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GAMMA RAYS FROM EXTRAGALACTIC RADIO SOURCES

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ABSTRACT

We propose that the important connection 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 radiation mechanism that focuses gamma rays in the superluminal direction, due to Compton scattering of accretion-disk photons by relativistic nonthermal electrons in the jet.

INTRODUCTION

A black-hole accretion disk with a collimated perpendicular jet currently represents the baseline model for explaining the origin of the luminous, broadband radiation emitted from the central engines of active galactic nuclei (AGN). In the unified scenario[1,2], line-of-sight determines family character: thus, Seyfert 2 galaxies are accretion disks seen through obscuring equatorial clouds; Sy 1s are the disks seen directly; and superluminal (SL) radio sources are seen when looking at small angles to the jet (polar) axis. > 100 MeV γ rays have now been detected from two extragalactic radio sources– 3C 273[3] and 3C 279[4]– both of which display strong SL behavior. We show that strong enhancements of gamma-ray emission near the SL direction occur when relativistic electrons in the outflowing radio-emitting blobs Comptonize UV and X-ray photons emitted by the accretion disk. An important consequence of this model is that BL Lac Objects should be rather feeble sources of high-energy radiation, because here we are looking nearly straight down the jet axis. Correlated radio and γ-ray observations will provide a strong test of this model and the AGN unification scenario.

MODEL

Radio observations of AGN are reviewed in Refs. 5 and 6, and theory in Ref. 7. In the relativistic jet model of Blandford & Rees[8], blobs of magnetized plasma with bulk velocity $\beta_\Gamma c$ and Lorentz factor $\Gamma = (1-\beta_\Gamma^2)^{-1/2}$ 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 $\approx \Gamma^{-1}$ about the jet axis *in the observer's frame (OF)*. The maximum apparent transverse velocity $\beta_{app}^{max} c = \beta_\Gamma \Gamma c$ is observed when the angle θ_s^* between the blob's velocity vector and the direction to the observer is given by $\theta_s^* \equiv \cos^{-1}\mu_s^* = \cos^{-1}\beta_\Gamma$ (see Fig. 1). The possible existence of sources showing apparent transverse velocities exceeding c was predicted by Rees[9]. The first-discovered and brightest known SLs, 3C 279 and 3C 273, respectively, each have exhibited SL components with $\beta_{app} > 8$ (Ref. 10).

In the standard model for jets from AGN, sketched in Figure 1, a plasma blob moves outward from the central nucleus with speed $\beta_\Gamma c$. We depart from this model[11] 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 emits 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); and (3) photons passing through the blob follow trajectories parallel to the jet axis. This last is true if the blob is sufficiently far from the central source. We also require that the blob be optically thin to Thomson scattering along the jet axis, which is necessary to produce highly polarized radio emission[8].

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

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

where d is the distance between the observer and the AGN. In the BF, photons have energy $\epsilon = \Gamma(1-\beta_\Gamma)\epsilon^* < \epsilon^*$, due to the Doppler effect. From the invariance[12] of $n_{ph}(\epsilon,\Omega)/\epsilon^2$, we find that the differential photon density in the BF is given by

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

where r is the distance of the blob from the central source and μ is the direction cosine

