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ON THE ORIGIN OF RELATIVISTIC PARTICLES AND GAMMA-RAYS IN QUASARS

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Abstract

A model for a class of quasars and active galactic nuclei is proposed in which a shock around a massive black hole randomizes the infall kinetic energy of spherically accreting matter producing a non-thermal spectrum of high energy protons. It is suggested that these protons are responsible for the secondary production (via $\pi^{\pm}$ decay) of the radio emitting high energy electrons and also of high energy γ-rays (via π^0 decay and inverse Compton interactions of the electrons). The correlation between radio and γ-ray emission implied by the model is in good agreement with observations of 3C273. Observation of the flux of high energy neutrinos from quasars may provide a test for the model.

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I. Introduction

Accretion onto compact objects has long been considered as an energy source for many astrophysical phenomena, both on stellar and galactic scales. Due to its potentially high efficiency (possibly up to 10%), it was one of the first mechanisms considered to power quasars (Lynden Bell 1969) and is thought to be the only mechanism capable of satisfying their enormous power requirements. However, it was realized early on that matter falling freely into a black hole need not radiate all its potential energy (Shapiro 1973). Accretion on to a black hole can be efficient only if the directed infall motion can be randomized near the black hole, e.g., by dissipation in an accretion disk (e.g. Shields, 1978), or by dissipation of magnetic fields and relativistic particles convected with the infalling plasma (e.g. Mészáros, 1975). Radio, X-ray and γ-ray observations show that some quasars emit roughly the same energy per decade (i.e. per logarithmic energy interval, d $\log_{10}E$) from radio to X-ray energies and, in the case of 3C273, to γ-ray energies. Since infall in a gravitational potential is unlikely to release more than ~ 0.1 mc^2 per particle, not sufficient to produce the observed γ-rays, we suggest that the relativistic particles required to account for the observed radio, X and γ-ray emission may result from acceleration in shocks via a first-order acceleration mechanism. This mechanism, efficient (up to 98%; Axford 1981) in transforming directed kinetic energy into relativistic particle energy, has already been proposed to account for the observed cosmic ray spectrum (Bell 1978a, b; Axford, Lear and Skadron, 1977; Blandford and Ostriker, 1978; Cowsik and Lee, 1981). For strong shocks, this process naturally produces a power law spectrum with index -2, i.e., equal energy per decade.

The nuclear interaction of protons accelerated by this process results in production of γ-rays and secondary electrons responsible for synchrotron and inverse Compton emission. X-ray emission will be due to the interaction of these relativistic particles with the ambient medium, photons, and magnetic fi lds. In this paper we will concentrate solely on the production of relativist... particles and γ-rays in quasars.

II. The Model

The model employs a shock around a massive black hole which serves both to randomize the infall kinetic energy of the spherically accreting gas and also to produce a non-thermal distribution of high energy (relativistic) protons. A thermal distribution of particles may also be produced at the shock and hence radiate by thermal bremsstrahlung; however we consider here only the radiation resulting from the non-thermal distribution which may actually contain most of the energy (Axford 1981). Because of the high photon energy densities ($\gtrsim$ 200 erg cm^{-3} for 3C273 if the source region has dimensions less than 10^{17} cm) and the magnetic fields present, electrons will suffer severe Compton and synchrotron losses, effectively prohibiting their direct acceleration. Direct production of electron-positron pairs by interactions of protons with photons may become important at very high energies (Blumenthal, 1970) but we shall consider here only those secondary electrons resulting from nuclear collisions of the non-thermal proton distribution (via pion production) as opposed to those produced by thermal distributions of protons (Marscher, Vestrand and Scott, 1980). Gamma-ray production via inverse Compton scattering of the relativistic electrons (Jones, 1979) and via π^0 decay are considered.

