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Tori and TeV gamma-ray emission in AGN

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Abstract. The absorption of TeV gamma-rays in active galactic nuclei by photon-photon pair production on infrared radiation from a parsec scale torus at temperature ~ 1000 K surrounding the accretion disk/base of jet was discussed by Protheroe and Biermann (Astropart. Phys., 6, 293, 1997). Here we briefly review the evidence for the existence of dusty infrared tori in blazars, and construct torus models consistent with infrared and optical polarimetry data. This leads us to propose a symbiosis between large and small-scale dust features and broad line regions in AGN. We discuss the radiation fields of the accretion disk, broad line region and dusty torus as target photons for pion photoproduction by protons and photon-photon pair production by γ-rays. We use our results to constrain the sites of emission of TeV gamma rays.

1 Introduction

We address the problem of one of the most controversial aspects of active galactic nuclei (AGN). Do blazars have dust tori, and if so how relevant is the geometry of the torus to the γ-ray emission in blazars? This is a very important subject since the infrared emission produced by tori could inhibit the escape of TeV γ-rays due to photon-photon pair-production (Protheroe and Biermann, 1997) and could also be an important source of target photons for the high energy interactions occurring in a relativistic jet (Sikora et al., 1994; Blazejowski et al., 2000). We mention that, despite of a large number of blazars detected at EGRET energies, only a few blazars (Mrk 501, Mrk 421, 1ES 2344-514, PKS 2155-304) are TeV emitters.

Since unification schemes propose that FR I and BL Lacs are related, FR I sources being the mis-oriented counterparts of BL Lacs (Urry and Padovani, 1995), we have searched the literature for information about dust structures associated with FRI. Since blazars, in fact, represent a large family of objects (optically violent variables, high-polarization quasars, BL Lac objects), an understanding of the physics of one of these objects may lead to a clarification of the properties of all objects of the same class.

There are two aspects which should be considered in connection with dust tori in blazars. Firstly, since there is no direct evidence of tori we should consider what the observations tell us, directly or indirectly, about the existence of dust at the centre of the host galaxy. Secondly, what kind of torus geometry would fit the observations made at different wavelengths best. A possible link between the torus and the Broad Line Region (BLR) is outlined in our discussion. We propose that the existing symbiosis between jet-accretion disks extrapolates into a large scale-symbiosis between other important constituents of an AGN. Photon-photon pair production on the infrared radiation produced in AGN by the torus is discussed. The BLR also produces low-energy photons which, in addition to the radiation from the accretion disk, also contributes to the pair production interactions. Finally, motivated by proton blazar models, we consider the importance of the various radiation fields for pion photoproduction.

2 Towards unification

The key point in our work is that the unification theory of different classes of AGN has already been demonstrated for several classes of objects. Relativistic outflows are very nicely described by a model of the small-scale symbiosis between the accretion disk and jet (Falcke et al. 1995 and references therein, Donea and Biermann, 1996), where the base of the jet covers radii $R_{jet} \leq 10R_g = 10^{-4}M_8$ pc, where $M_8 = M/10^8 M_\odot$. This model seems to work well for different types of AGN leading to a possible unification scheme.

What determines the class of an AGN is its orientation and the role played by its main five constituents: black hole, accretion disk, jet, torus, broad line region. In Seyfert galaxies

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and quasars the torus and the broad line region are active components, as can be inferred from the large forest of observed emission lines. In the case of blazars, any emission from the torus would be dwarfed by the radiation from the jet, making impossible the detection of any direct contribution from the inner dust structure.

We ask ourselves: "Why should blazars not have the same natural five-element composition which seems to suit nicely a large varieties of objects?" To find the answer to this question, we note that the unification scheme allows us to make analogies between different classes of AGN.

Despite the fact that the majority of BL Lacs do not show any type of emission lines, Corbett et al. (2000) confirmed the presence of a broad H_α emission line in BL Lacertae. The line luminosity and width have values typical of a moderately luminous Seyfert I nucleus. Narrow lines were also identified (NII, Fe VII, OI, SII) for this object. Although there seems to be no direct connection between BL Lacs objects and Seyfert galaxies, the discovery of emission lines in BL Lacs suggests that broad line regions are ubiquitous elements of these objects. Even Mrk 421 seems to have a low luminosity BLR (Morganti et al., 1992). Aditionally, Chiaberge et al. (2001) have concluded that BLR and obscuring tori are closely linked, and both are present only in association with accretion. The BLR-torus system appears to be less luminous in FRI/blazar objects than in quasars.

