

THE PRODUCTION OF VERY HIGH ENERGY PHOTONS AND NEUTRINOS FROM COSMIC PROTON SOURCES

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ABSTRACT

The emission of neutrinos and photons with energies of the order of 10^{12} eV from the matter surrounding a source of very high energy cosmic ray protons is computed. The optimum conditions for neutrino emission are shown to be: matter density $\rho \leq 10^{-8}$ g cm $^{-3}$ and integrated path length $z \geq 100$ g cm $^{-2}$, with significant emission for $z \geq 20$ g cm $^{-2}$. Optimum photon production occurs for $z \approx 50$ g cm $^{-2}$. Under these conditions 1 TeV photon emission can be as much as 2.6% and neutrino emission as much as 6.7% of the proton intensity at 1 TeV, for an E^{-2} proton spectrum. These results imply that compact objects are the best candidate sources. The fluxes of photons and neutrinos from possible galactic and extragalactic sources are estimated and shown to be adequate for current or proposed detectors, if the above optimum conditions are present. Since neutrinos probe hadronic interactions, a combination of photon and neutrino observations can be used to learn the details of particle acceleration in compact objects, as well as provide information about the matter surrounding the source.

Subject headings: neutrinos — radiation mechanisms

1. INTRODUCTION

The fact that cosmic rays have been observed with energies above 10^{20} eV, and the widespread occurrence of nonthermal sources of X-rays and higher energy photons on both galactic and extragalactic scales, demonstrate that there are processes of enormous energy taking place in the cosmos. Since the bulk of cosmic rays observed at Earth are protons or other charged nuclei, much of the information about their sources is destroyed by interactions with the matter and magnetic fields along the path to Earth. As a result, the fundamental question of the cosmic ray acceleration mechanism is still unanswered despite years of study.

Likewise, the mechanisms for the vast energy outputs of quasars and active galactic nuclei remain among the most important unanswered questions in astrophysics. Evidence is gradually accumulating that these phenomena may be related.

Some inferences on the sources of high-energy particles have been made from observations of electromagnetic radiation over the whole spectrum from radio to GeV γ -rays. But these data are the result of secondary processes many orders of magnitude down the energy chain from the primary reactions of interest, and their interpretation is bound to be problematical.

Clearly the most direct knowledge about astronomical sources of extremely high energy particles would be obtained by the observation of photons or other neutral particles of the highest possible energy from localized sources. By means of the ground-based atmospheric Cerenkov technique, γ -rays above 1 TeV have now been observed from a small number of sources (Grindlay 1982), with a typical flux of 10^{-11} cm $^{-2}$ s $^{-1}$. A statistically significant γ -ray source above 200 TeV with a flux of the order of 10^{-13} cm $^{-2}$ s $^{-1}$ is now reported in two independent experiments (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983). Recently it has been shown that it is feasible to build a detector underwater which will be sensitive to an extraterrestrial flux of muon neutrinos of similar energy and intensity (DUMAND 1982).

There is a close and complementary connection between

cosmic γ -rays and neutrinos at very high energy. High-energy γ -rays can result from electromagnetic or hadronic sources. In the latter case they are almost exclusively the decay products of π^0 mesons produced by the interaction of cosmic-ray protons or nuclei and matter. Since charged pions are also produced in these same reactions and neutrinos are a major product of their decay, there will be a direct relation between observed γ -rays and neutrinos. If observed high-energy γ -rays result from hadronic processes, then the measured fluxes are approximately a lower limit on what will be found for neutrinos. If no neutrinos are found at that level, this will imply an electromagnetic origin of the high-energy γ -rays which have been reported. If neutrinos are found without accompanying γ -rays, this will mean that the source is hadronic, but so deep in matter that the photons have been absorbed.

In this paper we consider the production of very high energy (> 100 GeV) γ -rays and neutrinos by hadronic processes in cosmic sources. Given the existence of protons in the source with a power law spectrum, the γ -ray and neutrino emissions from the matter surrounding the source are computed. The conditions for maximum emission are established in terms of the matter density and integrated path length, or column density, seen by the protons as they pass through this matter, either directly along the line of sight to Earth or as they circulate in high magnetic fields near the source. It is shown how observations of both γ -rays and neutrinos can be used to obtain information about primary proton flux at the source and the matter surrounding it. The energy luminosity of cosmic-ray protons required to produce a detectable signal at Earth in current and prospective experiments on very high energy γ -rays and neutrinos is estimated.

Previous studies of a similar nature (Berezinsky and Volynsky 1979; Eichler and Schramm 1978; Kafatos, Shapiro, and Silberberg 1981; Margolis, Schramm, and Silberberg 1978; Protheroe and Kazanas 1983; Stecker 1979) have largely considered specific models for the astrophysical sources of high-energy γ -rays and neutrinos. In this paper an attempt is made

to determine the general features required for a source and its environment to produce detectable fluxes at Earth and whether such sources may reasonably be expected to exist.