The question of the existence of a shock around a black hole is important and deserves further discussion. It has been argued, on general grounds, that accretion shocks can exist only if the gravitating object has a solid surface to provide the necessary boundary condition requiring the deceleration of the supersonically accreted matter. A black hole, since it does not provide such a surface, apparently violates this condition. The situation, however, is different if relativistic particles (protons, in the present case) of sufficient energy density, ϵ, are present around the black hole. These particles having kinetic energies much higher than their gravitational potential do not readily fall into the black hole. Moreover outward magnetic field gradients will tend to mirror them, thus further inhibiting their accretion. Thus the relativistic particles can provide sufficient pressure to satisfy the Rankine-Hugoniot conditions across the shock. The confinement of the particles is then achieved by the ram pressure of the accreting material, i.e. $\epsilon \simeq \rho v^2$. The position of the shock is then fixed by this condition and by the balance between injection and removal (by nuclear collisions) of the relativistic particles (protons). The initial formation of the shock can be attributed either to convection of ambient relativistic particles or to dissipation of magnetic fields as suggested in the literature (McCrea 1956; Scharlemann 1931).

The spectrum of protons accelerated by the shock has a power law momentum dependence, i.e., $Q_p(p) = K_p p^{-\Gamma}$ (protons GeV^{-1} c s^{-1}). For a strong shock (compression ratio = 4), $\Gamma = 2$. The relativistic protons are assumed to be trapped within a radius comparable to the shock radius by magnetic fields which are tied to the infalling matter. If the relativistic protons were not confined to the central region of the quasar, spallation of nuclei in the outer gas clouds responsible for the line emission in quasars would result in an overabundance of boron (Baldwin et al., 1977), contrary to observation. In addition, the matter density in this region is assumed to be sufficiently high that the relativistic protons are depleted mainly by nuclear interactions. This condition sets a lower limit on the accretion rate for a given black hole mass which however is not very restrictive. Nuclear interactions throughout the volume within the shock radius will result in a spectrum of pions at production given by:

$$Q_\pi(E) = \frac{\Gamma}{\Gamma-1} \int_E^\infty Q_p(E')\, \phi_\pi(E',E)\, dE' \quad \text{(pions GeV}^{-1}\text{ s}^{-1}\text{)} \tag{1}$$

where $\phi_\pi(E',E)$ is the probability of a proton of energy E' producing a pion of energy E in a single nuclear interaction and is obtained from accelerator data. The factor $\Gamma/(\Gamma-1)$ takes into account multiple interactions of the primary protons (Protheroe, 1981).

The production spectrum of γ-rays, $Q_{\pi\gamma}(E)$, resulting from π^0 decay (Stecker 1971) has been calculated and is plotted in Figure 1(a) where it is normalized to the proton production spectrum at high energies, K_pE^{-2}. The production spectrum of secondary electrons $Q_e(E)$ (e^+e^-) from π-μ-e decay has been calculated and is also plotted in Figure 1(a). Above ~ 1 GeV, $Q_e(E) \approx Q_{\pi\gamma}(E) \approx 0.15\ Q_p(E)$ for $\Gamma = 2$; the remaining energy goes into neutrino production, $Q_\nu(E) \approx 0.7\ Q_p(E)$. To obtain the absolute normalization of $Q_p(E)$ for 3C273, we shall consider its observed radio-optical spectrum. Based on the survey of flux measurements on 3C273 by Ulrich (1981) and using H_0 = 60 km s^{-1} Mpc^{-1}, we find that the luminosity emitted per decade is approximately constant at ~ 1.5 x 10^{46} erg s^{-1} from 3 x 10^{11} to 10^{15} Hz, and the total luminosity is about 2 x 10^{47} erg s^{-1} integrated over all wavelengths. If we attribute the flat ($F_\nu \sim \nu^{-1}$) part of the spectrum from the radio to the visible to synchrotron radiation, then we can relate the sychrotron luminosity to the total electron production rate:

$$L_{synch} \approx \frac{\alpha}{2(1+\alpha)}\, \ln 10\, \varepsilon^2 Q_e^{tot}(E) \quad (\text{erg s}^{-1}\text{ decade}^{-1}), \tag{2}$$

where α is the ratio of energy densities in the magnetic and radiation fields. $Q_e^{tot}(E)$ is the rate of production of electrons at high energies (electrons erg^{-1} s^{-1}) and is equal to $Q_e(E)$ plus the production spectrum of electrons and positrons resulting from photon-photon pair production interactions.

