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Letter to the Editor

High-energy gamma radiation from extragalactic radio sources

C.D. Dermer[1], **R. Schlickeiser**[2], **and A. Mastichiadis**[3]

[1] Department of Space Physics and Astronomy, Rice University, Houston, TX 77251, USA
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D/W-5300 Bonn 1, Germany
[3] Max-Planck-Institut für Kernphysik, Postfach 103980, D/W-6900 Heidelberg, Germany

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Abstract. We propose that the important relationship between 3C 273 and 3C 279, the first two extragalactic sources detected at > 100 MeV energies, is their superluminal nature. In support of this conjecture, we propose a kinematic focusing mechanism, based on Compton scattering of accretion-disk photons by relativistic nonthermal electrons in the jet, that preferentially emits gamma rays in the superluminal direction.

Key words: gamma rays - extragalactic radio sources - inverse Compton scattering - 3C273 - 3C279

1. Introduction

Observations with the telescopes on the Compton Gamma Ray Observatory (GRO), launched on April 5th, 1991, have resulted in the discovery of the optically violent variable quasar 3C279 (z=0.538) as a strong high-energy gamma ray source (Hartman et al.1992). It must have increased in gamma ray intensity at least by a factor of 8 since 1982, since it was not seen by COS-B. This increase has also been seen at radio and X-ray wavelengths (Makino et al.1989, 1991). Furthermore, the new observations with the EGRET detector on GRO show that 3C273 has diminished in intensity considerably. 3C273 is known to be strongly variable at radio frequencies (Aller et al.1985). In the galactic anticenter a possible new variable gamma ray source is apparent in the EGRET data (Kanbach et al. 1992). It could be associated with the quasar 0528+134, whose flat radio spectrum is known to vary between 1 and 5 Jy (Aller et al.1985). 0528+134 is also a prominent VLBI source (Charlot 1990).

Although the incoming GRO data are still preliminary, it seems significant that all three powerful extragalactic gamma ray sources (3C279, 3C273, 0528+134) are variable flat spectrum radio sources and compact VLBI sources and two (3C279, 3C273) are classical superluminal radio sources (Whitney et al.1971, Unwin et al.1989). So far no BL-Lac object has emerged as a strong gamma ray source, albeit simple Doppler-boosting models of relativistically beamed emission blobs would favour them as prominent gamma ray sources. Here we propose a gamma ray radiation mechanism, based on inverse Compton scattering of accretion disk photons by relativistic nonthermal electrons in the jet, that preferentially emits gamma rays in the superluminal direction.

2. Anisotropic inverse Compton scattering model in relativistically beamed emission blobs

In the relativistic jet model of Blandford and Rees (1978), blobs of magnetized plasma with bulk velocity Bc and Lorentz factor $\Gamma = (1 - B^2)^{-1/2}$ erupt from the central nucleus at nearly right angles to the plane of the accretion disk. Relativistic electrons with a quasi-isotropic distribution *in the rest frame of the blob (BF)* produce incoherent synchrotron radiation which, because of the blob's motion, is focused into a cone with half-angle $\simeq \Gamma^{-1}$ about the jet axis *in the observer's frame (OF)*. The maximum apparent transverse velocity $\beta_{app}^{max} c = B\Gamma c$ is observed when the angle θ_s^* between the blob's velocity vector and the direction to the observer is given by $\theta_s^* \equiv \cos^{-1} \mu_s^* = \cos^{-1} B$ (see Fig. 1). The possible existence of sources showing apparent transverse velocities exceeding c was predicted by Rees (1966). The first-discovered and brightest known SLs, 3C 279 and 3C 273, respectively, each have exhibited SL components with $\beta_{app} > 8$ (Porcas 1987).

