

PAIR CASCADES AND THE GAMMA-RAY SPECTRA OF ACTIVE GALACTIC NUCLEI

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Abstract

Our current understanding of the physics of Active Galactic Nuclei (AGN) suggests that intense optical, UV, and X-ray radiation fields should exist in the central regions of AGN. These radiation fields are intense enough that high energy γ -rays propagating through them are likely to pair produce and thus be absorbed before they can escape from the central source region of an AGN. If the absorbed γ -rays are sufficiently energetic, the electron-positron pairs created will initiate an electromagnetic pair cascade on the ambient radiation field. We review here the types of emission spectra that can be produced by a pair cascade and discuss their relevance to AGN spectra. In particular, we examine the possibility that cascades may be occurring in the blazar AGN sources detected by EGRET and are responsible for their observed γ -ray spectra. If this is the case, we do not expect these AGN to be strong TeV sources, and their spectra should show a strong cutoff due to *intrinsic* absorption at energies $E_\gamma \lesssim 50$ GeV.

1. Introduction

The important role that the process of photon-photon pair production can play inside sources of high-energy γ -rays and in the propagation of these γ -rays has long been realized[13]. The low energy radiation fields that pervade many sources and even intergalactic space represent a very abundant source of target matter for a photon of sufficiently high energy to interact with and pair produce. Since a γ -ray is effectively absorbed when it pair produces, photon-photon pair production places an upper limit on the distance a γ -ray can propagate through such radiation fields and, indeed, often represents the dominant source of absorption opacity for γ -rays. A γ -ray of energy E_γ can potentially interact with any background photon whose energy exceeds the threshold energy $E_{thr} = 2(m_e c^2)^2 / E_\gamma (1 - \cos \theta)$, where θ is the angle between the γ -ray and background photon momenta. The interaction cross-section[10] peaks at a value $\sigma_{\gamma\gamma} \sim 0.2$ time the Thomson cross-section (σ_T) when the γ -ray has roughly twice the threshold energy. If the background photon field is isotropic, this means the γ -ray interacts most favorably with background photons of energy $E_{lo} \sim (m_e c^2)^2 / E_\gamma \approx 0.26 eV (E_\gamma / 1 TeV)^{-1}$.

From this relation, we can see immediately why the levels of the diffuse IR and optical intergalactic radiation fields are of interest to TeV astronomy. Although these fields are quite weak (and still to be detected), the expected levels are high enough that for cosmological source distances $\gtrsim 100$ Mpc, the universe is opaque at TeV energies[24].

As important as this cosmological opacity is, it can be negligible compared to the opacity arising from intense radiation fields in or near some sources of high energy γ -rays. The sorts of sources for which this internal (intrinsic) opacity might be important are “compact” sources such as Active Galactic Nuclei (AGN) and γ -ray bursters which are extremely luminous yet, because of their rapid time variability, must also be small in size. One can make a simple estimate of the γ -ray opacity in such sources if one assumes that the background radiation field in such an object is uniform and isotropic, with a differential energy spectrum $n(E_{lo}) = dN/dE_{lo}$. Time variability gives us an upper limit on the background photon source size, i.e., $R_{source} < c\Delta t_{min}(E_{lo})$ where $\Delta t_{min}(E_{lo})$ is the shortest observed timescale for the background photon field to vary significantly. We then have a lower limit on the background photon density: $n(E_{lo}) \gtrsim L(E_{lo})[4\pi E_{lo}c]^{-1}[c\Delta t_{min}(E_{lo})]^{-2}$, where $L(\epsilon)$ is the source luminosity at energy ϵ . (The total source luminosity is $L_{tot} = \int L(\epsilon)d\epsilon$). Taking $E_{lo} \propto 1/E_\gamma$, the absorption optical depth for a γ -ray emitted inside the background photon source is then,

$$\tau_{\gamma\gamma}(E_\gamma) \sim 0.2\sigma_T E_{lo} n(E_{lo}) R_{source} \gtrsim 0.016 \left(\frac{E_\gamma}{m_e c^2} \right) \left[(E_{lo} L(E_{lo})) \frac{\sigma_T}{m_e c^3 [c\Delta t(E_{lo})]} \right] \quad (1)$$

