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ON THE LOCATION OF THE ACCELERATION AND EMISSION SITES IN GAMMA-RAY BLAZARS

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ABSTRACT

Compton scattering of external radiation by nonthermal particles in outflowing blazar jets is dominated by accretion-disk photons rather than scattered radiation to distances $\sim$ 0.01–0.1 pc from the central engine for standard parameters, thus clarifying the limits of validity of the model by the present authors and the model of Sikora, Begelman, & Rees. On the basis of contemporaneous *Ginga* X-ray and EGRET gamma-ray observations, we estimate the radius of 3C 279's gamma-ray photosphere to be smaller than estimated by Blandford. There is thus no need to require that the acceleration and emission sites of gamma-ray blazars to be located farther than $\sim 10^2$–10^3 gravitational radii from the central engine. We argue that lineless BL Lac objects, rather than quasars, are more likely to be detected in the TeV energy range.

Subject headings: acceleration of particles — BL Lacertae objects: general — galaxies: jets — gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

Gamma-ray observations of blazars provide a new probe of particle energization by supermassive black holes. The Energetic Gamma Ray Experiment Telescope (EGRET) on the *Compton Observatory* has now detected and identified more than 23 extragalactic sources of $\sim$100 MeV–1 GeV emission (for reviews, see Fichtel et al. 1992; Dermer & Schlickeiser 1992). The EGRET sources display blazar properties, which include flat-spectrum radio emission associated with a compact core, apparent superluminal motion, rapid optical variability, and large optical polarization. Although the origin of the gamma-ray emission is a subject of considerable theoretical controversy, a consensus has developed that the gamma-ray emission is produced in association with the radio jets. Dermer, Schlickeiser, & Mastichiadis (1992) proposed that the high-energy emission is produced when energetic electrons in the outflowing radio jets Compton-scatter external radiation emitted by the accretion disk. Because of the angular distribution of the radiating electrons in the comoving fluid frame, soft photons entering directly from behind are preferentially scattered near the superluminal direction. Even when the photons enter from a large angle with respect to the jet axis, detection of sources displaying superluminal motion is favored (Dermer & Schlickeiser 1993, hereafter DS).

In another blazar model also invoking the Compton scattering of external photons, Sikora, Begelman, & Rees (1993, 1994) propose that UV photons scattered by diffuse gas or emission-line clouds surrounding the central engine provide a more important soft photon source than accretion disk photons because of the strong dependence of the scattered flux on the angle that the soft photons make with respect to the radio axis. Indeed, DS show that the scattered flux in the direction that the emission is most intense varies as Γ^2 for photons entering from behind, and as Γ^6 for photons entering from the side, where Γ is the bulk Lorentz factor of the outflowing jet. However, Sikora et al. do not justify their assumption that accretion disk photons are unimportant. Here we quantitatively characterize the regime where scattered photons are more important than accretion disk photons. We find that the scattered photons dominate rather far from central engine, namely $\gtrsim$0.01–0.1 pc for a $10^8\ M_\odot$ black hole surrounded by scattering clouds with a mean Thomson scattering depth $\tau_{\rm sc} \sim 0.01$. Thus one can neglect the accretion-disk photons only if one maintains that the acceleration and emission site is found many thousands to tens of thousands of gravitational radii from the supermassive black hole.

In a study complementary with the Sikora et al. model, Blandford (1993) argues that GeV gamma rays will be strongly attenuated by scattered photons unless they are emitted farther than $\sim$0.1 pc from the central engine. We also perform this estimate and show that photon attenuation is not a serious problem for 3C 279 unless $\tau_{\rm sc} \sim$ unity within $\sim$0.1 pc, which is extremely unlikely. TeV gamma rays could, however, be seriously attenuated by central-source photons scattered by gas surrounding the jet. If BL Lac objects (unlike quasars) lack emission-line clouds, as is commonly argued in view of the weak or absent emission lines in their spectra (e.g., Lawrence 1987), then TeV photons in these objects can escape unattenuated, and such objects should be preferred candidates for VHE gamma-ray monitoring. We note, however, that many BL Lac objects, including BL Lac itself, do have moderately strong emission lines, so this argument principally applies to the lineless BL Lac objects.

2. ELECTRON ENERGY-LOSS RATES IN OUTFLOWING PLASMA JETS

We can most simply determine the relative importance of radiation fields by calculating the energy-loss rate of energetic electrons in the comoving frame of the relativistically outflowing plasma. Here we provide a simplified derivation of the gyrophased-averaged electron energy-loss rates. For a more detailed treatment, see DS.