Assuming the electrons are trapped within the shock radius, R, and lose energy by inverse Compton and synchrotron radiation, the ambient spectrum of electrons, $N_e(E)$, is determined by

$$Q_e^{tot}(E) - \frac{d}{dE}\left\{\frac{dE}{dt} N_e(E)\right\} = 0, \tag{3}$$

where $$Q_e^{tot}(E) = Q_e(E) + \int_E^{\infty} \frac{2}{E'} \{Q_{\pi\gamma}(E') + Q_{IC}(E')\} \phi_{\gamma\gamma}(E') \, dE'. \tag{4}$$

Here, $dE/dt = - 3.97 \times 10^{-2} (1 + \alpha) U_{rad} E^2$ erg s^{-1}, where U_{rad} is the radiation energy density, taken to be $L_{Total}/\pi R^2 c$. The second term of equation (4) is the energy spectrum at production of electrons from pair production and involves the γ-ray production spectrum resulting from inverse Compton interactions as well as that from π^0 decay. $\phi_{\gamma\gamma}(E)$ is the probability that a γ-ray of energy E will produce an electron-positron pair by annihilating with a lower energy photon before escaping from the source (discussed in detail later). For inverse Compton interactions, the γ-ray production rate is,

$$Q_{IC}(E) = \int_E^{\infty} N_e(E') \left\{ \int_{E/4\gamma^2}^{E} n_{ph}(\epsilon) \, \sigma(E,\epsilon,E') c \, d\epsilon \right\} dE' \tag{5}$$

where $\gamma = E'/mc^2$, $n_{ph}(\epsilon)$ is the number density of photons in the radiation field (photons cm^{-3} erg^{-1}), and $\sigma(E,\epsilon,E')$ is the differential cross section for an inverse Compton interaction in which an electron of energy E' interacts with a photon of energy ϵ, boosting its energy to E.

We have solved equation (3) for the two extreme cases where the source is optically thin ($\phi_{\gamma\gamma} = 0$) or thick ($\phi_{\gamma\gamma} = 1$) to γ-ray pair production interactions. At high energies, but below the Klein-Nishina limit, we obtain, for $\Gamma = 2$:

$$Q_e^{tot}(E) \approx \begin{cases} Q_e(E) & (\phi_{\gamma\gamma} = 0) \\ \left\{\frac{2(1+\alpha)}{(1+2\alpha)}\right\}\{Q_e(E) + Q_{\pi\gamma}(E)\} & (\phi_{\gamma\gamma} = 1) \end{cases} \tag{6}$$

The resulting inverse Compton γ-ray production spectra are plotted in Figure 1(a) for these two cases and $\alpha = 1$. (Not using the Klein-Nishina cross section may introduce an error of about a factor of 2 at 10 GeV.)

The observed γ-ray spectrum will be the total γ-ray production spectrum ($Q_{\pi\gamma} + Q_{IC}$) modified by photon-photon pair production interactions. To calculate this effect, we must know the radius of the object, R. We shall obtain R from the frequency below which the synchrotron radiation becomes optically thick to synchrotron self absorption. The number density of relativistic electrons of energy E within the source is

$$n_e(E) = \left\{\frac{1}{dE/dt}\int_E^{\infty} Q_e^{tot}(E')dE'\right\}/\tfrac{4}{3}\pi R^3 \text{ (electrons erg}^{-1}\text{ cm}^{-3}) \quad . \tag{7}$$

