RevMexAA (Serie de Conferencias), **7**, 110–117 (1998)

PAIR ABSORPTION OF HIGH ENERGY γ RAYS IN BLACK BODY DISK RADIATION FIELDS

A. Carramiñana

Instituto Nacional de Astrofísica Optica y Electrónica, Luis Enrique Erro 1, Tonantzintla, Pue., 72840, México; alberto@inaoep.mx

RESUMEN

Los rayos gama de alta energía en un campo de radiación intenso pueden ser absorbidos al producir pares electrón-positrón. Este mecanismo ha sido empleado anteriormente para estudiar la propagación de fotones de 10^{15} eV en el fondo de radiación de microondas y de fotones de más baja energía, atravesando un campo de radiación infrarroja. Se presenta un formalismo para resolver el problema de la absorción de rayos gama en el campo de radiación de discos de acreción con emisión térmica, mismo que se aplica a ejemplos relevantes de sistemas estelares y de galaxias activas. Las predicciones de este modelo probablemente estén al alcance de las observaciones existentes. En el caso específico de Mk421, el corte espectral predicho no es observado, indicando que los fotones de energías en el rango de los TeVs observados deben ser producidos en una región externa al disco de acreción.

ABSTRACT

High energy γ-rays in a strong radiation field can be absorbed by producing electron-positron pairs. Such mechanism has been previously used for studying the propagation of 10^{15} eV photons in the cosmic-ray background, and of lower energy photons through infrared background. A formalism to address the problem of γ-ray pair absorption in the radiation field of thermal accretion disks is presented and applied to relevant stellar and AGN examples. The predictions of these models might be within the reach of existing observations. In the specific case of Mk421, the spectral break that the accretion disk should produce is not observed, pointing to TeV emission in a region outside the accretion disk.

Key words: **ACCRETION, ACCRETION DISKS — GAMMA-RAYS: THEORY**

1. INTRODUCTION

The attenuation of high energy photons through pair production in a radiation field was addressed some thirty years ago (Gould & Schreder 1967). Shortly after the discovery of the microwave background, they realized that photons with energies $\sim 10^{15}$ eV were prone to pair production absorption in the CMB. The problem was readdressed more recently by Protheroe (1986), who included the effect of secondary photon production and the subsequent electromagnetic cascade process. More recently the problem has been expanded to other possible backgrounds, like the absorption of TeV photons by an IR background (Stecker, de Jager, & Salomon 1992; Stecker & de Jager 1997) —which would explain the lack of TeV detections among GeV blazars— and also by a radio background for the photons at the highest observable energies (Protheroe & Biermann 1996).

All these works refer to isotropic backgrounds, a disk geometry been first considered by Carramiñana (1992) and by Bednarek (1993). The detection of quasars and Bl Lac objects by EGRET has renewed the interest in this subjects, as testified by the more recent work by Becker & Kafatos (1995) and Zhang & Cheng (1997).

This article briefly summarizes the general problem of pair absorption of γ-rays in radiation fields, describes the case for a general disk geometry and points out some of the main improvements remaining to be done.

2. ABSORPTION OF γ-RAYS IN RADIATION FIELDS

2.1. Generalities

As for any absorption process, pair absorption of high energy γ-rays can be measured in terms of an optical depth, N, which will be function of the photon energy, E_γ. This optical depth is calculated integrating the interaction coefficient κ along the trajetory of the photon

$$N = \int \kappa \, dl \, . \qquad (1)$$

The probability that the photon can accomplish such trajectory is given by e^{-N}. Basically, if $N >> 1$ the γ-ray will interact through pair production and be effectively absorbed. Given that photons propagate along straight lines, $\vec{r}(t) = \vec{r}_0 + \hat{k}_\gamma \, ct$, where $\hat{k}_\gamma$ is the (unitary) propagation vector, eq. (1) becomes an integration over the parameter t.