We depart from this standard model for jets from AGN (Blandford and Königl 1979; Marscher 1980) only by assuming that the relativistic radio-emitting electrons are homogeneously distributed throughout the blob, and that the randomly-oriented magnetic field has uniform strength everywhere in the blob. This simplification does not affect the central result, and can be relaxed in more detailed treatments. We also assume that

(1) the energetic electrons have an isotropic energy distribution in the BF;

(2) the accretion-disk source and the core of the AGN emit target photons isotropically with spectrum $\dot{N}_{ph}(\epsilon^*)$ [photons s^{-1} ϵ^{*-1}] in the OF, where $\epsilon^* \equiv h\nu^*/m_e c^2$ is the dimensionless photon energy (asterisks refer to quantities measured in the OF). These photons illuminate the outflowing blob from behind;

Send offprint requests to: R.Schlickeiser

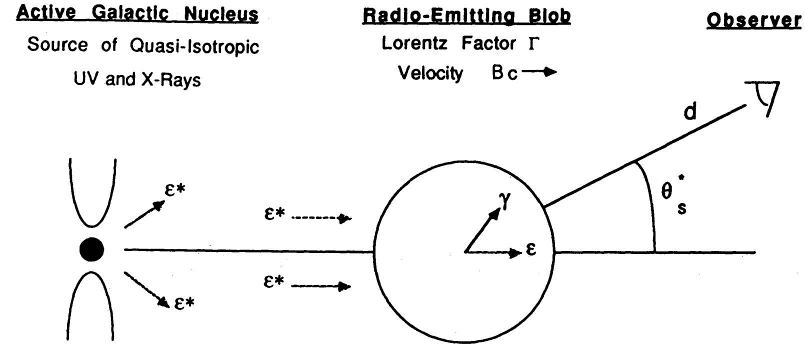

Fig. 1. Cartoon illustrating the proposed model for high-energy radiation from extragalactic radio sources. A plasma blob moving with speed Bc focuses its radio emission into a forward cone in the observer's frame. Relativistic electrons in the blob also scatter radiation from the central source. The most energetic of these photons are scattered preferentially in the direction $\cos\theta^*_s = 2 - B^{-1} \simeq B$.

(3) photons passing through the blob follow trajectories parallel to the jet axis. This last is true if the blob is sufficiently far from from the central source.
(4) the blob is optically thin to Thomson scattering along the jet axis, which is necessary to produce highly polarized radio emission (Blandford and Rees 1978).

Neglecting redshift corrections, the flux of target photons from the central source seen by the observer is given by

$$\Phi(\epsilon^*) \cong \frac{\dot{N}_{ph}(\epsilon^*)}{4\pi d^2}, \tag{1}$$

where d is the distance between the observer and the AGN. In the BF, photons have energy $\epsilon = \Gamma(1-B)\epsilon^* < \epsilon^*$, due to the Doppler effect. From the invariance (Rybicki and Lightman 1979, Ch.4) of $n_{ph}(\epsilon,\Omega)/\epsilon^2$, we find that the differential photon density in the BF is given by

$$n_{ph}(\epsilon,\Omega) = \frac{d^2}{2\pi r^2 c}\,\Phi[(1+B)\Gamma\epsilon]\;\delta(\mu-1), \tag{2}$$

where r is the distance of the blob from the central source and μ is the direction cosine of the photons in the BF. We describe the electron distribution in the BF by the function $n_e(\gamma,\Omega)$ [electrons cm^{-3} γ^{-1} sr^{-1}], where γ is the electron Lorentz factor. For the isotropic case, $n_e(\gamma,\Omega) = n_e(\gamma)/4\pi$.

The angle-dependent scattered photon number spectrum in the BF is given by (Reynolds 1982, Dermer 1990)

$$\dot{n}_{ph}(\epsilon_s,\Omega_s) = c\int_0^\infty d\epsilon\ \oint d\Omega \int_1^\infty d\gamma\ \oint d\Omega_e\,(1-\beta\cos\psi)$$

$$n_{ph}(\epsilon,\Omega)\;n_e(\gamma,\Omega_e)\;\frac{d^2\sigma}{d\epsilon_s d\Omega_s}\;ph\;cm^{-3}s^{-1}ster^{-1}\epsilon^{-1} \tag{3}$$

where the subscript s refers to scattered quantities, $\cos\psi \rightarrow \mu_e$ when $\mu = 1$, and $d^2\sigma/d\epsilon_s d\Omega_s$ is the differential scattering cross section.