Using $Q_e^{tot}(E)$ from equation (2), and substituting for dE/dt, we obtain $n_e(E) \approx n_0 E^{-3}$, where $n_0 = (4.9 \times 10^{11} L_{synch})/(\alpha L_{Total} R)$. For this spectrum, the frequency below which synchrotron self absorption becomes important, ν_1, is given by Pacholczyk (1970),

$$\nu_1 = 2C_1(SC_6)^{2/7}\, n_0^{2/7}\, B_\perp^{5/7} \tag{8}$$

where $B_\perp$ is the component of magnetic field perpendicular to the line of sight ($B_\perp \approx .8\langle B\rangle$), $S \approx \frac{4}{3} R$ is the average distance through the source, $C_1 = 6.3 \times 10^{18}$, and $C_6 = 7.8 \times 10^{-41}$. The synchrotron self absorption does not result in a sharp spectral break in 3C273. This may be understood in terms of non-uniform radial distributions of electron density and magnetic field (Condon and Dressel, 1973). For 3C273, ν_1 appears to be in the range 3×10^{11} - 10^{12} Hz, hence we find $R\alpha^{-1/10} \approx 5\times10^{17} - 10^{17}$ cm and $\langle B\rangle\alpha^{-2/5} \approx 14 - 75$ gauss.

We can now use these estimates of the radius to obtain the photon density in the X-ray region from the observed X-ray flux data and hence the effects of pair production interactions on the γ-ray spectrum. The optical depth to γ-rays of energy E is

$$\tau(E) = S \int n_{ph}(\varepsilon)\, \sigma\, (E,\varepsilon)\, d\varepsilon \qquad (9)$$

where $n_{ph}(\varepsilon)$ is the number density of photons of energy ε, and $\sigma(E,\varepsilon)$ is the differential cross section for pair production interactions of γ-rays of energy E with photons of energy ε, (Heitler, 1954). We have used X-ray data of Worrall et al. (1979) and Primini et al. (1979) and the assumed radius to obtain $n_{ph}(\varepsilon)$.

The energy spectrum of γ-rays escaping from the source is then down by a factor, $(1 - e^{-\tau})/\tau$, from that at production. For 3C273 this factor is plotted as a function of energy in Figure 2(a) for various assumed radii. We see that the source is optically thick to γ-rays above ~ 100 MeV for radii in the range obtained earlier. We have therefore plotted in figure 1(b) the γ-ray spectrum at production $(Q_{\pi\gamma} + Q_{IC})$ for $\phi_{\gamma\gamma} = 1$ and for values of α ranging from 1 to 1/16. The observed γ-ray luminosity (Bignami et al., 1981; Hermsen et al., 1981) is compared in Figure 2(b) with our prediction taking into account photon-photon absorption and is found to be in good agreement with the prediction for $\alpha \approx 0.1$ and $R \sim 10^{17}$ cm. This radius is consistent with that we obtained earlier by considering the radio spectrum some 12 decades lower in energy.

III. Discussion

We have presented above the main features and predictions of a model for a class of quasars and active galactic nuclei, gauged to 3C273. The model, deductively introduced, focuses on the high energy particles in these objects which are responsible for the radio and γ-ray emission. It predicts a correlation between these two extreme parts of the spectrum which appears to be in good agreement with observations of 3C273, the only quasar in which both radio emission and high energy γ-rays have been observed. The model provides estimates of the central source radius and its magnetic field. If the total observed luminosity ($L_{total} \approx 2 \times 10^{47}$ erg s^{-1}) is due to gravitational energy release at the surface of the shock, and the relativistic particle pressure balances the accretion ram pressure ρv^2, then the radius inferred above implies a mass of ~ 10^{10} M_Θ, and an accretion rate of ~10^2 M_Θ yr^{-1}.