If the optical emission is not seen directly, the interpretation of spectropolarimetric data on FR1 objects with strong evidence for infrared obscuration (Antonucci 2001, and references therein) could suggest some properties of BLR hidden by thick tori. The observed polarized broad lines would be scattered into the line of sight by free electron in zones whose geometry and orientation is dependent on the torus' inner parameters. Therefore, the detection of free electron scattering regions should be a good diagnostic of the geometrical properties of the inner region of the torus. Falcke et al. (1995) proposed that the opening angle of the torus might play a critical role for the FR I and FR II dichotomy. A closed torus (which covers a large fraction of 4π steradians as seen from the black hole) would obscure the internal activity of FR I objects. BLR luminosities are difficult to derive since the obscuration, in these conditions, may be total or partial. Additionally, the entrainment of torus material into the outflow causes deceleration of the jet, a phenomenon observed in FR I, but not in FR II. An open geometry would better fit the results of Chiaberge et al. (2001) who have concluded the obscuring torus could be missing or be geometrically very thin for FR I. However, their sample represents just under half of the FR I galaxies tabelled in Zirbel and Baum (1995).

2.1 Large-scale and small-scale tori: dust everywhere

We are interested in observational evidence for the existence of tori in blazars/BL Lacs/FR I. We have looked into the literature, and found that several objects show incontestable proof of having torus dust structures: Centaurus A (Alexander et al., 2000), 3C270 (Barth et al., 1999), 3C218 (Sambruna et al., 2000; Antonucci, 2001). The above results lead us to the conclusion that dust is undoubtedly present everywhere, even in FR I objects where the torus cannot be straightforwardly detected. At kiloparsec scales the contribution from starbursts dominates the infrared emission. As one goes deeper into the nucleus of the galaxy, de Koff et al.(2000) found that a well organized dust structure tends to develop in 3CR objects. This is a very important result. They emphasized that dust in FR I host galaxies is generally situated in sharply defined small-scales disks (≤ 2.5 pc).

The detection of large-scale dusty features (sometimes shaped as bars or dust-lanes) suggests that there could be an association between the small-scale infrared torus, such as those most Seyfert galaxies display, and a large-scale torus sometimes identified with the external dust structure of the galaxy. The structure of the nuclear torus would then depend on the large-scale dust distribution: it appears that well-organized kpc structures extend inward, towards smaller scales. We define this as a symbiosis between the large and small scale dusty features.

The fact that the dust is often seen to be clumpy in FR II, but not clumpy in FR I (de Koff et al., 2000) could indicate that the flow of matter towards the nucleus is rather steady in FR I, allowing for the formation of distinct torus features. We believe that a higly-variable flow would not facilitate the formation of well-defined dusty structures. This conjecture would also fit with the Seyfert galaxy geometry, where there is direct evidence for the existence of tori.

3 Geometry and the radiation fields in AGN

Since we believe that the BLR and the torus are linked elements, we shall proceed to define the geometry of the system. The inner radius of the torus is determined by the sublimation radius of the dust in the torus, $R_{\rm in,torus} \sim T_{s,1500}^{-2.8} L_{46}^{1/2}$ pc (Granato and Danese, 1998), where $L_{\rm UV} = 10^{46} L_{46}$ erg/s is the central luminosity . The jet-disk symbiosis relates the disk luminosity to the jet luminosity. For blazars we expect that $L_{\rm UV} \approx 10^{44} - 10^{46}$ erg/s, and the flaring state of a blazar could be related to an increase of the disk-flare activity and consequently, of the jet power. The disk luminosity is regulated by the internal physical parameters of the base of the jet, and we take a value of 10^{46} erg/s for our examples discussed below.

The torus emission has a thermal peak at infrared frequencies (Pier and Krolik, 1992). The dust is heated to temperatures $T \sim 10^3$ K. For an emission region in the jet at distance r from a black hole, the IR radiation is approximately isotropic for $r < H/2$; we consider a small scale torus with: $H = 3.3$ pc, $A = 1$ pc, $B = 2$ pc in this paper (see Fig. 1).

The BLR is represented by a spherical shell of small clouds with number density varying as $N_{\rm cloud} \sim (r/r_{in,\rm BLR})^{-\alpha}$ and cloud radii varying as $R_{\rm cloud} \sim (r/r_{in,\rm BLR})^{-\beta}$ (α=1.5 and β=2, Kaspi and Netzer, 1999). We consider the BLR to be an optically thin region extending between radii $r_{in,\rm BLR} = 0.01$ pc and $r_{out,\rm BLR} = 0.4$ pc (Hartman et al ., 2001).