The electrons that produce the nonthermal radio emission are highly relativistic, so that $\gamma \gg 1$. If the accretion-disk photons are in the UV to X-ray range, $\epsilon^* \sim 10^{-4} - 10^{-1}$, and thus $\epsilon \ll 1$. We treat the Thomson limit of Compton scattering, where $\gamma\epsilon(1-\beta\mu_e) \ll 1$. The average energy ϵ_s of scattered photons in the BF is $\approx \gamma^2\epsilon(1-\beta\mu_e)$, and these photons are beamed into a cone with half-angle angle $\theta_s \approx \gamma^{-1} \ll 1$ about the original direction of the electron's motion. We therefore approximate the differential Compton cross section by

$$\frac{d^2\sigma}{d\epsilon_s d\Omega_s} \cong \frac{\sigma_T}{2\pi}\,\delta[\epsilon_s - \gamma^2\epsilon(1-\beta\mu_e)]\;\delta(\mu_s-\mu_e). \tag{4}$$

Substituting equations (4) and (2) into equation (3), and transforming back to the OF using the invariance of $\dot{n}_{ph}(\epsilon_s,\mu_s)/\epsilon_s$, we find that

$$\dot{n}_{ph}(\epsilon^*_s,\mu^*_s) = \frac{\sigma_T\;d^2 D^2}{2\;r^2}\int_1^\infty d\gamma\;\gamma^{-2}\;n_e(\gamma)\;\Phi\{\frac{\epsilon^*_s}{\eta\gamma^2}\} \tag{5},$$

giving the photon emissivity per unit emission time. We have introduced the abbreviation

$$\eta \equiv \frac{1+\beta B - \mu^*_s(\beta+B)}{(1+B)\Gamma^2(1-B\mu^*_s)^2} \simeq D^2(1-\mu^*_s) \tag{6},$$

where the latter approximation holds for relativistic electrons, $\beta \simeq 1$, and D denotes the familiar Doppler factor

$$D = [\Gamma(1-B\mu^*_s)]^{-1} \tag{7}.$$

To determine the observed energy flux S^{rec}_s per unit reception time (Zdziarski et al.1991), we multiply Eq.(5) by ϵ^*_s and note that the two time intervals are related through $t_{rec} = t_{em}(1-B\mu^*_s)$. For a blob with volume $V^*_b = V_b/\Gamma$, $S^{rec}_s(\epsilon^*_s,\mu^*_s) = V_b\epsilon^*_s\dot{n}_{ph}(\epsilon^*_s,\mu^*_s)/2\pi d^2\Gamma(1-B\mu^*_s)$. Thus the observable flux density of inverse Compton scattered photons in terms of the number flux of target photons observed directly from the central source, is given by

$$S^{rec}_s(\epsilon^*_s,\mu^*_s) = \frac{V_b\;\sigma_T\epsilon^*_s D^2}{4\pi r^2}$$

$$\int_1^\infty d\gamma\;\gamma^{-2}\;n_e(\gamma)\;\Phi\{\frac{\epsilon^*_s}{\eta\gamma^2}\}\;cm^{-2}s^{-1} \tag{8}.$$

2.1. Discussion of the inverse Compton flux (8)

Let us first consider the δ-function properties of equation (8), i.e. we adopt

$$n_e(\gamma) = n^o_e\delta(\gamma-\bar{\gamma}) \tag{9a}$$

and

$$\Phi(\epsilon^*) = \Phi_o\delta(\epsilon^*-\bar{\epsilon}^*) \tag{9b}.$$

The energy of a scattered photon emitted into a given direction is related to the original photon energy $\bar{\epsilon}^*$ through the expression