The estimated radius is compatible with variability time scales of the order of several months which have been observed (Worrall et al. 1979). Variability reported on much shorter time scales (~ 1 day) (Marshall, Warwick and Pounds, 1981) would clearly be incompatible with our model. However, the statistical significance of these data is low and they may also be compatible with a much longer time scale variability. In any case, variability on time scales much less than R/c has been observed in the quasar NRAO 140 (Marscher and Broderick, 1981) and has been attributed to relativistic beaming effects. It is important to point out here that a radius of ~ 1 light day would render 3C273 completely opaque to γ-rays of energies greater than a few MeV, contrary to observation. However, emission of X-rays and γ-rays from the jet (McBreen, 1979; Bassani and Dean, 1981, Blandford and Konigl, 1979; see also Konigl, 1981) has been suggested and might be a possible remedy if the observed X-rays are beamed with the γ-rays.

In the present model, pair production by high energy γ-rays and production of electrons by pion decay throughout the source volume avoids the Compton Catastrophe

(Hoyle, Burbidge and Sargent, 1966) and allows a higher energy density in the radiation field than in the magnetic field (i.e. $\alpha < 1$). The model also provides a situation similar to that considered in the literature for the formation of jets (Smith et al. 1980), i.e., a hot gas (the relativistic particles) underneath a cold gas (the infalling cold gas).

A prediction of the model would be the emission of high energy γ-rays from other quasars and active galactic nuclei. Unfortunately sources of luminosity similar to 3C273 are typically ~10 times farther away and difficult to detect in γ-rays at present. The present model may also apply to Seyfert galaxies and, if so, many of these objects may be detectable in γ-rays (Bassani and Dean, 1981). However, their radii are at present uncertain and do not preclude their being optically thick to γ-rays.

Finally, the model predicts a higher flux of high energy neutrinos than in models where electrons are directly accelerated. We predict a flux of $\sim 1.4 \times 10^{-10} \times (1+2\alpha)$ neutrinos (all types) $cm^{-2}\ s^{-1}$ above 1 TeV for 3C273. This may be within the detection capability of the proposed DUMAND neutrino telescope (Stenger, 1981) and thus may provide a test of the model.

In conclusion, we have presented a model for a class of quasars and active galactic nuclei which naturally provides the relativistic particles needed to account for their spectra. It also avoids the Compton catastrophe, inherent in most models, and predicts a correlation between the spectrum at radio and γ-ray energies. We have successfully applied this model to 3C273.

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Figure Captions

Figure 1. (a) Production spectra of electrons (Q_e), γ-rays from π° decay ($Q_{\pi\gamma}$) and γ-rays from inverse Compton interactions for α = 1 (Q_{IC}) relative to the production rate of protons. Separate curves are given for Q_{IC} corresponding to $\phi_{\gamma\gamma}$ = 0 and 1. (b) Total production rate of γ-rays for $\phi_{\gamma\gamma}$ = 1 relative to the radio synchrotron luminosity for different values of α.

Figure 2. (a) Reduction factor applied to predicted optically thin γ-ray spectra for 3C273 for various assumed radii in order to obtain the expected γ-ray emission. (b) Gamma-ray luminosity of 3C273 based on the observed spectrum (Hermsen et al., 1981) compared with the luminosity predicted for α = 1 and α = 1/10 and for the range of radii obtained as described in the text.