The primary motivation for this work is the question of the likelihood of detectable point sources of neutrinos. Since the mechanism for neutrino production also results in γ -rays, and since data already exist on sources of γ -rays at very high energy, it was natural to include this as well. However, no attempt has been made to provide a complete review of all the electromagnetic processes which may result in γ -ray production.

II. METHOD OF CALCULATION

The standard cosmic-ray transfer equations proposed by Ginzburg and Syrovatskii (1964) and now commonly used in the one-dimensional approximation to study the propagation of cosmic ray nuclei in the Galaxy (Shapiro and Silberberg 1974), and similar phenomena, have been used to compute the γ -rays and neutrinos emitted by high energy protons passing through matter. The method generalizes similar calculations made by Berezhinsky and Volynsky (1979).

Protons having a power law spectrum

$$N_p(E_p) = N_p(1)E_p^{-\alpha} \quad (1)$$

protons per second per TeV, where E_p is the proton energy in TeV, are assumed to pass into a region of matter having density ρ g cm $^{-3}$ and column density $z = \int \rho dl$ g cm $^{-2}$ integrated over the path of the proton. The number of particles of type j which emerge from the region will be governed by the transfer equation

$$\frac{dN_j(E_j, z)}{dz} = -N_j(E_j, z) \left[\frac{1}{\lambda_j} + \frac{1}{\Lambda_j} \right] + \sum_i \int_{E_j}^{\infty} \frac{N_i(E_i, z)}{L_i(E_i, z)} P_{ij}(E_i, E_j) dE_i. \quad (2)$$

The first term on the right represents the loss of particles j with energy E_j from the "beam" by (i) interaction, with λ_j the interaction mean free path, and (ii) decay, with

$$\Lambda_j = \frac{E_j}{m_j c^2} c \tau_j \rho \quad (3)$$

the mean decay length, τ_j being the mean lifetime. Both lengths are measured in g cm $^{-2}$. The terms on the far right of equation (2) represents the production of particles j with energy E_j by the interaction or decay of particles i in the beam with energy E_i , where $L_i = \lambda_i$ or Λ_i depending on whether the reaction $i \rightarrow j$ is an interaction or a decay. In the first case,

$$P_{ij}^{int} = \frac{1}{\sigma} \frac{d\sigma(E_i, E_j)}{dE_j} \quad (4)$$

where $\sigma(E_i, E_j)$ is the interaction cross section. In the second case, P_{ij}^{decay} is the probability for particle i with E_i to decay giving particle j with E_j .

The one-dimensional nature of the transfer equation (2) is justified by the very high energy of the reactions. A 1 TeV proton has a Lorentz factor of 1000, which implies that the majority of secondary particles will be within 1 milliradian of the beam direction. This is further reinforced by the strong tendency of high-energy hadronic interactions to produce mostly forward secondaries.

The solution of the transfer equation (2) for protons which

comprise the original cosmic ray beam is trivial if we assume no protons are produced in the region z . Then

$$\frac{dN_p(E_p, z)}{dz} = -\frac{N_p(E_p, z)}{\lambda_p}. \quad (5)$$

Using (1) and taking λ_p to be constant,¹

$$N_p(E_p, z) = N_p(1)E_p^{-\alpha} \exp[-(z/\lambda_p)]. \quad (6)$$

Next let us consider the pions produced by the inclusive reaction

$$p + N \rightarrow \pi + X, \quad (7)$$

where N is the target nucleus and X represents all the remaining particles produced in the reaction. The production probability $P_{p\pi}$ given in (4) is computed assuming radial scaling (Taylor *et al.* 1976). For our purposes this is equivalent to Feynman scaling (Feynman 1969). If we define $x_R = E_\pi/E_p$, then the cross section for the inclusive production of pions by protons scales with energy and we can write

$$\frac{d\sigma_{p\pi}}{dx_R} = f(x_R), \quad (8)$$

independent of E_π and E_p individually. This property is found to approximately hold even in the highest energy cosmic ray interactions in the atmosphere (Gaisser and Yodh 1980) for the bulk of the forward going pions. Deviations from scaling attributable to quantum chromodynamics (QCD) are observed even at accelerator energies, but these effects involve a small fraction of the particles produced and can be neglected for our purposes. Thus

$$P_{p\pi}^{int} dE_p = \frac{1}{\sigma} \frac{d\sigma}{dE_p} dE_p = -\frac{1}{\sigma(x_R)} \frac{1}{x_R} \frac{d\sigma}{dx_R} dx_R; \quad (9)$$

and, using (6) and $L_p = \lambda_p$, the integral in (2) becomes

$$\int_{E_\pi}^{\infty} \frac{N_p(E_p, z)}{L_p(E_p)} P_{p\pi}^{int}(E_p, E_\pi) dE_p = \frac{N_p(1)}{\lambda_p} \exp\left(-\frac{z}{\lambda_p}\right) E_\pi^{-\alpha} g_{p\pi}, \quad (10)$$

where

$$g_{p\pi} = \int_0^1 x_R^{\alpha-1} \frac{1}{\sigma} \frac{d\sigma}{dx_R} dx_R = \langle x_R^{\alpha-1} \rangle, \quad (11)$$

where we recall that α is the spectral index of the primary cosmic ray proton beam. Using the parameterization for σ of Hillas (1979), we have calculated

$$g_{\pi^+} = \int_0^1 x_R^{\alpha-2} [0.61(1-x_R)^{3.5} + 0.49 \exp(-18x_R)] dx_R \quad (12)$$

We take $g_{\pi^-} = g_{\pi^0} = 0.7g_{\pi^+}$.

