above
the torus it is necessary for the emission region to be located for $\gamma$-rays of a particular energy to escape. Here we see that going far above the torus helps very clearly, with TeV photons possible already at the top plane of the torus, and with a level of $5a$ even the majority of 30 TeV photons would escape.

Fig. 5 shows how different surfaces of the torus contribute to the optical depth. The case considered is the outermost case of Fig. 3, namely $b = 2a$, $a/h = 0.3$, and $\ell = -a$; this means that we are considering a source inside the torus, but not all the way down to the central source. From the top down the curves first show the total, i.e. the top most curve from Fig. 3, then the contribution from the inside surface of the torus for the time while the presumed $\gamma$-ray is still inside the torus (dot-dash line), next the contribution from the inside surface of the torus for the time while the $\gamma$-ray is above the top surface of the torus (long dashed line; note we always integrate the optical depth along the path from the initial point to infinity), then the contribution from the top surface the torus (dotted line), and finally, the contribution from the outer disk outside the torus (short dashed line). It is clear that the contribution from inside the torus along the path inside the torus itself is dominant. It is also clear that the outer disk does not contribute significantly.

4 Discussion

The spectrum of $\gamma$-rays from Mrk 421 observed by the Whipple Observatory [6] extends well beyond 1 TeV and shows some evidence of a steepening and possible cut-off at energies above 2 TeV. We now discuss whether this cut-off is likely to be due to attenuation on the intergalactic infrared background radiation or in the radiation field of the torus. We show in Fig. 6 the observed spectrum together with an attempt by Entel and Protheroe [62] to estimate the spectrum emerging from the AGN using an inverse problem approach (the allowed source spectrum would lie within the shaded region). In doing this, they assumed $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and that the infrared background was as given in ref. [38]. The infrared background is not well known and there have been several attempts recently to estimate the infrared background by integrating the emission expected from distant galaxies contributing to the background [38, 64, 65, 66]. However the spectrum in ref. [38] is consistent with the most recent estimates based on COBE data [67]. Note that source spectrum obtained by Entel and Protheroe [62] is consistent with an $E^{-2}$ spectrum with no attenuation or cut-off. Mrk 421 is a relatively low-luminosity blazar and has an infrared luminosity $\sim 4 \times 10^{44} \text{ erg s}^{-1}$ assuming a distance of $\sim 180 \text{ pc}$ (see e.g. ref. [68]). Such an infrared luminosity and a temperature of the torus of 1000 K would imply a torus radius of $\sim 0.1 \text{ pc}$. We show in Fig. 6 the effect on an $E^{-2}$ spectrum of $\gamma$-rays of attenuation on the radiation from the torus for the parameters used in Fig. 3 and $a = 0.1 \text{ pc}$. To be consistent with the inferred source spectrum requires $\ell$ to be greater than 0.25 pc for the assumed parameters or, more generally, $\tau_{\gamma\gamma} < 1$ up to $\sim 4$ TeV implying an emission region well above the upper surface of the torus (see Fig. 4). If we had assumed that the observed spectrum was equal to the spectrum emerging from
the AGN (i.e. no intergalactic attenuation) we would require $\tau_{\gamma\gamma} < 1$ up to at least 2 TeV, and we would still conclude that the emission region must be well above the upper surface of the torus.

The results demonstrate that a photon of high energy cannot escape the pair creation opacity in the bath of the far-infrared radiation of the torus. Quantitatively, the opacity is too high for a source very close to the central source at 300 GeV, and requires an initial point of departure far above the torus at energies such as 30 TeV.

Therefore, any source which is observed to have TeV photons, requires the origin of these photons to be above the torus. For standard parameters, i.e. parsec scale tori, this means that any source at such photon energies requires the TeV photons to originate at several parsecs from the central source of activity. We next discuss which blazar models may be consistent with this constraint.

There are various models in the literature which try to explain the ubiquitous high energy $\gamma$-ray emission detected for many flat-radio-spectrum blazars. These models basically fall into two main classes:

- In the first group of models, the $\gamma$-ray emission is due to an inverse Compton process, using high energy electrons colliding with external photons directly from an accretion disk or scattered by hot gas surrounding the disk. The electrons in turn, may be produced by various processes. Such models have been described by groups involving Begelman, Blandford, Dermer, Schlickeiser, Sikora, and others e.g. [69, 70, 71, 72, 18, 73, 74].