where $(E_{lo} L(E_{lo}))$ is approximately the total luminosity emitted at energies $\epsilon \sim E_{lo}$ (within an energy band of width $\Delta E \sim E_{lo}$). The dimensionless factor inside the brackets, $\propto L_{source}/R_{source}$, is commonly referred to as the “compactness parameter” $l(E_\gamma)$ [11] and is an easy-to-compute quantity for estimating the pair production optical depth across a source. If the source is small and very luminous, i.e., if $l(E_\gamma)$ is large, then the source is opaque to γ -rays of energy $\sim E_\gamma$ produced inside it. Often a source has an energy spectrum that does not fall off rapidly at low energies (in an AGN, to first order $E_{lo} L(E_{lo}) \sim \text{constant}$). Then, if a source is opaque at some energy E_γ^* , it is likely to be opaque at all energies $E_\gamma > E_\gamma^*$.

In the first section of this paper, we discuss the low energy radiation fields thought to exist near the centers of AGN and compute the compactness parameters and optical depths arising from these fields. Even for weak AGN, the compactness parameters above 10 MeV can be quite large. This leads to the (slightly naive) conclusion that AGN should *not* exhibit strong emission above 10 MeV, let alone at a TeV. At the same time, however, theorists suspected (and continue to suspect) that very energetic processes might be occurring in AGN and that a large fraction of the AGN’s luminosity might initially be carried by particles accelerated to energies well above 10 MeV. Because of the large opacity above ~ 10 MeV, the energy carried by these particles cannot escape the source without being reprocessed into particles of lower energy. The process by which this occurs is called an electromagnetic pair cascade and is the subject of the second and third sections of this paper. In the second section, we examine the “non-linear” cascades that might occur in an isotropic, homogeneous source of the type assumed in making the compactness estimates. (The cascades are non-linear because the γ -ray opacities are determined by the cascade.) Unfortunately, current AGN observations do not appear to give spectra consistent with this simple version of the cascade model. In particular, nearby Seyfert galaxies seem to have a spectrum that rolls over at ~ 100 keV and does not have significant emission above 1 MeV, while certain radio-loud quasars (blazars) appear to have enormous γ -ray luminosities extending to 10 GeV and perhaps beyond. In the third section, we examine why the compactness estimates of §I might be inapplicable to blazar AGN and discuss the source constraints which result from requiring that their GeV and perhaps TeV emission be observable. We briefly review the models proposed for this emission and conclude by proposing that “linear” pair cascades, cascades on ambient radiation not produced in the cascade, are a viable but not unique explanation for some blazar γ -ray spectra.

2. Ambient Radiation Fields and Pair Production Opacities in AGN

Leaving aside temporarily the emission from blazars which can be rapidly variable at all wavelengths, the variability timescales in AGN tend to decrease with increasing photon energy. At X-ray energies (1-100 keV) the time required for the intensity to change by a factor 2 can be as short as an hour, implying a compact emission region of size $R_x \lesssim 10^{14} - 10^{15}$ cm. Current thinking is that this emission comes from near the inner edge of the central black hole accretion disk, perhaps from a corona above the disk. Inserting this sort of size and typical X-ray luminosities $\sim 10^{44} - 10^{46}$ erg/sec into the formulas given above, one obtains AGN compactness parameters for γ -rays in the 10-100 MeV range that are $\sim 1 - 100$ [8]. In other words, one expects pair production optical depths for MeV γ -rays traversing the X-ray emitting region to be $\gtrsim 1$. If the most energetic particles and γ -rays are produced in this same region, which would not seem unreasonable, then we do not expect to see strong emission above 10 MeV or so. If these energetic particles and γ -rays initially dominate the energy output in the X-ray emission region, as suggested in many models, then we should also see the spectral signatures of the pair cascades initiated when the γ -rays pair produce to create energetic electron-positron pairs. (If they are sufficiently energetic, the pairs will create energetic γ -rays by Compton upscattering, and these new γ -rays will in turn pair produce to create more pairs, etc.) It is interesting to note that the γ -ray emitting blazar 3C279 has, according to this type of estimate, an optical depth $\sim 10^4$ at 100 MeV [18]. We shall discuss this implications of this later.