Let $m_ec^2u_{\rm ph}(\epsilon, \Omega)d\epsilon d\Omega$ represent the total energy density of photons with dimensionless energy $\epsilon = h\nu/m_ec^2$ between ϵ and $\epsilon + d\epsilon$ that are directed into solid angle element $d\Omega$ in the direction Ω. The quantity $u_{\rm ph}(\epsilon, \Omega)/\epsilon^3$ is invariant (Rybicki & Lightman 1979). We denote photon angles and energies in the stationary (accretion-disk) frame by asterisks. Quantities in the comoving fluid frame will be unstarred. The relevant Lorentz transformation equations are given by $\epsilon^* = \Gamma\epsilon(1 + \beta_\Gamma\mu)$ and $\mu^* = (\mu + \beta_\Gamma)/(1 + \beta_\Gamma\mu)$, where $\cos^{-1}\mu^*$ is the angle a photon makes with respect to the jet axis. Assuming azimuthal symmetry,

$$u_{\rm ph}(\epsilon, \mu) = \frac{\epsilon^3}{\epsilon^{*3}}\, u^*_{\rm ph}[\epsilon^*(\epsilon, \mu), \mu^*(\mu)]\,. \qquad (1)$$

If photons are isotropic in the stationary frame,

$$u^*_{\rm ph}(\epsilon^*, \mu^*) = \frac{u^*_i(\epsilon^*)}{2}\,. \qquad (2)$$

If photons enter directly from behind,

$$u^*_{\rm ph}(\epsilon^*, \mu^*) = u^*_b(\epsilon^*)\delta(\mu^* - 1)\,. \qquad (3)$$

The total energy density of soft photons in the comoving frame is given by

$$u_{\rm ph} = \int_{-1}^{1} d\mu \int_0^\infty d\epsilon\, \frac{u^*_{\rm ph}[\Gamma\epsilon(1 + \beta_\Gamma\mu), (\mu + \beta_\Gamma)/(1 + \beta_\Gamma\mu)]}{\Gamma^3(1 + \beta_\Gamma\mu)^3} \qquad (4)$$

Substituting equations (2) and (3) into equation (4) and performing the elementary integrals gives

$$u^i_{\rm ph} = u^*_{{\rm ph},i}\Gamma^2(1 + \beta_\Gamma^2/3)\,, \qquad (5)$$

$$u^b_{\rm ph} = \frac{u^*_{{\rm ph},b}}{\Gamma^2(1 + \beta_\Gamma)^2}\,, \qquad (6)$$

where $u^*_{{\rm ph},i}$ and $u^*_{{\rm ph},b}$ represent the total photon energy densities measured in the stationary frame for isotropic photons and photons entering from behind, respectively.

As is well known, the energy-loss rate of a relativistic electron with Lorentz factor γ in an isotropic radiation field with energy density $u_{\rm ph}$ is given in the Thomson limit by

$$-\dot{\gamma} = \tfrac{4}{3}c\sigma_{\rm T}u_{\rm ph}\gamma^2\,. \qquad (7)$$

We perform a gyrophase averaging of the electron energy-loss rate in the outflowing fluid frame. This is equivalent to calculating the energy-loss rate of an electron in an isotropic radiation field with energy density given by equations (5) or (6), assuming all scattering takes place in the Thomson regime. Thus the gyrophase-averaged electron energy-loss rate of an electron in a relativistically outflowing fluid immersed in a radiation field that is isotropic is the stationary frame is given by

$$-\dot{\gamma}_i = \tfrac{4}{3}c\sigma_{\rm T}u^*_{{\rm ph},i}\gamma^2\Gamma^2(1 + \beta_\Gamma^2/3)\,. \qquad (8)$$

If the photons impinge on the outflowing fluid directly from behind, the gyrophase-averaged loss rate is given by

$$-\dot{\gamma}_b = \frac{4}{3}\,c\sigma_{\rm T}u^*_{{\rm ph},b}\,\frac{\gamma^2}{\Gamma^2(1 + \beta_\Gamma)^2}\,. \qquad (9)$$

These results were originally derived by DS.

Letting $L_{\rm ad}$ represent the total luminosity emitted by the accretion disk, we can write

$$u^*_{{\rm ph},i} \cong \frac{L_{\rm ad}\tau_{\rm sc}}{4\pi R_{\rm sc}^2 cm_ec^2}\,, \qquad (10)$$

where $\tau_{\rm sc}$ is the mean scattering depth of the electron scattering cloud, assumed to be spherically symmetric about the central source, and $R_{\rm sc}$ is the radial extent of the scattering cloud. If we make the assumption that the central source is sufficiently compact that directly produced photons impinge on the outflowing plasma jets almost directly from behind, then

$$u^*_{{\rm ph},b} \cong \frac{L_{\rm ad}}{4\pi z^2 cm_ec^2}\,, \qquad (11)$$

where z is the distance of the plasma blob along the jet axis from the central source.