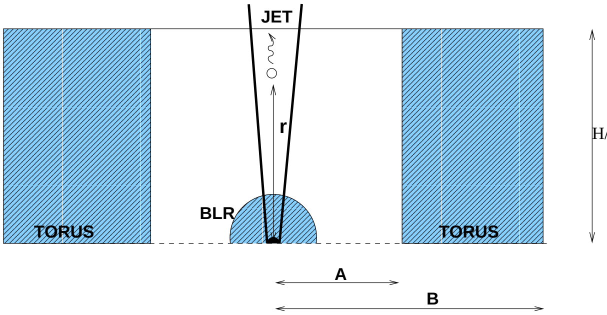

Fig. 1. Schematic AGN model (upper section) showing the broad-line spherical shell and the torus surrounding the central engine. The jet penetrates the BLR region on its way out of the central AGN. γ-rays originate at different positions along the jet.

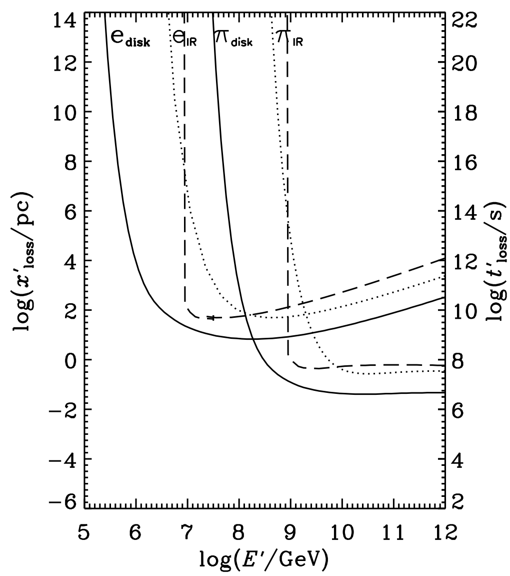

Fig. 2. Mean jet-frame energy loss distance of protons for pion photoproduction (π) and Bethe-Heitler pairproduction ("e") in the jet frame, averaged for an isotropic distribution of protons in the jet frame, vs. jet frame proton energy. The radiation fields are: direct anisotropic accretion disk radiation (solid lines), infrared torus radiation field (dotted lines), BLR photons (dashed lines). In this example $r = 0.02$ pc. The infrared photon number density is approximately constant over a large scale given by the height of the torus.

The optical depth of the BLR region is assumed to be $\tau = 0.01$ giving a total luminosity of the BLR region $L_{\rm BLR} = 10^{44}$ erg/s. Lower values of $L_{\rm BLR}$ could describe better objects with reduced broad line emission. Accretion disk photons exite the BLR material, and emission lines such as H_α, H_β, $OIII$, NII, etc., are produced. We simplify our problem by assuming that the entire BLR luminosity is emitted in the $H_\alpha(6563\AA)$ line. The full angular dependence of the BLR intensity at diferent positions r along the jet is taken into account. At $r \geq r_{out,\rm BLR}$ the BLR photon energy density is $u_{\rm BLR} \approx L_{\rm BLR}/4\pi c r^2$.

We now discuss the radiation fields existing in AGN which can include several components: accretion disk radiation (anisotropic), line emission from BLR clouds (also anisotropic), infrared emission from heated dusty torus. The symbiosis between the jet and the accretion disk is reflected mostly in a modified distribution of photons from the disk (Donea and Biermann, 1996). This is important for the calculation of the γ-ray spectra when the direct disk radiation is involved. The important aspect of these models is that as one moves away from the black hole, along the jet, one travels trough the BLR. The contribution from the UV disk photons decreases, while the energy density of isotropic IR radiation remains constant over a scale equal to the height of the torus. The energy density of BLR peaks at the region where the ionizing contribution from the disk photons dominates, i.e. $r \approx r_{in,\rm BLR}$.

4 Pion photoproduction and γ-ray escape

Hadronic models (Mannheim, 1993; Mücke and Protheroe, 2001) may explain the γ-ray part of the SED of blazars if the interaction between the accelerated protons with the AGN radiation fields is considered. Protons may interact via pion photoproduction and Bethe-Heitler pair production with the radiation fields mentioned above. The mean energy loss distances/times for all processes are given in Fig. 2.