The interaction coefficient contains the information about the interaction process itself: in the case under consideration, the pair production cross section, $\sigma_{\gamma\gamma}$, the characteristics of the γ-ray, E_γ and $\hat{k}_\gamma$, and the radiation field, basically its spectral and geometrical properties. For an arbitrary radiation field, $I_\nu(\{x_i\})$, described through a set of parameters $\{x_i\}$, the absorption coefficient is given by

$$\kappa(E_\gamma, \{x_i\}) = \int_{\Delta\Omega} \int_0^\infty \left(\frac{1}{c} \frac{I_\nu(\{x_i\})}{h\nu} \right) \sigma_{\gamma\gamma} \, d\nu \, d\Omega \, . \qquad (2)$$

The pair production cross section (Berestetskii, Lifshitz, & Pitaevskii 1982) is given by $\sigma_{\gamma\gamma}(s) = (\pi r_e^2/2)\Psi(\beta)$, where $\beta = 1/\sqrt{1-1/s}$ is the velocity of the electron and positron in the center of momentum reference frame, related to the four momentum invariant $s = E_\gamma \nu \, (1 - \cos i)/2$ for the pair interaction of two photons of energies E_γ and ν propagating with relative angle i (photon energies and frequencies are here measured in units of mc^2 and mc^2/h respectively), (see Figure 1).

The term under brackets in eq. (2) denotes the density of photons from the radiation field, per volume, frecuency and solid angle. The integral is done over the geometry and spectrum, which are determined by the radiation field. In the particular case of a black body radiation field, κ is computed from the Planck photon distribution, $n_\nu(T)$, and the pair production cross section, from where we obtain

$$\kappa(E_\gamma; T) = \frac{\alpha^2}{\lambda_c} \int T^3(\Omega) \, \mathcal{J}\left[E_\gamma T(1 - \cos i)/2\right] \frac{d\Omega}{4\pi}, \qquad (3)$$

where temperatures are expressed in units of mc^2/k_B, and in the auxiliary function,

$$\mathcal{J}(x) = \int_0^\infty \frac{u^2 \Psi(xu)}{e^u - 1} \, du \, , \qquad (4)$$

with $xu = (1 - \beta^2)$, is where the actual computation is made.

Clearly other radiation fields can be treated in an analogous way by considering a different $\mathcal{J}$ which might depend on more than one parameter. Note also that the natural scale for this process, given in terms of the fine structure constant, α, and the Compton wavelength, is obviously very small λ_c, as $\lambda_c/\alpha^2 \approx 4.55 \times 10^{-6}$ cm.

The solid angle integral is to be performed once the geometry of the problem is known. Of astrophysical interest are isotropic and disk related geometries.

2.2. Pair Absorption in an Isotropic Black Body Background

Gamma-ray propagation in an isotropic black body, namely the CMB, was solved by Gould & Schreder (1967), and further treated by Protheroe (1986). The temperature is independent of the position and the absorption coefficient becomes

$$\kappa(E_\gamma; T) = \frac{\alpha^2}{\lambda_c} \left(\frac{T^2}{E_\gamma} \right) \int_0^{E_\gamma T} \mathcal{J}(\mu) \, d\mu. \qquad (5)$$

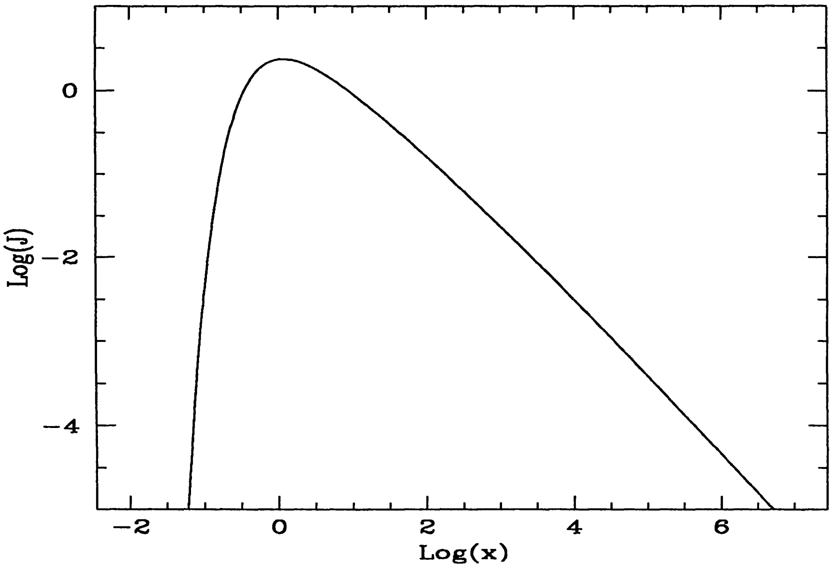

Fig. 1. Dimensionless function representing the pair absorption of γ-rays in a black body radiation field as a function of $s = E_1 E_2\,(1 - \cos i)/2$.