$$\frac{\epsilon^*_s}{\bar{\epsilon}^*} = \eta\bar{\gamma}^2 \tag{10}.$$

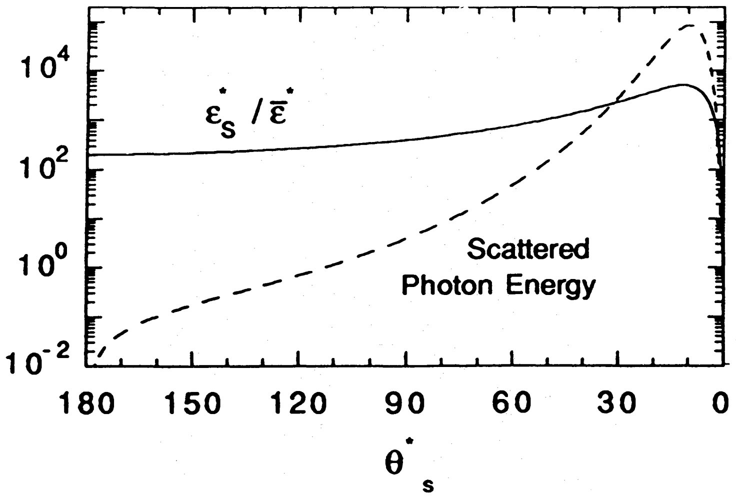

Fig. 2. Angle-dependences of the ratio of the photon energy before and after scattering as measured by an observer (solid curve), and of the relative amount of energy in scattered photons per unit reception time $F_1(\mu^*_s)$ (dashed curve). In this calculation, the blob's Lorentz factor $\Gamma = 5$ and the electrons' Lorentz factor $\gamma = 100$. The most energetic photons are scattered in the direction $\theta^*_s \cong \cos^{-1}(2 - B^{-1}) = 11.7^o$, and the largest fraction of photon energy is scattered in the direction $\theta^*_{s,E} \simeq \cos^{-1}[(3B-1)/2B] = 8.2^o$. The maximum apparent superluminal velocity is observed at the angle $\cos^{-1} B = 11.5^o$. For a power law energy dependence $n_e(\gamma) \propto \gamma^{-3}$ of the differential relativistic electron density in the blob the dashed curve F_1 is directly proportional to the angular dependence $F_2(s = 3, \mu^*_s)$ (see Eq.15) of the inverse Compton scattered energy flux in gamma rays; for $\Gamma = 5$ we have $F_2(s = 3, \mu^*_s) = 1.63 \cdot 10^{-5} F_1(\mu^*_s)$. If $\Gamma = 10$, the most energetic photons are scattered at the superluminal angle 5.7^o, with the bulk of the energy scattered in the direction $\theta^*_{s,E} \simeq 4.1^o$.

Equation (10) can also be obtained by making a series of transformations of a photon's energy and angle from the OF to the BF and then to the electron rest frame, and then retracing the steps after scattering. Figure 2 shows values of the ratio (10) for a blob moving with $\Gamma = 5$, and for isotropically-distributed electrons with $\bar{\gamma} = 100$ in the BF. As can be seen, the scattered photon energy is increased relative to the original photon energy at all angles except in the extreme forward direction, where $\mu^*_s \cong 1$ and $\epsilon^*_s/\bar{\epsilon}^* \cong 1/2$. The weak forward scattering is a consequence of the factor $(1 - \beta\mu_e)$, which reduces both the scattering rate (Eq. 3) and the photon energy (Eq. 4) in the electron's rest frame. The energy increase is greatest at shallow angles with respect to the forward direction. The angle $\mu^*_{s,max}$ of the peak scattered energy is

$$\mu^*_{s,max} = \frac{B + 2\beta B^2 - \beta}{B(\beta + B)} \simeq 2 - \frac{1}{B} \rightarrow \mu^*_{SL} - \frac{1}{4\Gamma^4} + O(\Gamma^{-6}) (11).$$