- In another group of models, the basic processes to produce the $\gamma$-ray photons are either inverse-Compton scattering or inelastic proton-photon scattering of locally produced photons; in their application to $\gamma$-ray blazars, synchrotron self-Compton models have been developed by Maraschi, Ghisellini and Celotti [75], Zdziarski and Krolik [76], and Bloom & Marscher [77], and a hadronic model by Mannheim and collaborators e.g. [20, 78, 79, 21].

Of the published models which attempt to explain the high energy $\gamma$-ray emission from blazars, it appears that all models in the first class above, with the likely exception of [18], fail the test of the constraint described in the present paper, whereas the models in this second class are consistent with the new constraint.

However, it is premature to eliminate all the models in the first class above, because the authors of the propositions can be trusted to reconstruct their models, or at least a subset of them, to meet the constraints described here. The basic argument used by many of these authors is that the time-variability observed for the $\gamma$-ray emission strongly argues for a distance from the emitting region to the central engine, which is small; it is this step in the argument which requires the most severe change, with all its consequences.

Apparently, rapid $\gamma$-ray variability means that the jet has a very small opening angle between the inner accretion disk and the top of the circum-nuclear torus and that the $\gamma$-rays are produced where the jet leaves the torus.
Finally we note that in a very recent paper, Ommer, Westerhoff and Meyer [80] have searched in the HEGRA data for \( \gamma \)-ray emission above 50 TeV from a superposition of 14 blazars with redshifts less than 0.062, and find weak evidence for enhanced \( \gamma \)-ray emission from the directions of the blazars. If these observations are confirmed they will have important implications for the infrared background radiation field, and for models of \( \gamma \)-ray emission in blazars. For example, from Fig. 4 we see that 50 TeV \( \gamma \)-rays would have to be emitted a distance of at least 5 inner torus radii above the upper surface of the torus.

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References

[1] Thompson, D.J., et al., *Ap. J. Suppl.*, **101** (1995) 259.

[2] Hartmann, R.C., et al., *Ap. J. Lett.*, **340** (1992) L1.

[3] Hunter, S.D., et al., *Ap. J.*, **409** (1993) 134.

[4] Kniffen, D.A., et al., *Ap. J.*, **411** (1993) 133.

[5] Punch, M., et al. *Nature* **358**, (1992) 477.

[6] Mohanty, G. *et al.* in *Proc. 23rd Int’l Cosmic Ray Conf.* (Univ. of Calgary Press, Calgary) **1** (1993) 440.

[7] Kerrick, A.D., et al., *Ap. J. Lett.*, **438** (1995) L59.

[8] Petry, D., at al., *Astroparticle Phys.* **4** (1996) 199.

[9] Quinn, J., Akerlof, C. W., Biller, S., et al., *Ap. J.*, **456** (1996) 83

[10] Gaidos, J.A., et al., *Nature* in press (1996).

[11] Melia, F., Königl, A., *Ap. J.*, **340**, (1989) 162

[12] Dermer, C.D., Schlickeiser, R., Mastichiadis, A., *Astron. Astrophys. Lett.*, **256**, (1992) L27.

[13] Dermer, C.D., Schlickeiser, R., *Ap. J.*, **416**, (1993) 458.

[14] Bednarek, W., Kirk, J.G, and Mastichiadis, A., *Astron. Astrophys. Lett.*, **307** (1996) L17.

[15] Protheroe, R.J., and Stanev, T., in Proc. 24th Int. Cosmic Ray Conf. (Rome), **2**, (1995) 499.

[16] Blandford, R.D., in *Proc. Compton Symposium*, eds. M. Friedlander, N. Gehrels and D.J. Macomb (New York, IAP, 1993), 533.

[17] Sikora, M., Begelman, M.C., and Rees, M.J., *Ap. J.* **421** (1994) 153.

[18] Blandford, R.D., and Levinson, A., *Ap. J.* **441** (1995) 79

[19] Protheroe, R.J., in Proc. IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. D. Wickramasinghe et al., in press (1996) astro-ph/9607163

[20] Mannheim, K. and Biermann, P.L., *Astron. Astrophys.** **221**, (1989) 211.

[21] Mannheim, K., *Astron. Astrophys.* **269**, (1993) 67
[22] Mannheim, K., *Phys. Rev.* **D48**, (1993) 2408.