A direct comparison of the resulting energy-loss rates shows that, in the limit $\beta_\Gamma \rightarrow 1$, $|\dot{\gamma}_i/\dot{\gamma}_b| > 1$ implies

$$z\,({\rm pc}) \gtrsim 0.043\,\frac{R_{\rm sc}\,({\rm pc})}{\Gamma_{10}^2\tau_{-2}^{1/2}}\,, \qquad (12)$$

where $\Gamma = 10\Gamma_{10}$ and the scattering depth $\tau_{\rm sc} = 0.01\tau_{-2}$. In this point source approximation for the accretion-disk radiation, we see that scattered radiation dominates at $z \lesssim 0.01$–0.1 pc only when $\tau_{\rm sc} \gg 0.01$, $R_{\rm sc} \ll 1$ pc, or $\Gamma \gg 10$.

The previous estimate does not, however, take into account the physical extent of the disk. Due to the strong angle-dependence of the scattered flux on the angle that the soft photons make with respect to the axis of the jet, photons produced far out in the disk that enter the jet from the side can make a more important contribution to the loss rate than the luminous emission emitted from the innermost regions of the supermassive black hole. DS have derived the gyrophase-averaged electron energy-loss rate when the external photon source is a cool outer blackbody. Here we give an illustrative derivation of this result.

Photons which impinge at large angles with respect to the jet axis, namely, those produced at accretion-disk radii $R \cong z$, dominate the electron energy-loss rate in the comoving fluid frame. The energy density of these photons in the accretion-disk frame can be approximated by

$$u^*_{\rm ph,ad} \approx \frac{L\,(R \cong z)}{4\pi(z^2 + R^2)cm_ec^2}\,. \qquad (13)$$

The luminosity emitted within a decade of radii about R is approximately given by

$$L(R \cong z) \cong L_{\rm ad}\left(\frac{R_g}{z}\right), \qquad (14)$$

where $L_{\rm ad}$ is the total luminosity radiated by the accretion disk, and $R_g \equiv GM/c^2 = 1.48 \times 10^{13}\, M_8$ cm is the gravitational radius of a black hole of mass $10^8\, M_8$ solar masses.

Photons produced at $R \cong z$ can be treated as an isotropic photon source, since in either case the photons enter the relativistic moving blob at large angles. Replacing $u^*_{{\rm ph},i}$ with $u^*_{\rm ph,ad}$ in equation (8) gives, in the limit $\beta_\Gamma \rightarrow 1$,

$$-\dot{\gamma}_{\rm ad} \approx 8.6 \times 10^{-7}\, \frac{L_{\rm tot}\,({\rm ergs\ s^{-1}})M_8}{z^3\,({\rm cm})}\, \gamma^2\Gamma^2\,. \qquad (15)$$

This agrees favorably with the result derived in detail by DS (from eqns. [4.2], [4.3], [5.4] and [5.7]), namely

$$-\dot{\gamma}_{\rm ad} \cong 7.4 \times 10^{-8}\, \frac{L_{\rm tot}\,({\rm ergs\ s^{-1}})M_8}{\epsilon_f z^3\,({\rm cm})}\, \gamma^2\Gamma^2\,. \qquad (16)$$

In equation (16), the radiation efficiency $\epsilon_f = 0.057$–0.25 for a Schwarzschild black hole, depending on the assumed value of the angular momentum deposited at the inner edge of the accretion disk.

A direct comparison of equations (8) and (15) shows that the electron energy-loss rate from scattered photons with energy density described by equation (10) dominates the loss rate from accretion disk photons only at distances

$$z\,({\rm pc}) \gtrsim 0.06\, \frac{M_8^{1/3} R_{\rm sc}^{2/3}\,({\rm pc})}{\tau_{-2}^{1/3}}\,. \qquad (17)$$

Note that equation (17) is independent of Γ.