While the hot X-ray emitting part of an accretion disk or corona is perhaps the most obvious source of pair production opacity inside AGN, there are other sources too, particularly if one is interested in the propagation of TeV γ -rays. Most AGN, including some blazars in states of low nonthermal emission, show an excess of optical/UV emission relative to the power law continuum obtained by interpolating between the optical flux at some frequency and the X-ray flux at some higher frequency. This excess or “blue bump” emission is thought to originate in the cooler, outer parts of the accretion disk and represents a significant fraction of the AGN’s total power output. (See [21] for many examples of the broadband spectra of quasars.) It should not be surprising then that this emission can also give rise to large compactness parameters. In Figure 1, we show the pair production optical depths encountered by an outward propagating photon emitted at a height z above the center of an accretion disk. The accretion disk used in the calculation was a standard, Newtonian disk which at a given a radius R , emits isotropically as a blackbody of temperature $T(R) \sim T_{max}(R/R_{in})^{-3/4}$. The assumed mass of the central black hole was 10^8 solar masses, and the total disk luminosity was 4×10^{46} erg/sec, typical of what might be found in the more powerful quasars. In the example shown, the gravitational radius $R_g = GM/c^2$ was 1.5×10^{13} cm, and γ -rays of energy $\gtrsim 50$ GeV are thus not observable if they are emitted within $\sim 10^{15}$ cm of the disk.

Note that the opacity falls off rapidly with height. The further an escaping γ -ray is from the disk, the more the disk photons appear to be coming from behind and the smaller the typical interaction angles between the γ -ray and disk photons. (The smaller the interaction angle, the smaller the absorption probability.) Now if even a small fraction of the disk photons are scattered or absorbed and re-emitted so that their interaction angle with the γ -ray increases, then the opacity at large heights above the disk will increase dramatically. It appears that such a scattering and reprocessing of disk photons might indeed occur inside AGN. The evidence for this comes from observations of broad optical/UV emission lines in quasars. The Doppler widths of the lines are large, suggesting that the origin of these lines, the so-called BLR (Broad Line Region), lies fairly deep in the gravitational potential of the black hole. A more precise estimate of the location of the line-emitting gas can be made by the “reverberation mapping” technique where one studies how the line intensities track the UV and X-ray continuum intensities. This is still a subject of ongoing study, but the current thinking is that the BLR starts near the accretion disk (within a light travel day, $\sim 3 \times 10^{15}$ cm) and extends

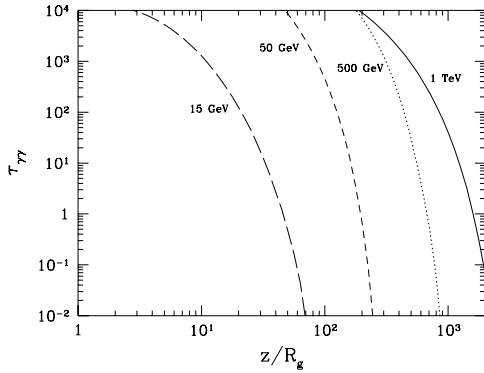


Fig. 1. The optical depth for photon-photon pair production ($\tau_{\gamma\gamma}$) off disk photons as a function of incident photon energy and of height z above the disk. The disk model had an inner radius of $5R_g$ and outer radius of $100R_g$. The maximum temperature at the inner edge of the disk was 2×10^5 K.

out to a distance $R_{BLR} \sim 3 \times 10^{17}$ cm. To estimate the density of scattered/reprocessed BLR photons at a given radius from the AGN center, we need the total BLR photon luminosity and the radial density profile of the emitting gas. The BLR luminosity is typically ~ 0.1 of the disk luminosity, but the gas density profile is not well-constrained. For the purposes of making a simple (conservative) estimate, let us assume that the gas is distributed in such a way that BLR radiation is produced uniformly throughout the BLR. Since the BLR radiation field is also presumably rather isotropic, we can use again the formulas given above to estimate the γ -ray optical depth. Taking the mean energy of the BLR photons to be $\langle E_{BLR} \rangle \sim 5$ eV, we get an optical depth at energy $(m_e c^2)^2 / E_{BLR} \sim 50$ GeV of