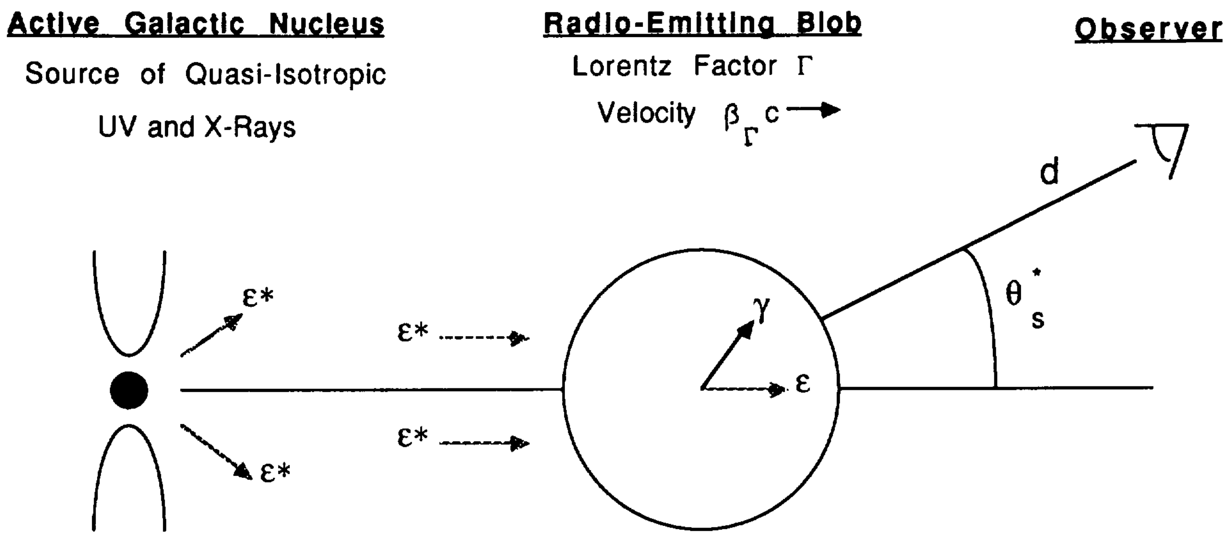

Fig. 1–Cartoon illustrating the proposed model for high-energy radiation from extra-galactic radio sources. A plasma blob moving with speed $\beta_\Gamma c$ focuses its radio emission into a forward cone in the observer's frame. Relativistic electrons in the blob also scatter radiation from the central source. The most energetic of these *jai alai* photons (see final paragraph) are scattered preferentially in the direction $\cos\theta_s^* = 2 - \beta_\Gamma^{-1} \approx \beta_\Gamma$.

of the photons in the BF. We describe the electron distribution in the BF by the function $n_e(\gamma,\Omega)$ [electrons $\mathrm{cm}^{-3}\ \gamma^{-1}\ \mathrm{sr}^{-1}$], 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 spectrum in the BF is given by[13,14]

$$\dot{n}_{ph}(\epsilon_s,\Omega_s) = c\int_0^\infty d\epsilon \oint d\Omega \int_1^\infty d\gamma \oint d\Omega_e\ (1-\beta\cos\psi)\ n_{ph}(\epsilon,\Omega)\ n_e(\gamma,\Omega_e)\ \frac{d^2\sigma}{d\epsilon_s d\Omega_s}, \quad (3)$$

where the subscript s refers to scattered quantities, $\cos\psi \to \mu_e$ 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

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

Substituting equations (4) and (2) into equation (3), and transforming back to the OF using the invariance[12] of $\dot{n}_{ph}(\epsilon_s, \mu_s)/\epsilon_s$, we find that

$$\dot{n}_{ph}(\epsilon_s^*, \mu_s^*) = \frac{\sigma_T \, d^2}{2\Gamma(1-\beta_\Gamma\mu_s^*)\, r^2} \int_1^\infty d\gamma \, \gamma^{-2} \, n_e(\gamma) \, \Phi\{\frac{(1+\beta_\Gamma)\Gamma^2\epsilon_s^*(1-\beta_\Gamma\mu_s^*)^2}{\gamma^2[1+\beta\beta_\Gamma - \mu_s^*(\beta+\beta_\Gamma)]}\}, \qquad (5)$$

giving the photon emissivity per unit emission time. To determine the observed flux Φ_s^{rec} per unit reception time[15], note that the two time intervals are related through $t_{rec} = t_{em}(1-\beta_\Gamma\mu_s^*)$. For a blob with volume $V_b^* = V_b/\Gamma$, $\Phi_s^{rec}(\epsilon_s^*, \mu_s^*) = V_b\dot{n}_{ph}(\epsilon_s^*, \mu_s^*)/2\pi d^2\Gamma(1-\beta_\Gamma\mu_s^*)$. Thus the scattered photon flux, in terms of the flux observed directly from the central source, is given by