[23] Mannheim, K., *Rev. Mod. Astr.* in press (1996) [astro-ph/9512149](http://arxiv.org/abs/astro-ph/9512149)

[24] Drury, L.O.C., *Space Sci. Rev.*, **36** (1983) 57

[25] Blandford, R, & Eichler, D., *Phys. Rep.* **154** (1987) 1

[26] Berezhko, E.G., & Krymski, G.F., *Usp. Fiz. Nauk*, **154** (1988) 49

[27] Jones, F.C., & Ellison, D.C., *Space Sci. Rev.*, **58** (1991) 259

[28] Biermann, P.L., and Strittmatter, P.A., *Ap. J.* **322** (1987) 643

[29] Falcke, H., Biermann, P.L., *Astron. & Astroph.* **293** (1995) 665.

[30] Falcke, H., Malkan, M.A., Biermann, P.L., *Astron. & Astroph.* **298** (1995) 375.

[31] Falcke, H., Gopal Krishna, Biermann, P.L., *Astron. & Astroph.* **298** (1995) 395.

[32] Falcke, H., Biermann, P.L., *Astron. & Astroph.* **308** (1996) 321.

[33] Barthel, P.D., Hooimeyer, J.R., Schilizzi, R.T., Miley, G.K., Preuss, E., *Astroph. J.*, **336** (1989) 601.

[34] Barthel, P.D., *Ap. J.*, **336** (1989) 606.

[35] Gould, R.J., and Schreder, G., *Phys. Rev. Lett.* **16** (1966) 252

[36] Jelley, J.V., *Phys. Rev. Lett.* **16**, 479 (1966)

[37] Stecker, F.W., de Jager, O.C., Salamon, M.H., *Ap. J. Lett.*, **390** (1992) L49

[38] Protheroe R.J. and Stanev T.S. *Mon. Not. R. Astron. Soc.* **264** (1993) 191

[39] Becker P.A. and Kafatos, M., *Ap. J.* **453** (1995) 83

[40] Bednarek, W., *Astrophys. & Space Sci.*, **235** (1996) 277

[41] Bednarek, W., *Astron. & Astroph.*, **278** (1993) 307

[42] Scheuer, P.A.G., Readhead, A.C.S., *Nature* **277** (1979) 182

[43] Orr, M.J.L., Browne, I.W.A., *Monthly Not. Roy. Astron. Soc.* **200** (1982) 1067

[44] Strittmatter, P.A., *et al.*, *Astron. & Astroph. Letters* **88** (1980) L12

[45] Falcke, H., Sherwood, W., Patnaik, A., *Ap. J.* **471** (1996) in press, [astro-ph/9605163](http://arxiv.org/abs/astro-ph/9605163)

[46] Antonucci, R.R.J., Miller, J.S., *Ap. J.* **297** (1985) 621
[47] Wills, B.J., Browne, I.W.A., Ap. J. 302 (1986) 56
[48] Mushotzky, R.F., Ap. J. 256, (1982) 92
[49] Lawrence, A., Elvis, M., Ap. J. 256 (1982) 410
[50] Chini, R., Kreysa, E., Biermann, P.L., Astron. & Astroph. 219 (1989) 87
[51] Chini, R., et al., Astron. & Astroph. Letters 221 (1989) L3
[52] Sanders, D.B. et al., Ap. J. 347 (1989) 29
[53] Pier, E.A., and Krolik, J.H., Astroph. J. 401 (1992) 99
[54] Niemeyer, M., Biermann, P.L., Astron. & Astroph. 279 (1993) 393
[55] Barvainis, R., Nature 373 (1995) 103
[56] Miyoshi, M., et al., Nature 373 (1995) 127
[57] Greenhill, L.J. et al., Ap. J. (1996) in press [astro-ph/9609082]
[58] Antonucci, R.R.J., Ann. Rev. Astroph. & Astroph. 31 (1993) 473
[59] Urry, M. & Padovani, P., Publ. Astron. Soc. Pacific 107 (1995) 803
[60] Jauch J.M., Rohrlich F., “The theory of photons and electrons: the relativistic quantum field theory of charged particles with spin one-half” (Springer-Verlag, New York, 1976)
[61] Protheroe R.J., A. Mastichiadis and C.D. Dermer, Astroparticle Physics, 1 (1992) 113.
[62] Entel, M.B., and Protheroe, R.J., in Proc. 24th Int. Cosmic Ray Conf. (Rome), 2 (1995) 532.
[63] De Zotti, G., Franceschini, A., Mazzei, P., Toffolatti, L., Danese, L., Planetary and Space Science, 43 (1995) 1439
[64] Madau, P., and Phinney, E.S., Ap. J. 456 (1996) 124
[65] MacMinn, D., and Primack, J.R., Space Science Rev., 75 (1996) 413
[66] Väisänen, P., Astron. & Astroph. (1996) in press
[67] Puget, J.-L., et al., Astron. & Astroph. Lett. 308 (1996) L5
[68] von Montigny, C., et al. ApJ, 440, (1995) 525.
[69] Sikora, M., et al., Ap. J. Lett. 320 (1987) L81