$$\tau_{\gamma,\gamma}^{BLR}(50 \text{ GeV}) \sim 600 \left(\frac{L_{disk}}{4 \times 10^{46} \text{ erg/s}} \right) (R_{BLR} / 3 \times 10^{17} \text{ cm})^{-1}$$

where L_{disk} is the accretion disk luminosity. Photons of energy greater than 50 GeV are likely to see comparable or higher opacities. In other words, we expect fairly powerful AGN to be opaque to high energy γ -rays emitted within $\sim 10^{17}$ cm of the black hole. If high energy, say TeV, γ -rays are observed from an AGN, then either the accretion disk/BLR luminosity of the source is anomalously low or the location of the γ -ray emission mechanism must be far from the black hole. If, based on theoretical prejudices, we expect the γ -ray emission site to lie near the black hole, the ultimate energy source for the emission, then most AGN to show an intrinsic absorption cutoff at $E \gtrsim 50$ GeV. TeV γ -rays have of course been observed from Mkn 421. However, Mkn 421 is a very weak AGN with no observed broad emission lines and, hence, we do not obtain a constraint on the emission site.

Finally, we note that the same BLR gas which reprocesses the disk emission can also scatter X-rays from a disk corona. This can extend considerably the region where an AGN is opaque to even MeV photons. The probable size of this region is somewhat controversial in the case of the γ -ray emitting blazars detected by EGRET (e.g., see [3][7]) since, as we shall argue below, the observed X-ray emission is almost entirely beamed emission from the AGN jet, i.e., the much fainter emission from an X-ray disk/corona is not observable except in very low source states and typically not well-known. Assuming blazars like 3C279 have an accretion disk/BLR comparable to that in radio quiet quasars, we estimate that absorption of MeV photons by X-rays can be important within $\lesssim 200R_g$ ($\lesssim 6 \times 10^{15}$ cm) of the black hole. If so, the γ -ray emission mechanism in powerful blazars like 3C279 must produce at least some power at distances greater than this.

3. Non-Linear Pair Cascades and Seyfert AGN

The process of photon-photon pair production first came under serious scrutiny in the context of AGN when attempts were made to model the X-ray spectra of AGN as Compton upscattering of accretion disk photons by nearby hot, thermal electrons, e.g., [22]. Because the estimated electron temperatures could be mildly relativistic, with $KT_e \gtrsim m_e c^2$, significant numbers of disk photons could be upscattered to \sim MeV energies. Now from the estimates made above, an AGN model such as this one, where γ -rays and X-rays are produced in the same region, is “compact” for MeV γ -rays, i.e., any MeV γ -rays created near the disk should promptly pair produce before escaping. The newly created pairs will increase the Compton scattering optical depth in the source which increases the number of upscattered MeV photons, which in turn causes more pairs to be produced. Hence, relativistic electron temperatures lead to an electron-positron pair cascade inside the the source which stops only when the pair production rate is balanced either by the pair escape rate from the source or, if pairs are trapped by magnetic fields or produced too rapidly, by the annihilation rate of pairs with each other[25]. If AGN contain significant numbers of relativistic particles, as was inferred from the apparent detection of strong MeV emission in a few Seyfert galaxies like NGC 4151 and MCG 8-11-11, the study of their spectra is thus a study of the spectra produced in pair cascades. Note that these cascades are not of the type usually considered in high energy physics since the target matter, the X-ray photons, are produced by the cascade particles. This makes the cascades “non-linear” in the sense that the photon opacity and thus the shape of the final spectrum are dependent on the number of primary particles.

While simple, models which assumed thermal electron and positron distributions fell into disfavor for two reasons. First, the radiative cooling times in powerful compact sources like AGN can be very short, shorter than the usual (e.g., Coulomb collision) thermalization timescales. It is not at all clear then that the distributions should be thermal Maxwellians. Second, the 2-10 keV X-ray spectra of radio quiet AGN, in particular Seyfert 1 galaxies, seem to have a preferred spectral index α_x ($dN/dE \propto E^{-\alpha_x-1}$) of 0.7 with only a few exceptional cases outside the range $0.5 < \alpha_x < 1$. For thermal models, however, the hardness of the X-ray spectrum scales simply with the electron/pair scattering optical depth and temperature, and the spectral index α_x has no *a priori* special value. Attention therefore switched to nonthermal models where electrons or pairs are accelerated to high Lorentz factors $\gtrsim 10^3$, cool rapidly on the surrounding radiation field, and only then thermalize to form a Maxwellian of relatively low temperature [16][8][9][4].