Sikora et al. (1993, 1994) deduce that the emission site in their model is located between ≈ 0.01 and 0.1 pc from the central source. The minimum distances at which the accretion-disk radiation can be neglected is the larger of equation (12), representing losses from the luminous emission made close to the central source, and equation (17), representing losses from the lower luminosity radiation emitted by the outlying portions of the disk. This assumption can be justified if there are dense scattering clouds ($\tau_{-2} \gg 1$) much closer than 1 pc from the central source. *Ginga* observations (e.g., Turner et al. 1989) of quasars, however, do not support the existence of clouds with $N_{\rm H} \gg 10^{22}$ cm^{-2} in the line of sight, and observations of 3C 279 (Makino et al. 1989) imply values of $N_{\rm H} < 4 \times 10^{21}$ cm^{-2} in 1987 June and 1988 July. *Ginga* X-ray observations made during the Viewing Period 3 gamma-ray flare of 3C 279 are consistent with galactic absorption, i.e., $N_{\rm H} < 10^{21}$ cm^{-2} (Makino 1993). The acceleration and emission site in the model of DS is located between $\sim 10^{-3}$ and 10^{-2} pc from the black hole, so the neglect of the scattered radiation is justified.

3. PHOTON ATTENUATION FROM SCATTERED RADIATION

Blandford (1993) has recently argued that GeV radiation produced within $\sim 10^{17}$ cm of the central engine will be pair attenuated in collisions with scattered central-source emission when $\tau_{-2} \sim 1$ within ~ 0.1 pc. If the photon spectral index $\alpha > 1$ for the soft photons, higher energy gamma rays are even more strongly attenuated. The absence of any clear pair attenuation cutoff in the spectra of gamma-ray blazars (Fichtel et al. 1993) would therefore imply that the GeV emission is made at rather large distances ($\gtrsim 0.1$ pc) from the galactic nucleus. A further consequence would be that the variability time scale increases with increasing gamma-ray energy. We reconsider this estimate and show, on the basis of contemporaneous *Ginga* observations, that the 1 GeV pair attenuation depth $\tau_{\gamma\text{-}\gamma} \ll 1$ for likely parameters of 3C 279.

The photon-photon pair attenuation optical depth between heights z_i and z for a photon with dimensionless energy $\epsilon_1 \equiv h\nu_1/m_e c^2$ is given by

$$\tau_{\gamma\text{-}\gamma}(\epsilon_1) = \frac{1}{2}\int_{z_i}^{z} dz' \int_{-1}^{1} d\mu(1-\mu) \times \int_{[2/\epsilon_1(1-\mu)]}^{\infty} d\epsilon\,\sigma_{\gamma\text{-}\gamma}(\epsilon_1, \epsilon, \mu)\, n_{\rm ph}(\epsilon, \mu; z') \qquad (18)$$

(e.g., Gould & Schréder 1967; for corrections, see Brown, Mikaelian, & Gould 1973), where z_i is the height at which a photon is ejected radially outward and $n_{\rm ph}(\epsilon, \mu; z')$ is the angle- and energy-dependent photon density at height z' above the central engine.

If the scattering gas is assumed to be spherically distributed about the central nucleus (note that a flattened disk distribution of scattering clouds would be less effective at attenuating the radiation because the threshold would be harder to satisfy), then we can roughly describe the scattered UV and X-ray radiation by an isotropic radiation field. Equation (18) can be approximated by

$$\tau_{\gamma\text{-}\gamma}(\epsilon_1) \cong \int_{z_i}^{z} dz' \int_{2/\epsilon_1}^{\infty} d\epsilon\,\sigma_{\gamma\text{-}\gamma}(\epsilon_1, \epsilon)\, n_{\rm ph}(\epsilon; z')\,. \qquad (19)$$

We use the convenient approximation

$$\sigma_{\gamma\text{-}\gamma}(\epsilon_1, \epsilon) \cong \frac{1}{3}\,\sigma_{\rm T}\,\epsilon\,\delta\!\left(\epsilon - \frac{2}{\epsilon_1}\right) \qquad (20)$$

for the pair-attenuation cross section (Zdziarski & Lightman 1985), after correcting the misleading notation.

Assume that the central source produces total radiant luminosity $L = 10^{46} L_{46}$ ergs s^{-1} and spectral luminosity $L(\epsilon) = L_0 \epsilon^{1-\alpha}$ in the 1–10 keV band. This energy band is most effective at attenuating ≈ 100 MeV–1 GeV gamma rays. If $\alpha = 1.7$, it is easy to show that

$$n_{\rm ph}(\epsilon; z') \approx \frac{L(\epsilon)\tau_{\rm sc}(z')}{4\pi z'^2 c\epsilon m_e c^2} \cong 6.5 \times 10^{38}\, \tau_{-2}(z')\, \frac{L_{46}\epsilon^{-1.7}}{z'^2} \qquad (21)$$

(compare eq. [10]). Defining $E_{\rm GeV} \cong \epsilon_1/2000$ and substituting equations (20) and (21) into equation (19), we obtain

$$\tau_{\gamma\text{-}\gamma}(E_{\rm GeV}; z) \cong 1.8 \times 10^{18}\, E_{\rm GeV}^{0.7} L_{46} \int_{z_i}^{z} dz'\, \frac{\tau(z')}{z'^2}\,. \qquad (22)$$