[70] Begelman, M.C., Rudak, B., Sikora, M., Ap. J. 362 (1990) 38 (Erratum in Ap. J. 370, 791).

[71] Dermer, C.D., Schlickeiser, R., Science 257, (1992) 1642

[72] Dermer, C.D., Schlickeiser, R., Ap. J. 416 (1993) 458

[73] Dermer, C.D., Schlickeiser, R., Ap. J. Suppl. 90 (1994) 945

[74] Böttcher, M., Schlickeiser, R., Astron. & Astroph. 306 (1996) 86

[75] Maraschi, L., Ghisellini, G., and Celotti, A., Ap. J. Lett. 397 (1992) L5

[76] Zdziarski, A.A. and Krolik, J.H., Ap. J. Lett. 409, (1993) L33.

[77] Bloom, S.D., Marcher, A.P., Ap. J. 461 (1996) 657

[78] Mannheim, K., Krülls, W. M., Biermann, P.L., Astron. & Astroph. 251 (1991) 723

[79] Mannheim, K., Biermann, P.L., Astron. & Astroph. Lett. 253 (1992) L21

[80] Ommer, S., Westerhoff, S., Meyer, H., in Proc. 5th Int. Workshop on New Computing Techniques in Physics Research, Lausanne 1996, ed. M. Werlen Nucl. Instr. Methods. A, special issue (1996) in press
Figure 1: Geometry of the disk, torus and outer disk (not to scale) used in the present work showing a $\gamma$-ray originating at point A at height $z = \ell$ above the upper surface of the torus, and travelling outwards along the jet axis to interact at point B with a photon emitted from the upper surface of the torus.
Figure 2: Optical depth for $\gamma$-rays produced at the centre of the torus $\ell = -h/2$. Results are given for $a = 1$ pc, $b = 2a$, for $h = a$ (bottom solid curve), $2a$, ..., $10a$ (top solid curve). Dotted curve shows the contribution to $\tau_{\gamma\gamma}$ from $z > 0$. 

$\log(\tau_{\gamma\gamma}/a \text{ / pc}^{-1})$ vs. $\log(E \text{ / GeV})$.
Figure 3: Optical depth for $\gamma$-rays produced at $\ell = -a, 0, a, ... 10a$ (from left to right) for $b = 2a$ and $a/h = 0.3$. 
Figure 4: Height above the centre of the AGN ($\ell + 0.5h$) of the emission point (divided by $a$) where $\tau_{\gamma\gamma} = 1$ for $a = 2, 1, 0.5, 0.2,$ and $0.1$ pc (from top to bottom). Dotted line corresponds to the level of the upper surface of the torus.
Figure 5: Optical depth for $\gamma$-rays produced at $\ell = -a$, for $b = 2a$ and $a/h = 0.3$ showing how different surfaces of the torus contribute: inside surface of the torus for the time while the $\gamma$-ray is inside the torus (dot-dash line), the contribution from the inside surface of the torus for the time while the $\gamma$-ray is above the top surface of the torus (long dashed line), the contribution from the top surface the torus (dotted line), and the contribution from the outer disk outside the torus (short dashed line).
Figure 6: The observed VHE spectrum of Mrk 421 (ref. [5, 6]) and the inferred range of source spectra (shaded) calculated in ref. [62] assuming $H_0 = 50\,\text{km\,s}^{-1}\,\text{Mpc}^{-1}$ and the infrared background given in ref. [38]. Dashed curves show the effect on an $E^{-2}$ $\gamma$-ray spectrum of attenuation on the radiation from the torus for the parameters used in Fig. 3 and $a = 0.1\,\text{pc}$, i.e. $b = 0.2\,\text{pc}$, $h = 0.33\,\text{pc}$ and $\ell = -0.1, 0, 0.1, ... 0.5\,\text{pc}$ (from left to right).