In Fig. 2, we show how a typical emergent spectrum from a nonthermal plasma evolves with increasing source luminosity. If the effects of pair production are ignored, the calculated spectra should change only in overall luminosity but not shape since the ratio of accelerated electron to background photon luminosity is kept constant. However, as the source luminosity (number of accelerated electrons) increases and the number density of upscattered X-rays rises, the source becomes compact for energies above an MeV and the relative flux of escaping γ -rays decreases as more and more γ -rays are absorbed. Since pairs are created when γ -rays are absorbed, the pair density in the source also increases with increasing source luminosity. The presence of these secondary pairs leads to three important effects which can be seen in Fig. 2. First, the pairs have a lower mean energy than the energetic (primary) electrons that started the cascades which produced them. Hence the X-rays upscattered by cooling secondary pairs have a lower mean energy those upscattered by cooling primary electrons. This causes the X-ray spectrum to steepen and approach an asymptotic spectral index $\alpha_x = 1$ [26]. Second, pairs can annihilate with each other to produce γ -rays. Since the pair cooling timescales are typically shorter than the annihilation timescales, the pairs are cool when they annihilate and produce a relatively narrow spectral emission feature at ~ 511 keV ($m_e c^2$). Finally, Compton downscattering of γ -rays by cooled pairs acts as an effective γ -ray absorption process since a γ -ray typically loses much of its energy in Compton scatterings with cold pairs. The spectral

break at ~ 40 keV in the $l_e = 2500$ model of Fig. 2 is due to downscattering by cold pairs. Note that the higher the γ -ray energy, the lower the probability for the γ -ray to Compton scatter off a pair before escaping. The strong decrease in downscattering opacity for energies $\gtrsim m_e c^2$ plus the presence of annihilation radiation at energies $\sim m_e c^2$ usually causes the spectrum from a nonthermal model with significant cascading to show an upturn at 511 keV (e.g., as in Fig. 2).

The fact that the nonthermal cascade models had a special or asymptotic X-ray spectral index of $\alpha_x \sim 1$ made them especially attractive. When reprocessing of this emission by ambient cold matter (inferred from the strong iron emission line features seen in many AGN) was taken into account, the result was a spectrum that had a 2-10 keV spectral index ~ 0.7 and then steepened at higher energies – exactly as had been observed[27]. Unfortunately, recent observations by the GRO and GRANAT satellites have strongly damped the early enthusiasm. Contrary to previous balloon observations, no Seyfert AGN have been detected above a few hundred keV in energy. Many of the high energy spectra appear to show a strong break at $\sim 100 - 200$ keV and there is no strong evidence for the expected annihilation feature or upturn in the spectrum at 511 keV. Ironically, models invoking thermal Comptonization by a moderately hot ($kT \sim 150$ keV), optically thin thermal plasma in an accretion disk corona seem to fit best now. [12] Nonthermal models are not entirely excluded, provided that the typical Lorentz factors of accelerated electrons are low enough ($\lesssim 4$) that not too many MeV γ -rays and pairs are produced[28]. In neither case is pair cascading very important.

Because of the apparent lack of very energetic particles and the the large opacities expected for high energy γ -rays, Seyfert galaxies and their more powerful counterparts, radio quiet quasars, are not promising TeV sources at the current sensitivity levels. This does not mean, however, that these AGN do not have some low level GeV-TeV emission. In particular, there has been considerable discussion of the possibility that hot protons might exist near the AGN accretion disk, and that these protons could produce significant numbers of energetic neutrons [14][19][1]. Since neutrons are not charged particles, they would not suffer strong radiation drag and could travel large distances from the central engine before they decayed back into energetic protons. Although the models are somewhat constrained by current GRO observations, a non-negligible amount of energy could be transported in this way to distances where GeV γ -rays could escape the AGN.