The central source emission is scattered by electrons with scattering optical depth $\tau(z') \ll 1$ according to the relation

$$\tau(z) = \sigma_{\rm T} \int_0^z dz' n_e(z') \,, \tag{23}$$

where $n_e(z')$ denotes the radial density distribution of electrons. If we assume that $n_e(z') = n_e^0$, a constant, and let $n_e^0 \sigma_{\rm T} z = 0.01\tau_{-2}$ at $z = 0.1$ pc, equation (22) implies

$$\tau_{\gamma\text{-}\gamma}(E_{\rm GeV}; z) \cong 0.06 E_{\rm GeV}^{0.7} L_{46} \tau_{-2} \ln\left(\frac{z}{z_i}\right) . \tag{24}$$

For these parameters, pair attenuation is not significant for GeV photons.

If we make the unphysical assumption that $\tau(z) = 0.01\tau_{-2}$, independent of z, then we find that $\tau_{\gamma\text{-}\gamma} = 1$ at

$$z_i\,({\rm pc}) \lesssim 0.006 E_{\rm GeV}^{0.7} L_{46} \tau_{-2} \,. \tag{25}$$

This still shows that pair attenuation is considerably less important than estimated by Blandford.

The difference between our result and Blandford's estimate for 3C 279 stems partly from his approximation for $\tau(z)$ and primarily from his assumption for the soft photon luminosity. He assumes a 1–10 keV luminosity $\approx 2 \times 10^{47}$ ergs s^{-1}, which approximately matches the *Ginga* observations in the high state (Makino et al. 1989). The rapid variability of the X-rays and the failure to detect a UV bump imply, however, that the X-rays are probably beamed emission from the jet, so that the level of isotropic emission must be considerably smaller. Contemporaneous *Ginga* observations (Makino et al. 1993) reportedly show that the 2–10 keV X-ray energy flux measured early in the gamma-ray flare (1991 June 17–18) is 1.68×10^{-11} ergs cm^{-2} s^{-1}, implying a 2–10 keV luminosity $\sim 10^{46}$ ergs s^{-1} ($H_0 = 75$ km s^{-1} Mpc^{-1}). Combined with the evidence for the lack of significant X-ray absorption in the line of sight, we see that the location of the gamma-ray emission site during this time interval is apparently limited primarily by pair attenuation with accretion-disk photons rather than scattered photons. A stronger conclusion regarding the location of the gamma-ray emission sites will require additional contemporaneous X-ray and gamma-ray observations.

4. DISCUSSION

There is no compelling evidence that the 100 MeV–1 GeV gamma rays from blazars are made farther than $\approx 10^2$–$10^3 R_g$ from the central engine. This considerably reduces demands on models of particle acceleration in gamma-ray blazars; for example, the gamma-ray flaring of 3C 279 by a factor of 400% in a two-day period (Kniffen et al. 1993) would be more difficult to explain (even with beaming) if the emission site were located ≈ 1 light-month from the black hole.

The Compton-scattering energy-loss rate of relativistic electrons in outflowing plasma blobs is dominated by accretion-disk photons rather than scattered photons at distances $\lesssim$ 0.01–0.1 pc from the central source, and even farther if the source lacks scattering clouds. This eliminates any need to invoke separate source models for quasars and BL Lac objects on the basis of the standard AGN scenario which views BL Lac objects as weak quasars which lack emission-line clouds; of course, the true situation is undoubtedly more complicated, with a gradation of scattering-cloud column densities.

Our estimate (24) for the pair attenuation depth implies that TeV photons will nonetheless be strongly attenuated ($\tau_{\gamma\text{-}\gamma} \approx 10$) by scattered radiation for the stated parameters. Indeed, no quasars have been detected with the Whipple observatory (Fennell et al. 1993), but a BL Lac object, Mrk 421, has been detected (Punch et al. 1992). This is in accord with the AGN unification scenario if accretion-disk photons instead of scattered photons are the primary source of radiation which is Compton-scattered by the jet. An important implication follows: in order to avoid attenuation by intergalactic radiation fields, the most likely sources of extragalactic TeV radiation are nearby (redshift $z \lesssim 0.1$–0.2) sources (Stecker, de Jager, & Salamon 1992). But they are less likely to be detected from nearby quasars (such as 3C 273) or FR II radio galaxies because of the presence of emission-line clouds. Rather, TeV gamma rays are more likely to be seen from nearby lineless BL Lac objects.

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