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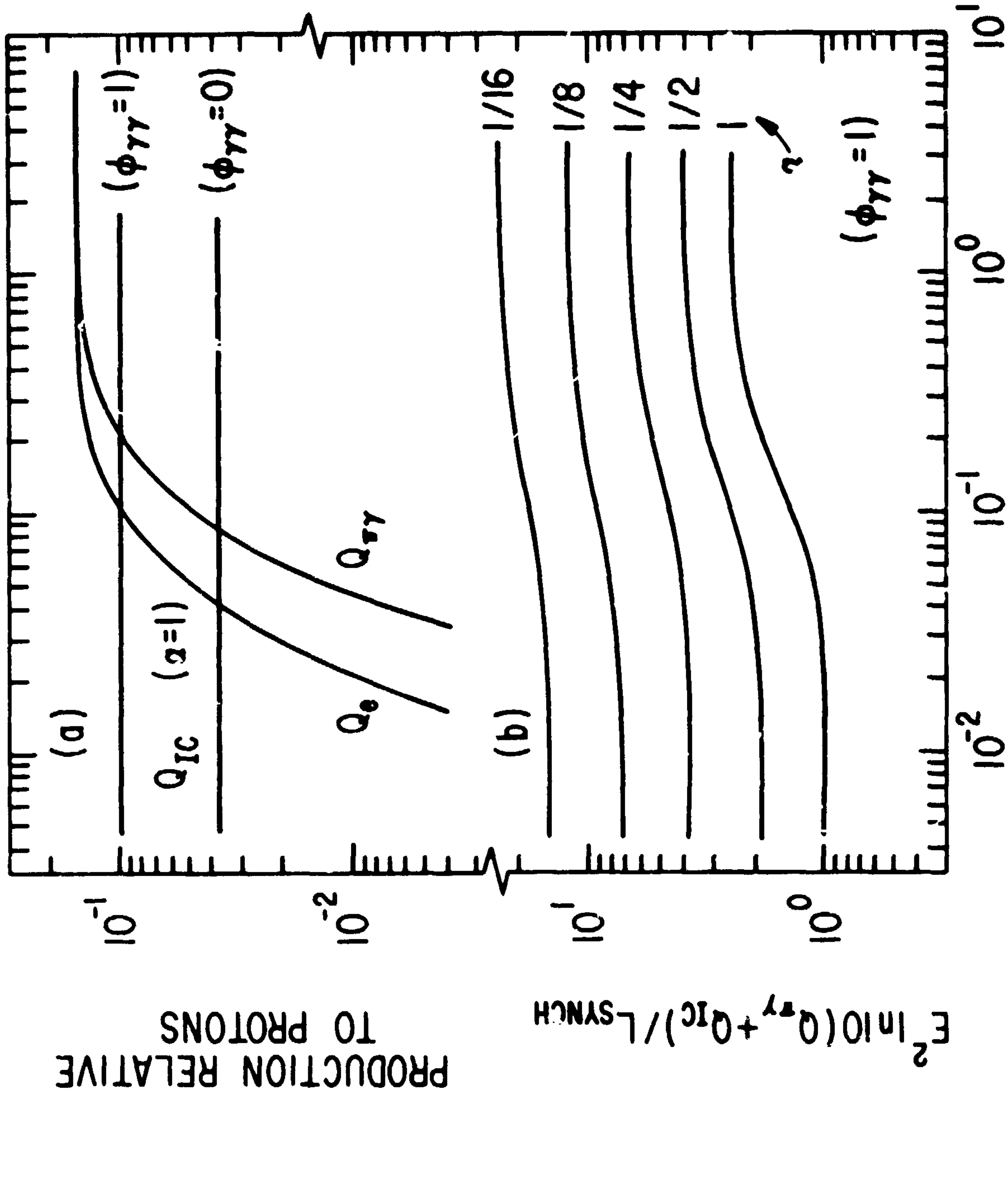

FIGURE 1.