If $\bar{\gamma} \gg \Gamma$, then $\beta \approx 1$ and $\mu^*_{s,max} \rightarrow 2 - B^{-1}$. If the blob is also moving at relativistic speeds such that $\Gamma \gg 1$, which indeed is required for SL effects, then $B \simeq 1 - (2\Gamma^2)^{-1}$, and $\mu^*_{s,max} \simeq B = \mu^*_{SL}$. *This is equal to the observer's direction at which the apparent SL velocity is greatest.* The maximum value of the scattered photon energy is given, from equations (10) and (11), by $(\epsilon^*_s/\bar{\epsilon}^*)_{max} = \bar{\gamma}^2(\beta+B)^2/4\beta B(1+B) \rightarrow \bar{\gamma}^2/2$, where the limiting expression holds when $\bar{\gamma} \gg \Gamma \gg 1$.

We can also determine the directional dependence of the total energy in scattered photons from monoenergetic relativistic electrons and target photons by evaluating the quantity $\int_0^\infty d\epsilon^*_s S^{rec}_s(\epsilon^*_s, \mu^*_s)$. The principal angular dependence of this quantity, given by

$$F_1(\mu^*_s) = [1 + \beta B - \mu^*_s(\beta + B)]^2/(1 - B\mu^*_s)^6$$

$$\simeq (1 + B)^2 \Gamma^6 D^6 (1 - \mu^*_s)^2 \qquad (12),$$

is also plotted in Fig. 2. In the limit $\bar{\gamma} \gg \Gamma$, the greatest amount of energy in scattered photons per interval of μ^*_s is produced in the direction

$$\mu^*_{s,E} \simeq (3B - 1)/2B \rightarrow \mu^*_{SL} + \frac{1}{4\Gamma^2} - \frac{1}{16\Gamma^4} + O(\Gamma^{-6}) \qquad (13),$$

which is close to the superluminal direction μ^*_{SL}.

Our results show that SL radio sources should scatter the most energetic photons in this direction, with the largest fraction of photon energy scattered at a slightly shallower angle. However, the amount and energy of photon emission scattered directly forward is weak. Thus SL radio sources should be strong γ-ray emitters, but if observations are made directly down the symmetry axis of the jet, we should see very little X-ray and γ-ray emission. According to the unified AGN scenario (e.g. Blandford and Königl 1979, Scheuer and Readhead 1979, Barthel 1989), BL Lac objects are sources where we happen to be looking very nearly directly down the jet axis. Thus we conclude that for this radiation mechanism SL radio sources should be strong γ-ray sources, and BL Lac objects should be weak γ-ray sources.

2.2. Influence of a power law energy distribution functions for relativistic electrons

Although the mono-energetic distribution of relativistic electrons and target photons provides clear insight into the kinematic focusing mechanism of our anisotropic inverse Compton model, these distribution functions are not very realistic when modelling the broadband emission from extragalactic radio sources. The gamma ray observations of 3C279 have revealed a power law behaviour $S \propto (\epsilon^*_s)^{-1.0 \pm 0.1}$ (Hartman et al.1991) of the gamma ray energy flux over the full EGRET energy range, while the anisotropic Compton model with mono-energetic electrons and target photons would yield a mono-energetic inverse Compton scattered photon spectrum at each viewing angle. We therefore consider the effects of a power-law energy distribution of the radiating electrons, given by $n_e(\gamma) = n_o \gamma^{-s}$ for $1 << \gamma_1 \leq \gamma \leq \gamma_2$, and zero otherwise, on the angular distribution of the Compton-scattered photons. The EGRET spectral measurements suggest that the value of $s \simeq 3.0$. Since earlier studies of the inverse Compton process (e.g. Schlickeiser 1979) have revealed only a slight dependence of the Compton scattered photon flux on the actual target photon distribution function we adopt the monoenergetic distribution (9b) for ease of exposition. We then obtain from Eq.(8) that

$$S^{rec}_s(\epsilon^*_s, \mu^*_s) = \frac{V_b \, \sigma_T \, \Phi_o \, n_o}{8\pi r^2} D^2 \, \eta^{(s+1)/2} \, (\epsilon^*_s/\bar{\epsilon}^*)^{(1-s)/2} \qquad (14)$$