4. Linear Cascades and the EGRET AGN

While EGRET provided only upper limits on radio quiet AGN, the results were quite different for radio loud AGN. Somewhat unexpectedly, EGRET detected several blazars, AGN with radio jets pointing at us, out to redshifts $z \sim 2$. The observed emission was consistent with a power law of average spectral index 2 ($dN/dE \propto E^{-2}$) extending unbroken to energies ~ 10 GeV where EGRET runs out of photon statistics. The inferred luminosities were often huge, $\sim 10^{48}$ erg/s, with the EGRET emission apparently dominating the power output of the AGN at lower energies. Perhaps for the first time, we had solid evidence for the existence of high energy particles that could initiate cascades in AGN. Unfortunately, these AGN also turn out to be extremely compact to MeV and GeV emission during their outburst phases. (In 3C279, the compactness for 100 MeV γ -rays during a source high state is estimated to be $\gtrsim 1000$. [18],[20]). In other words, if the arguments of the preceding sections applied, none of this γ -ray emission should have been seen.

To evade the compactness arguments, either the γ -rays and X-rays must come from spatially distinct regions and do not interact, or something is wrong with the estimate of the pair production opacity. The current prejudice is that the X-ray and γ -ray emission are probably well-correlated even on short timescales, i.e., they are produced by the same particles in the same region. Thus, the problem probably lies in the pair opacity estimate. This seems quite likely given that the γ -ray luminosity of blazars appears to be correlated with their

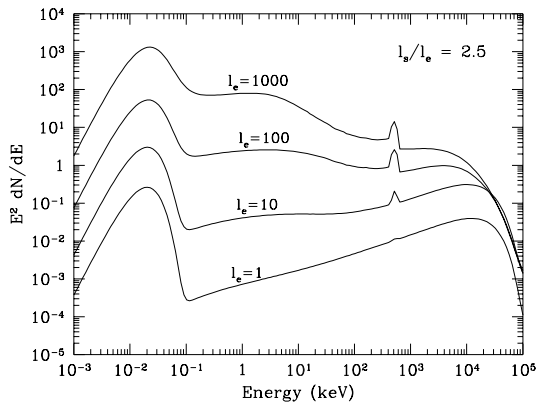


Fig. 2. Nonlinear pair cascade spectra from an isotropic, homogeneous source. Adjacent spectra differ by a factor ten in the assumed source luminosity, and the relative normalizations of the spectra are correct. For all calculations shown, the ratio of the ambient soft photon luminosity to the accelerated primary electron luminosity is $l_s/l_e = 2.5$, the primary electrons have initial Lorentz factors $\gamma_i = 10^3$, and the ambient photon energy distribution has the shape of a blackbody with temperature $kT_{bb} = 5$ eV.

radio luminosity, and that their radio emission appears to be highly beamed and is produced in relativistic jets that are viewed nearly head on. It seems reasonable then (though not absolutely certain) that the γ -ray and X-ray emission is also relativistically beamed. In this case, the size of the X-ray emitting region can be much larger (by up to a factor γ_{jet}^2 , where the γ_{jet} is the bulk Lorentz factor of the radio jet) than that naively inferred from rapid time variability observations. Also, the fact that the X-rays and γ -rays are beamed along one another means that their typical interaction angle is small ($\theta \lesssim 1/\gamma_{jet}$), and their interaction rate is correspondingly reduced. If the X-ray and γ -ray emission is sufficiently beamed then, γ -rays do not pair produce before escaping the jet and there is no contradiction with the observations. (Another way of seeing this is to note that the absorption probability is a Lorentz invariant and can be computed in the rest frame of the jet. Since the X-ray and γ -ray distributions are presumably fairly isotropic in this frame, one can use the compactness estimates above but with all luminosities reduced by a Doppler boosting factor which can be as large as γ_{jet}^4 .) A bulk jet Lorentz factor $\gamma_{jet} \sim 10$, of the same order as that inferred from radio observations, seems enough for most EGRET AGN to prevent the absorption and cascading of γ -rays on the jet X-rays.