The intense radiation fields needed for pion photoproduction interactions may present a problem for the escape of high energy γ-rays. We calculate the optical depth along the jet axis from the emission region for photon-photon pair production in the radiation fields of the disk, BLR and torus.

The optical depth for escaping γ-rays at various locations along the jet axis is represented in Fig. 3. The left-hand curves (below the label "BLR") show the contribution to $\tau_{\gamma\gamma}$ at different locations within BLR. At all these locations the emission region is totally embeded in BLR photons. For larger $L_{\rm BLR}$ the optical depth $\tau_{\gamma\gamma}$ increases accordingly, while a stronger dependence of the BLR cloud density with radius ($\alpha = 2.5$) could decrease $\tau_{\gamma\gamma}$ by one order of magnitude. For blazars, the BLR can be either completly hidden by a closed torus (Falcke et al. 1995) forcing us to estimate its luminosity by analogy with other AGN, or partially covered by an open torus. For the case of an open geometry, the lack of BLR activity could translate into a low $L_{\rm BLR} = 1.5 \cdot 10^{40}$ erg/s (Morganti et al., 1992 for Mrk 421). Such a low value would make the optical depth $\tau_{\gamma\gamma}(\rm BLR)$ insignificant, unless the local distribution of the BLR clouds depends strongly on radius.

As noted previously by Protheroe and Biermann (1997), we see from the curve labeled "IR torus" that for photon energies above about several hundreds of GeV the opacity is large enough that no radiation can emerge if the source of γ-ray is near the centre of the torus. In addition, the BLR region would absorb the $10^2 - 10^3$ GeV photons, if they are to produced within the very inner region of the BLR. For distances

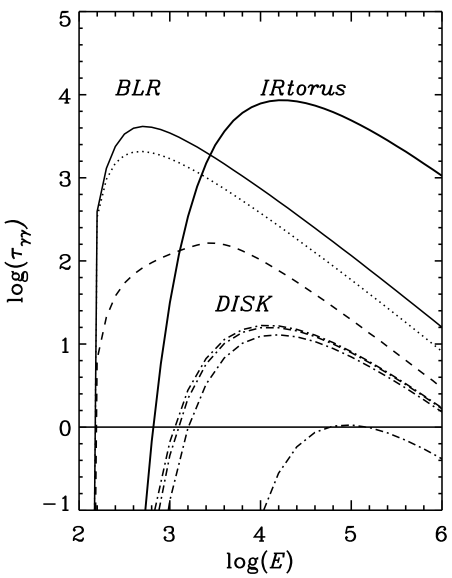

Fig. 3. Optical depths for γ-rays produced at three different locations in the BLR region ($r = 0.01$ pc, solid line; $r = 0.001$ pc, dotted line; $r = 0.02$ pc, dashed line). For larger r the optical depth decreases for photon energies of $10^2 - 10^3$ GeV ($L_{\rm BLR} \approx 10^{44}$ erg/s). The curve labeled "IRtorus" shows the contribution to $\tau_{\gamma\gamma}$ from IR photons interacting with jet photons emitted at $r \ll H/2$. Optical depths due to disk radiation (chain curves below "DISK") are plotted for γ-rays produced at $r = (0.001, 0.01, 0.02, 0.1)$ pc (from top to bottom) with $L_{\rm UV} = 10^{46}$ erg/s..

$r \geq 0.04$ pc up to $> H/2$ only the IR contribution remains important. A close/open torus geometry (corresponding to FR1-blazars and quasars, respectively) would lightly modify the optical depth IR curve in Fig. 3.

Our results show that the γ-ray attenuation by interaction of γ-rays emitted from the jet with photons from the BLR, as well from the IR torus is important. If a γ-ray is emitted close to the accretion disk, then there is a non negligible contribution from the disk photons to the γ-γ opacity. We conclude that, whether or not accelerated protons or electrons are responsible for the GeV-TeV emission through a leptonic or hadronic model, the injection and acceleration of particles should occur at distances above ~ 0.04 pc, the distance above which the attenuation on the BLR photons decreases. However, at these distances γ-γ interactions on the IR emission is the main attenuation process for TeV photon absorption. This is in agreement with the recent result of Kataoka et al.(2001) which implies that, due to the lack of short term variability at X-ray energies for Mrk 421 and Mrk 501, the acceleration of particles does not occur at distances $r \leq 10^{17}(\Gamma/10)^2$ cm$= 0.03$ pc for a jet Lorentz factor $\Gamma = 10$. Of course, for quasars the emission regions in the jet could be located at completely different positions to those in blazars.

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