for gamma ray energies between $\eta\bar{\epsilon}^*\gamma_1^2$ and $\eta\bar{\epsilon}^*\gamma_2^2$ and zero otherwise. At all angles we obtain the same power law dependence of the inverse Compton flux (14) on the gamma ray energy ϵ_s^* within the two limiting energies provided by the low- and high-energy cutoffs in the assumed relativistic electron energy distribution. The principal angular dependence of the inverse Compton gamma ray flux (14)

$$F_2(s,\mu_s^*) = D^{3+s}(1-\mu_s^*)^{(s+1)/2} \tag{15}$$

attains its maximum in the direction

$$\mu_{s,F}^* = 2\frac{s+3}{s+5} - \frac{s+1}{s+5}\frac{1}{B} \rightarrow \mu_{SL}^* + \frac{[\frac{2}{\Gamma^2} - \frac{s-1}{4\Gamma^4} + O(\Gamma^{-6})]}{(s+5)} \quad (16),$$

which is very close to the SL direction for relativistic flows ($\Gamma >> 1$). Notice that for $s = 3$ the function F_2 is directly proportional to the function F_1 given in Eq.(12), $F_2(s=3,\mu_s^*) = F_1(\mu_s^*)/[(1+B)^2\Gamma^6]$. Therefore the dashed curve in Fig.2 also shows the angular dependence of the inverse Compton gamma-ray energy flux (14) for $s = 3$. From this variation we emphasize again the strong directional dependence of the emitted inverse Compton scattered gamma rays. The greatest amount of energy in scattered photons is produced in the direction (16) which for all realistic values of the power law spectral index s is close to the SL direction. On the other hand, no gamma rays are produced by this process into the forward direction. Again we note that for this radiation mechanism SL radio sources should be strong gamma ray sources in contrast to BL Lac objects, which should be much weaker. In reality, the directional-dependence of the scattered photons will not be as strongly peaked as derived here, because of the jet's finite opening angle, and the possible presence of photons impinging from the side of the jet. Nevertheless, a hollow cone emission geometry is still obtained in more realistic models, and constitutes perhaps the most interesting property of this anisotropic inverse Compton scattering model.

The importance of this process also depends on whether synchrotron and synchrotron-self-Compton losses dominate the total energy-loss rate of the nonthermal electrons in the jet. We therefore require that the energy density of the central source photons be greater than the magnetic field energy density at the emission site. Assuming that the soft photons are emitted isotropically from the central source, we find that for anisotropic inverse Compton scattering to be important, the distance r of the blob from the central source must be $\leq 1.3 L_{46}^{1/2}\Gamma^{-1}H_{0.1}^{-1}$ pc, where the soft photon luminosity is given by $10^{46} L_{46}$ erg s^{-1} and $H_{0.1}$ is the magnetic field strength at the emission site in units of 0.1 G. Thus this process is important if the outflowing radio-emitting relativistic electrons are sufficiently near the central source, or if there are knots of high magnetic field in the jet near which electrons are accelerated and emit radio emission, surrounded by regions of low magnetic field into which the relativistic electrons diffuse and Compton-scatter the soft photons. Both possibilities are currently being studied by the authors.

3. Summary

We have proposed a model in which the relativistic electrons in an outflowing blob Comptonize photons from a central source. This model avoids γ-γ pair attenuation of > 100 MeV photons from a compact highly variable source such as 3C 273 (e.g. Bassani and Dean 1981) by upscattering UV and X-ray photons far from the compact nucleus. Correlated multiwavelength variability could be associated with either the central photon source or the outflowing blob: each implies different relationships. The model predicts that superluminal radio sources are strong gamma ray sources whereas BL-Lac objects should be much weaker. The gamma ray intensity should be positively correlated with the existence and velocity of superluminal blobs, and the proximity of these blobs to the compact core. Correlated VLBI and EGRET observations can be used to test this model. More detailed spectral and temporal calculations will be reported elsewhere.

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