This does not mean, however, that pair cascading cannot occur on other photon fields that may be present. In the proton-initiated cascade model of Mannheim [7], for example, it is supposed that far down the jet, say in one of the observed “knots” of intense radio emission, a strong shock occurs and produces very energetic particles, in particular protons with Lorentz factor $\gtrsim 10^8$. These protons are energetic enough to interact with synchrotron photons in the jet and since the jet is compact to the γ -rays produced by these protons (which have energies $E_\gamma \gg 1$ GeV), a cascade develops that reprocesses the energy initially in protons to much lower photon energies. Since the synchrotron target photon distribution is assumed to be fixed, i.e., not produced by cascade particles, the cascade is a “linear” one in contrast to the case considered above. (It is linear in the sense that the target photon distribution and consequently the shape of the output photon spectrum do not depend on the source luminosity.) By varying parameters like the proton energy injection spectrum and observer viewing angle, the model can be made to match current observations fairly well.

An important prediction of this model is the amount of GeV and TeV radiation produced. Since the target synchrotron photons are low energy (radio to millimeter wavelengths), the

threshold energy for a γ -ray to pair produce on them is correspondingly high, and the GeV-TeV radiation produced in the jet can escape. Since the cascading occurs far away from the central engine, the ambient radiation fields discussed in §I also do not represent a significant pair production opacity, and this GeV-TeV radiation can escape the AGN nucleus. Thus, while pair production on the intergalactic IR field and possibly the IR field produced by dust in the most powerful quasars can absorb some of the TeV radiation, the Mannheim model generally predicts observable emission in the 100 GeV to TeV range from a fair fraction of blazars with redshift $z \lesssim 1$. Detection of this emission would tell us that very energetic particles are indeed produced in the jet and that the γ -rays are created far away from the AGN central engine. A non-detection of this emission would imply either: (i) that there are no very energetic particles in jet, and as is in the Seyfert discussed above there is little or no cascading, or (ii) that the source is located closer to the central engine where pair production on say the BLR can absorb this radiation and cascading could be quite important.

Needless to say there is little theoretical agreement on the location of the γ -ray emission region. The luminosity coming out in γ -rays is large, comparable (even after possible beaming of the emission is taken into account) to the inferred kinetic luminosities of the radio jets. It is not obvious how this much energy is transported to the large distances considered by Mannheim and then released rapidly in a region significantly smaller, as deduced from time variability arguments, than the characteristic length scales at those distances. Radio “knots” presumably produced by particle acceleration in a shock are indeed observed at such distances from the central engine, but the luminosity of an individual knot is typically much less than the total radio power of the source and varies on much longer timescales than the γ -ray emission. Also, especially in the strong radio jets of powerful AGN like Cygnus A and 3C279, nothing catastrophic appears to be happening to the jet structure on these distance scales. This is not what one might have expected if the jet were to suddenly lose a significant fraction of its power there. Finally, when one maps out the jet emission after a strong radio flare using VLBI techniques, one often finds a bright, compact emission region propagating rapidly down the jet which originated much closer to the central black hole than the disturbances postulated by Mannheim. While there is no proof these blobs produce γ -rays and Mannheim’s scenario is not ruled out (especially if 100 GeV or TeV γ -rays are detected from EGRET sources), it seems quite possible the particle acceleration and γ -ray emission occur closer to the black hole.

Sikora, Begelman and Rees [23] and Takahara and Inoue (see their contribution in these proceedings for a more detailed discussion) consider an intermediate case where emission occurs at distances from the black hole $\sim R_{BLR}$. Cooling of the energetic electrons responsible for the emission is dominated by the Compton scattering of external (quasi-isotropic) BLR photons, and pair production on the BLR UV photons could be marginally important depending on the exact location of the emission region. An additional reason why cascading is not considered in these models is that the emission is typically inferred to come from electrons with initial Lorentz factors $\lesssim 10^4$, i.e., electrons not energetic to make γ -rays that can pair produce. (The upper cutoff of the initial electron energy distribution is obtained by estimating the jet magnetic field and measuring where the AGN UV/X-ray spectrum, assumed to be synchrotron emission from the γ -ray emitting electrons, turns over.)