The interaction length, for $T \simeq 2.73$ °K $\simeq 4.60 \times 10^{-10}\ m_e c^2$, is plotted as a function of gamma-ray energy in Figure 2. For high energy photons to travel a cosmological distance, say 1 Gpc or more, we require $E_\gamma \simeq 85$ TeV (see Fig. 2). This limit, which constrains photons with energies between 2×10^{14} eV and 10^{19} eV to come only from galatic sources, is more than an order of magnitude lower than what one would expect naively from the condition $E_\gamma T \sim 1$.

The interaction length for photons with energies of 10^{20} eV through the CMB, $E_\gamma T \simeq 9.0 \times 10^4$, is $k^{-1} \approx 7$Mpc. As in the case of massive and charged cosmic-rays, photons at these energies must come from non-cosmological distances. Furthermore, at energies above 10^{21} eV double-pair production becomes important. Protheroe (1986) has further developed this problem, studying the particle cascades triggered by ultra high energy photons, through inverse Compton scattering of the $e^\pm$ produced.

3. ACCRETION DISKS

Only Keplerian thin disk models are considered here. In these models the radiation field is given as a superposition of black body rings of effective temperature $T(R) = T_*(R/R_*)^{-3/4}$, where R_* is the radius of the accreting object and

$$T_* = \left(\frac{3G\dot{M}M_*}{8\pi\sigma_{sb}R_*^3}\right)^{-1/4} \tag{6}$$

is the characteristic disk temperature and σ_{sb} is the Stefan-Boltzmann constant. The functional form of $T(R)$ does not depend on unknown viscosity related parameters, like the Shakura Sunyaev alpha parameter, as was considered by Zhang & Cheng (1997). It relies on the requirement that at any radius half of the potential energy has to be released, which is in turn imposed by the Keplerian nature of the disk (Frank, King, & Raine 1992).

In the case of an accreting black hole eq. (6) can be expressed in terms of its mass, through $R_* = 2GM_*/c^2$, and the luminosity of the accretion process, through $L = \eta\dot{M}c^2$, from where

$$\begin{aligned} T_* &= \left(\frac{3Lc^4}{64\pi\sigma_{sb}\,\eta\,G^2M^2}\right)^{1/4} \\ &\approx 1606\,\mathrm{eV}\,\left(L/10^{38}\mathrm{erg}\cdot\mathrm{s}^{-1}\right)^{1/4}\,(M/10\,M_\odot)^{-1/2}\,(\eta/0.1)^{-1/4}\ , \\ &\approx 160.6\,\mathrm{eV}\,\left(L/10^{48}\mathrm{erg}\cdot\mathrm{s}^{-1}\right)^{1/4}\,\left(M/10^8\,M_\odot\right)^{-1/2}\,(\eta/0.1)^{-1/4}\ , \end{aligned} \tag{7}$$

or about $3.14 \times 10^{-3}\ mc^2$ and $3.14 \times 10^{-4}\ mc^2$ for stellar or AGN black hole systems respectively.