$$\Phi_s^{rec}(\epsilon_s^*, \mu_s^*) = \frac{V_b \, \sigma_T}{4\pi r^2 \, \Gamma^2(1-\beta_\Gamma\mu_s^*)^2} \int_1^\infty d\gamma \, \gamma^{-2} \, n_e(\gamma) \, \Phi\{\frac{(1+\beta_\Gamma)\Gamma^2\epsilon_s^*(1-\beta_\Gamma\mu_s^*)^2}{\gamma^2[1+\beta\beta_\Gamma - \mu_s^*(\beta+\beta_\Gamma)]}\}. \qquad (6)$$

We now consider the δ-function properties of equation (6). Let $n_e(\gamma) = n_e^o\delta(\gamma - \bar{\gamma})$ and $\Phi(\epsilon^*) = \Phi_o\delta(\epsilon^* - \bar{\epsilon}^*)$. The energy of a scattered photon emitted into a given direction is related to the original photon energy $\bar{\epsilon}^*$ through the expression

$$\frac{\epsilon_s^*}{\bar{\epsilon}^*} = \frac{\gamma^2[1+\beta\beta_\Gamma - \mu_s^*(\beta+\beta_\Gamma)]}{(1+\beta_\Gamma)\Gamma^2(1-\beta_\Gamma\mu_s^*)^2}. \qquad (7)$$

Equation (7) 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 (7) for a blob moving with $\Gamma = 5$, and for isotropically-distributed electrons with $\gamma = 100$ 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 determined by letting $\partial(\epsilon_s^*/\bar{\epsilon}^*)/\partial\mu_s^* = 0$, giving

$$\mu_{s,max}^* = \frac{\beta_\Gamma + 2\beta\beta_\Gamma^2 - \beta}{\beta_\Gamma(\beta+\beta_\Gamma)}. \qquad (8)$$

If $\gamma \gg \Gamma$, then $\beta \approx 1$ and $\mu_{s,max}^* \rightarrow 2 - \beta_\Gamma^{-1}$. If the blob is also moving at relativistic speeds such that $\Gamma \gg 1$, which indeed is required for SL effects, then $\beta_\Gamma \approx 1 - (2\Gamma^2)^{-1}$, and $\mu_{s,max}^* \approx \beta_\Gamma$. *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 (7)