Given the current state of observations, however, there appears to be no strong reason that singles out even this distance scale. Indeed, the location of the emission region might vary significantly from blazar to blazar. The possibility that it lies nearer to the black hole, as close as a few hundred R_g , has thus also been examined, e.g., see [6][15][2][5]. Note that the likely presence of unbeamed X-rays near the accretion disk (§I) means that at least some of the emission must be at distances $\gtrsim 100R_g$ or the 100 MeV/GeV emission would be completely absorbed. The various models all produce γ -rays by Compton upscattering of ambient accretion disk and BLR photons, and as before, the effects of cascading can be dominant or negligible depending on the energy distribution of the accelerated particles and where the particle acceleration is occurring, i.e., how many of the γ -rays produced by the particles are absorbed.

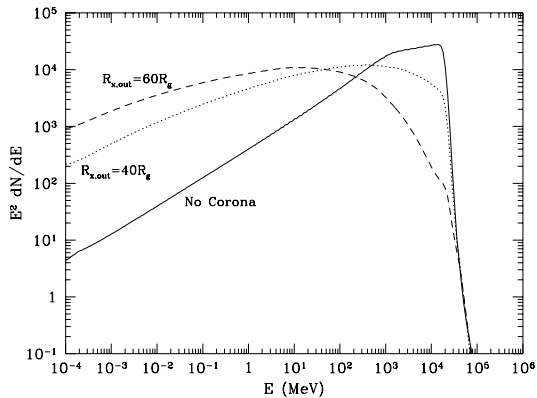


Fig. 3. Cascade spectra produced by protons with initial Lorentz factors $\gamma_p = 10^7$ decelerating in an AGN accretion disk radiation field. The protons start decelerating at a height $z_{init} = 35R_g$ above the disk, and the disk has an X-ray corona whose intensity falls off with height above the disk on a characteristic length scale $R_{x,out}$. Note the reprocessing of cascade radiation to lower energies as the size of the corona increases and protons lose their energy in a region which is increasingly opaque (compact) to γ -rays.

In Figures 3 and 4 we show calculations where the accelerated particles are assumed to be protons (which suffer much less radiation drag than electrons). The protons are accelerated to high energies near the base of the jet, and as they propagate outwards and cool, their energy is eventually transformed into cascade radiation. The shape of the final cascade spectrum is insensitive to the initial distribution of proton energies (as long as most protons have initial Lorentz factors $\gtrsim 10^5$) and is determined mainly by the ambient radiation field and where in this field the proton acceleration occurs. In contrast, the final spectrum in non-cascade models depends mainly on the initial accelerated particle energy distribution. Note that in all models, the accelerated particles are beamed so that their radiation is also beamed and does not interact catastrophically with itself. (This means that all the cascade models involve *linear* cascades.) Unfortunately there are enough free parameters that both the cascade and non-cascade models can be made to fit current observations. Only *simultaneous* observations (blazars are extremely variable) over a wide range of energies (radio to γ -ray) will be able to discriminate between the various possibilities. The need for and desirability of coordinated, broad band observations (not just of AGN) should be borne in mind by future Cherenkov experiments.

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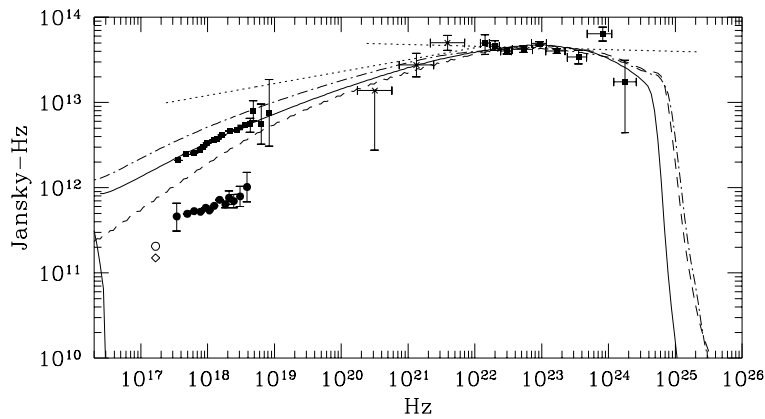


Fig. 4. Attempt to fit the broadband energy spectrum of 3C279 using cascade spectra of the type shown in Figure 3. Three models corresponding to different initial proton Lorentz factors γ_p , starting heights z_{init} , and x-ray corona sizes are shown. Note that the low energy (1-30 keV) GINGA data is not simultaneous with the EGRET γ -ray data.

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