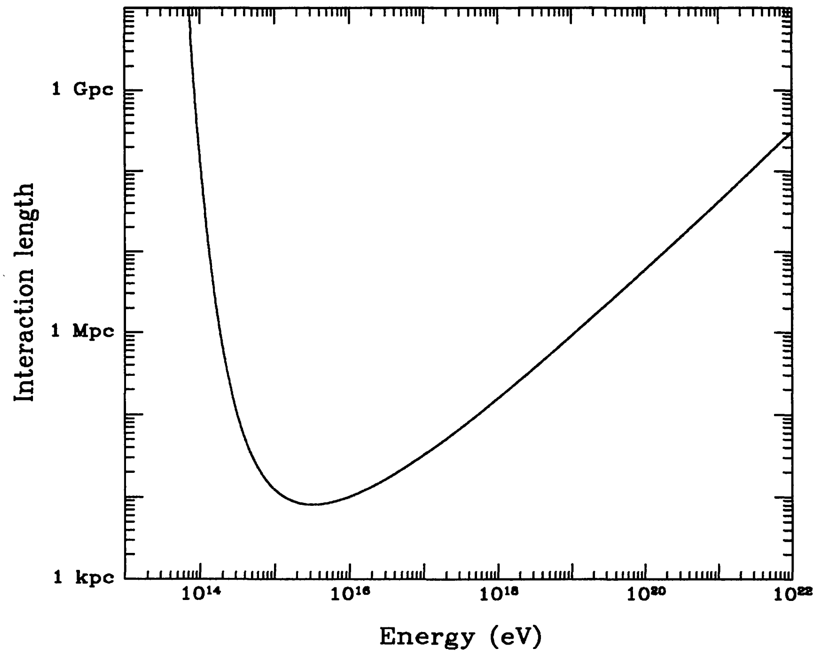

Fig. 2. Interaction length of γ-rays in the CMB.

We note that the AGN disk is cooler, although the distances involved are also several orders of magnitude larger. Proper quantification of these scenarios will be made in the next sections.

3.1. Plane Parallel Model

This is the geometry solved by Carramiñana (1992), where thermal photons from the accretion disk were assumed to propagate perpendicularly to the disk plane (i.e., along the $\hat{z}$ axis), (see Figure 3). The main simplification comes in that the argument $E_\gamma(1\cos i)$ inside eq. (3) is constant and, together with the $T \propto R^{-3/4}$ dependence, it permits to express the interaction coefficient and a function of radial distance R

$$\kappa(E_\gamma; R) = \frac{\alpha^2}{\lambda_c} T^3(R)\, \mathcal{J}\left(\frac{E_\gamma T(R)}{2}(1-\cos i)\right) . \qquad (8)$$

The optical depth for a gamma-ray of energy E_γ, emitted at an angle i relative to the disk axis ($=\hat{z}$ axis) is then given by

$$N(E_\gamma) = \frac{4\alpha^2 R_*}{3\lambda_c}\, E_{geom}^{-5/3}\, T_*^{4/3} \int_{w_{ou}}^{w_{in}} w^{2/3}\mathcal{J}(w)dw \,, \qquad (9)$$

where $w_{in} \equiv E_{geom} \cdot T(R_{in})$ and $w_{out} \equiv E_{geom} \cdot T(R_{out}) \to 0$, R_{in} and R_{out} are the inner and outer disk radii, and $E_{geom} = E_\gamma(1-\cos i)/2$. The optical depth of the disk radiation field can be finally expressed in terms of a typical optical depth N_0 and a characteristic energy E_c

$$N(E_\gamma) = N_0\ (E_\gamma/E_c)^{-5/3} \int_0^{E_\gamma/E_c} w^{2/3}\mathcal{J}(w)dw \,, \qquad (10)$$

with $N_0 \equiv (4\alpha^2 R_{in}/3\lambda_c)T_{in}^3$ and $E_c = 2/T_{in}(1-\cos i)$, where $T_{in} = T(R_{in})$. This function is shown in Figure 4. Note that there is a strong dependence on the value of R_{in}.

This model can be applied basically to galactic systems, namely X-ray binaries, where the inclination angle is relatively large and most parameters are fairly well known.

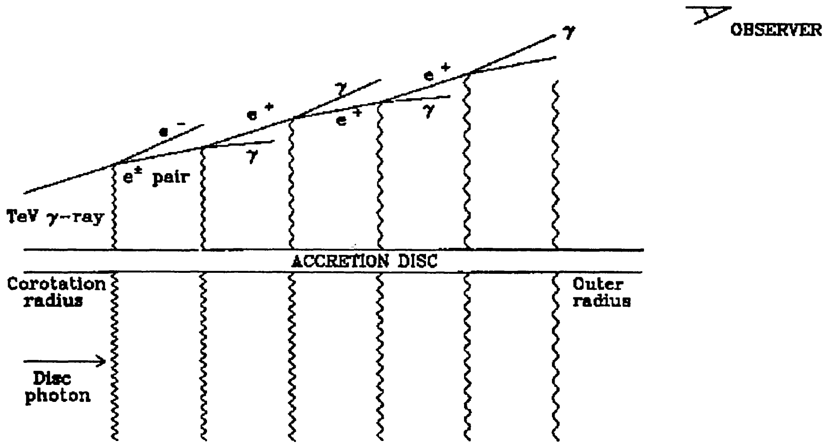

Fig. 3. Diagram of the model for the plane parallel case.