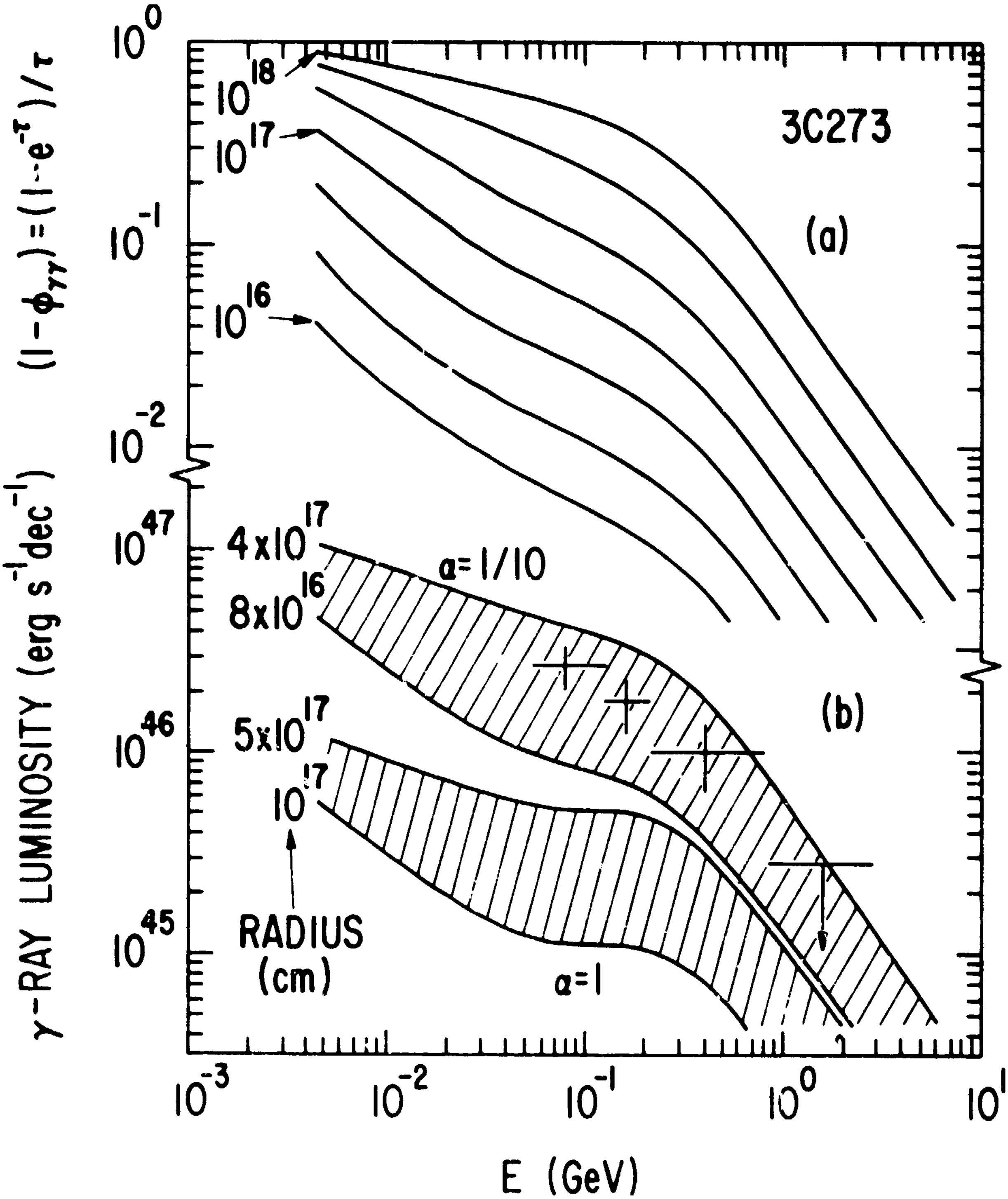
3C273
(a)
(b)
$(1-\phi_{\gamma\gamma}) = (1-e^{-\tau})/\tau$
γ-RAY LUMINOSITY (erg s⁻¹ dec⁻¹)
E (GeV)
10^{18}
10^{17}
10^{16}
4×10^{17}
8×10^{16}
5×10^{17}
10^{17}
α=1/10
α=1
RADIUS
(cm)
10^{0}
10^{-1}
10^{-2}
10^{47}
10^{46}
10^{45}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

FIGURE 2.