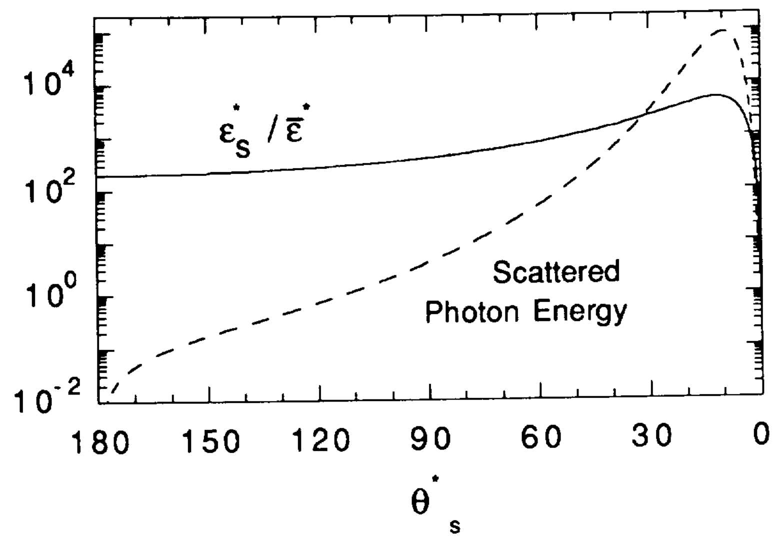

Fig. 2–Angle-dependences of the ratio of the photon energy before and after scattering as measured by an observer (solid curve), and of the relative amount of energy in scattered photons per unit reception time (dashed curve). In this calculation, the blob's Lorentz factor $\Gamma = 5$ and the electrons' Lorentz factor $\gamma = 100$. The most energetic photons are scattered in the direction $\theta^*_s \cong \cos^{-1}(2 - \beta_\Gamma^{-1}) \approx 11.7^o$, and the largest fraction of photon energy is scattered in the direction $\theta^*_s \cong \cos^{-1}[(3\beta_\Gamma - 1)/2\beta_\Gamma] \approx 8.2^o$. The maximum apparent superluminal velocity is observed at the angle $\cos^{-1}\beta_\Gamma \approx 11.6^o$. 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 $\theta^*_s \approx 4.1^o$.

and (8), by $(\epsilon^*_s/\bar{\epsilon}^*)_{max} = \gamma^2(\beta + \beta_\Gamma)^2/4\beta\beta_\Gamma(1 + \beta_\Gamma) \rightarrow \gamma^2/2$, where the limiting expression holds when $\gamma \gg \Gamma \gg 1$.

We can also determine the directional dependence of the total energy in scattered photons by evaluating the quantity $\int_0^\infty d\epsilon^*_s \epsilon^*_s \Phi^{rec}_s(\epsilon^*_s, \mu^*_s)$. The principal angular dependence of this quantity is $\propto [1 + \beta\beta_\Gamma - \mu^*_s(\beta + \beta_\Gamma)]^2/(1 - \beta_\Gamma\mu^*_s)^6$, and is also plotted in Fig. 2. In the limit $\gamma \gg \Gamma$, the greatest amount of energy in scattered photons per interval of μ^*_s is produced in the direction $\mu^*_s \cong (3\beta_\Gamma - 1)/2\beta_\Gamma$. This is close to the direction into which the highest energy photons are scattered.

Recall that the maximum SL velocity occurs when $\mu^*_s = \beta_\Gamma$. Our results show that SL radio sources should scatter the most energetic photons in this direction, with the largest fraction of scattered 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, BL Lac objects are sources where we happen to be looking very nearly directly down the jet axis. Thus we conclude that SL radio sources should be strong γ-ray sources, and BL Lac objects should be weak γ-ray sources.

Attempts to observe γ-ray emission from BL Lac objects have so far been unsuccessful[16], and the X-ray emission that has been observed is soft, with energy spectral index $\approx$1.6 in the 1-3 keV range[17]. The X-rays are probably the result of Comptonization of the synchrotron radiation emitted in the outflowing blob[18]. According to our model, the intensity of gamma-ray emission should be positively correlated with the appearance and apparent transverse velocity of SL components. By contrast, BL Lac objects that display no SL character should not be γ-ray sources. We strongly encourage correlated VLBI radio observations and GRO EGRET observations to test these predictions. Superluminal sources such as 3C 120 or 3C 345[5,10] are obvious candidate sources of extragalactic gamma radiation. Comparatively weak X-ray and γ-ray emission is expected from subluminal BL Lac objects such as 1803+78[19,5].

SUMMARY

We have proposed a model in which the relativistic electrons in an outflowing blob Comptonize photons from a central source. This process has much in common with the game jai alai, where the combined motions of the player and his basket shoot the ball forward with a much greater energy than would be possible were either the player stationary or his basket immobile. This model avoids γ-γ pair attenuation of $>$ 100 MeV photons[20] from a compact highly variable source such as 3C 273 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 speed of the blobs may be explained by a Compton-rocket effect[21] produced by the Compton-scattering impulse. Such an interpretation avoids the difficulties in Rees' suggestion[22] that Compton drag of a parallel ultrarelativistic jet by disk photons regulates the jet's speed (for example, such jets should be highly unstable[23]). As discussed earlier, our model is in accord with the AGN unification scenario, and it could be argued that evidence in favour of it strengthens the unifying scheme. Spectral implications, which imply additional predictions that can be used to test this model, will be reported elsewhere.

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