3.1.1. Magnetic Neutron Stars

This specific problem was addressed by Carramiñana (1992), in the context of possible TeV emission from neutron stars in X-ray emitting binary systems, and will not be repeated here. Fast-rotators, with periods below a few seconds, were found to be prone to heavily absorb any TeV emission originated at the corotation radius. In the particular case of Cen X-3, pulsed γ-rays with photon energies above $\sim$ 9GeV cannot escape the system. Recently, Vestrand, Sreekumar, & Mori (1997) have shown evidence for GeV emission from this system in the 30 MeV–10 GeV energy range.

3.1.2. Stellar Black Hole: Cygnus X-1

Cygnus X-1 remains the prototype of a stellar system containing a (candidate) black hole (Shore, Livio, & van den Heuvel 1994). Gamma-ray emission has been found from this system by COMPTEL for energies up to a few MeV (Mc Connell et al. 1994), with no positive report from the EGRET team.

The disk luminosity, taken as that of the X-ray emission, is about 2×10^{37} erg s^{-1}, and the inclination angle is bounded to $i < 70°$. Assuming a black hole of 10 $M_\odot$, taking the inner radius to be that of the last stable orbit, $3R_s$, and $i = 45°$ we find $N_0 \approx 850$ and $E_c \approx 6.4$ GeV. As $N_0 >> 1$, no photons with energies above $\sim$ 1 GeV should be able to escape the system (from Fig. 4, absorption starts around $0.1E_c$).

This geometry is limited and cannot treat γ-rays propagating parallel to the axis of the disk, as $E_c \to \infty$. A second simplified model is found for the exact geometry of an accretion disk when the inclination is equal to zero, i.e., γ-rays travel along the disk axis.

3.2. A γ-Ray Propagating Along the Axis of the Disk

For a γ-ray propagating along the axis of the accretion disk the exact solution can be found. In general, if we fix the coordinates at the center of the disk, one can characterize the trajectory of a gamma-ray emitted at that point using the angle θ it forms relative to the axis of the disk and its distance to the origin, given by ct

$$\vec{r}_\gamma = ct\;(\hat{z}\cos\theta + \hat{x}\sin\theta)\;. \tag{11}$$

Fixing $\theta = \pi/2$ as the plane of the disk and describing each surface element by its polar coordinates, $\vec{R} = R(\hat{x}\cos\phi + \hat{y}\sin\phi)$, viewed from the position of the γ-ray this surface element covers a solid angle

$$d\Omega = \frac{\hat{k}_\gamma \cdot \hat{n}\;dA}{|\vec{r}_\gamma - \vec{R}|^2} = \frac{\vec{r}_\gamma \cdot \hat{n}\,dA}{|\vec{r}_\gamma - \vec{R}|^3} = \frac{ct\cos\theta\;RdR\;d\phi}{\left(R^2 + c^2t^2 - 2R\,ct\sin\theta\cos\phi\right)^{3/2}}\,, \tag{12}$$

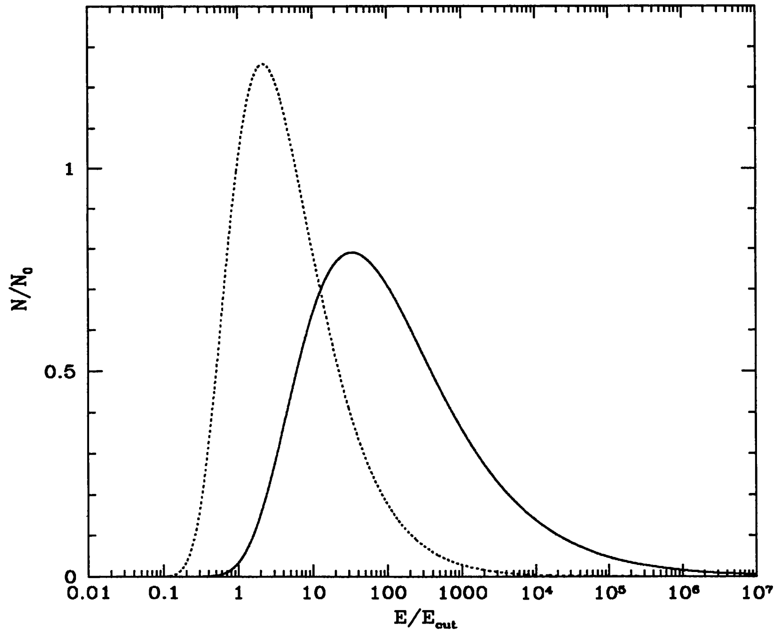

Fig. 4. γ-ray optical depth, in units of N_0 as defined in the text, for simplified accretion disk geometries. The full line represents propagation along the disk axis while the dotted line shows the approximate plane parallel case. Note the vertical axis is in units of N_0 which can easily be much larger than 1.

where $\hat{n}$ is the unitary vector normal to the disk plane –usually, $\hat{n} = \hat{z}$, although the radiation pressure dominated regions of hot accretion disks depart from thin disk geometries– while $\hat{k}_\gamma = (\vec{r}_\gamma - \vec{R})/|\vec{r}_\gamma - \vec{R}|$ is the propagation angle of disk photons at the gamma-ray position.

For a superposition of black-body rings, the optical depth for a γ-ray as a function of its energy E_γ, propagation angle θ, disk characteristic temperature T_* and inner radius R_{in} (outer radius $\to \infty$) can be computed integrating over ct

$$\begin{aligned} N(E_\gamma, \theta; T_*) &= \int k(E_\gamma; T)\, d(ct) \\ &= \frac{\alpha^2}{4\pi\lambda_c} \cos\theta \int_0^\infty \int_0^{2\pi} \int_{R_{in}}^\infty \frac{T^3(R)\, \mathcal{J}\left[E_\gamma T(1 - \hat{k}_\gamma \cdot \hat{r}_\gamma)/2\right]\; R\, dR\, ct\, d(ct)\, d\phi}{(R^2 + c^2t^2 - 2R\, ct\, \sin\theta\cos\phi)^{3/2}} . \end{aligned} \quad (13)$$

The limit $\theta \to \pi/2$, corresponding to gamma-rays grazing the surface of the disk, is singular and should be approximated by the plane parallel case. The plane parallel approach fails for $\theta = 0$, as this implies $1 - \hat{k}_\gamma \cdot \hat{r}_\gamma = 0$. Fortunately, in this case the dependence on ϕ is lost and integral over $d\phi$ gives simply a factor of 2π. The integral over $d\nu$ is done using expression (2), remaining then a double integral

$$N = \frac{\alpha^2}{2\lambda_c} \int\int \frac{T^3(R)\, \mathcal{J}\left[E_\gamma T(R)(1 - ct/\sqrt{R^2 + c^2t^2})\right]\; ct\, d(ct)\, RdR}{(R^2 + c^2t^2)^{3/2}} . \quad (14)$$

The integration over the photon trajectory, assumed to go from $ct = 0$ to ∞, is simplified by the substitution $ct = R\tan u$, from where

$$N(E_\gamma) = N_0\, (E_\gamma T_{in})^{-5/3} \int_0^{E_\gamma T_{in}} w^{2/3} \mathcal{G}(w) dw\, , \quad (15)$$

with the function $\mathcal{G}$ defined as

$$\mathcal{G}(w) = \int_0^{\pi/2} \mathcal{J}\left(w(1-\sin u)/2\right) \sin u \, du. \tag{16}$$

The pair absorption process starts at $E_c = 1/T_{in}$ and the optical depth has a characteristics value $N_0 = (2\alpha^2 R_{in}/3\lambda_c)T_{in}^3$. We recover an expression totally analogous to equation (10). However, in this case the more favorable geometry makes the absorption process to start at a higher point, roughly at $ET_{in} \sim 1$, almost a decade latter than for the plane parallel geometry. The dimensionless peak absorption is lower, although for $N_0 >> 1$ this makes little difference.

3.2.1. AGN Black-Hole Systems: γ-Ray Blazars

The second EGRET catalog of high-energy sources (Thompson et al. 1995, 1996) lists 43 sources positively identified as AGNs, and 11 sources that might be AGNs. Probably the two cases most studied are those of 3C279 (Hartman et al. 1992) and Mk421 (Lin et al. 1992), which we discuss here briefly.

3C279 is often taken as the prototype of a gamma-ray emitting "blazar": its highly variable, with flux changes of factors ~ 5 in few days (Kniffen et al. 1993), and most of the observed energy distribution comes in GeV photons (Hartman et al. 1996). No emission has been detected in the TeV energy range, this been attributed to TeV pair absorption by infrared photons (Stecker et al. 1992; Stecker & de Jager 1997), more than to local photon absorption. Assuming the quiescent optical and X-ray emission to be isotropic, and ascribing it to an accretion disk, one gets $L_{disk} \approx 10^{46}\,\mathrm{erg\,s^{-1}}$. On the other hand, a black hole of $\sim 10^8 M_\odot$ can produce this energy output and remain below the Eddington limit. For such a black hole, gamma-rays emitted from 3 Schwarschild radii can vary in timescales of hours without the need of relativistic beaming effects to account for the variability. Using these numbers, one obtains $N_0 = 3.23 \times 10^6$ and $E_c = 1/T_{in} \approx 11.7\,\mathrm{GeV}$ for 3C279. According to this, gamma-rays of energy above E_c would not be able to escape the system. The emission observed by EGRET certainly extends above 5 GeV, but there might not be enough photons to test a break above 12 GeV. Pair absorption would suppress any emission in the TeV energy range.

The non detection of TeV photons from 3C279, combined with the TeV detection of Markarian 421, both in quescient (Schubnell et al. 1996) and strong flaring states (Gaidos et al. 1996), are taken as a support for the attenuation of TeV emissions in the infrared stellar background (Stecker et al. 1992; Stecker & de Jager 1997). The TeV flare was accompanied by a X-ray flare (Takahashi et al. 1996). Assuming the quiescent X-ray emission is isotropic and due to the accretion disk, one gets $L_{disc} \sim 2 \times 10^{43}\,\mathrm{erg\,s^{-1}}$. A black hole mass of $10^7 M_\odot$ is consistent with L_{disc} been below the Eddington limit and variability in timescales of a few minutes. Using these numbers, one obtains $N_0 = 641$ and $E_c = 1/T_{in} \approx 93\,\mathrm{GeV}$ for Mk 421. Pair absorption is much less important in this system, but still should produce an obvious cut below the observed TeV energy range. The model can only be consistent with the observations if the high energy photons are produced at some distance above the disk. This can be quantified by modifying the limits in the definition of $\mathcal{G}$. Further work on this line is needed.

4. CONCLUSIONS AND LINES OF FUTURE WORK

Pair absorption of high energy γ-rays is a process which deserves consideration not only for the propagation of photons in the extragalactic medium but also within the sources themselves. Accretion disks in both stellar and AGNs black-hole systems have powerfull radiation fields and GeV or TeV photons are prone to be absorbed in systems like Cen X-3, 3C279 and Mk421. We note that the spectral breaks found in this work are very close to the limits of detection and in some cases —namely 3C279— they might be tested. The absence of such a break, as in Mk421 where emission is found at photon energies beyond the models presented here, can be used to give bounds on the region where TeV photons are produced. This lower limit on the distance of the emitting region to the center of the disk can be combined with the upper bounds found from variability arguments to further define the sites of GeV and TeV photon production.

Finally, pair absorption models for accretion disks can be refined one more step by adding a comptonization component to the thermal spectrum, in agreement with X-ray data from accreting systems. One expects that a harder spectrum would lower the value of E_{cut}, but probably also that of N_0, as the radiation field would be constitued of less photons of higher frequencies. Quantification is now pending.

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