The pion transfer equation thus can be written

$$\frac{dN_\pi(E_\pi, z)}{dz} = -N_\pi(E_\pi, z) \left[\frac{1}{\lambda_\pi} + \frac{1}{\Lambda_\pi} \right] + \frac{N_p(1)}{\lambda_p} \exp\left(-\frac{z}{\lambda_p}\right) E_\pi^{-\alpha} g_{p\pi}. \quad (13)$$

¹ For the fairly steep power law spectra involved in cosmic rays, most events occur near the lowest energy (determined by the detection threshold), justifying this assumption.

Defining

$$\frac{1}{L_\pi} = \frac{1}{\lambda_\pi} + \frac{1}{\Lambda_\pi(E_\pi)} \quad (14)$$

we can write the solution

$$N_\pi(E_\pi, z) = N_p(1)E_\pi^{-\alpha}g_{p\pi} \frac{\exp(-z/\lambda_p) - \exp[-z/L_\pi(E_\pi)]}{\lambda_p/L_\pi(E_\pi) - 1}. \quad (15)$$

This expression will be applicable to charged pions. For neutral pions a simplification results from the fact that the π^0 mean lifetime is only 10^{-16} s, so $\Lambda_{\pi^0} \ll \lambda_{\pi^0}$ for any reasonable case. That is, the π^0 has no chance of interacting before it decays, even at the highest energies we might consider. By the same token, $\Lambda_{\pi^0} \ll \lambda_p$. Thus (15) for neutral pions becomes

$$N_{\pi^0}(E_{\pi^0}, z) = N_p(1)E_{\pi^0}^{-\alpha}g_{p\pi^0} \frac{\Lambda_{\pi^0}}{\lambda_p} \exp\left(-\frac{z}{\lambda_p}\right). \quad (16)$$

A similar procedure can be followed for the other types of hadrons which are produced in pN collisions. For kaons and other strange particles with lifetimes comparable to charged pions, an expression like (15) will apply. For charmed particles and other heavy particles whose lifetimes are much shorter, an expression like (16) will apply, although these are likely to be unimportant. A simplified expression also will apply to the case of produced nucleons or antinucleons, where only interactions need be considered.

The particles of our main interest, photons and neutrinos, are produced when unstable particles, particularly neutral and charged pions, decay:

$$\pi^0 \rightarrow 2\gamma, \quad (17a)$$

$$\pi^\pm \rightarrow \mu^\pm \nu_\mu. \quad (17b)$$

The branching ratio for these decays is virtually 100%, so we need not worry about other decay modes. However, neutrinos will also be produced when the muons from (17b) decay by

$$\mu^\pm \rightarrow e^\pm \nu_e \nu_\mu. \quad (18)$$

Note that muon neutrinos will tend to be the major component, electron neutrinos resulting from a tertiary process.

The photon transfer equation thus becomes

$$\frac{dN_\gamma(E_\gamma, z)}{dz} = -\frac{N_\gamma(E_\gamma, z)}{X_{\text{rad}}} + \int_{E_\gamma}^{\infty} \frac{N_{\pi^0}(E_{\pi^0}, z)}{\Lambda_{\pi^0}(E_{\pi^0})} \frac{dE_{\pi^0}}{E_{\pi^0}}, \quad (19)$$

where the γ -ray interaction mean free path is taken to be the radiation length X_{rad} and

$$P_{\pi^0\gamma}^{\text{decay}}(E_{\pi^0}, E_\gamma) = \frac{1}{E_{\pi^0}}. \quad (20)$$

Substituting (16) in (19), we get

$$\frac{dN_\gamma}{dz} = -\frac{N_\gamma}{X_{\text{rad}}} + \frac{g_{p\pi^0}}{\alpha\lambda_p} N_p(1) \exp\left(-\frac{z}{\lambda_p}\right) E_\gamma^{-\alpha} \quad (21)$$

which can be integrated to give

$$N_\gamma(E_\gamma, z) = N_p(1)E_\gamma^{-\alpha} \times \frac{g_{p\pi^0}}{(\alpha+1)} \frac{\exp(-z/\lambda_p) - \exp(-z/X_{\text{rad}})}{\lambda_p/X_{\text{rad}} - 1}. \quad (22)$$

Unfortunately the calculation of the neutrino production rate is not so simple. First let us write the muon transfer equation:

$$\frac{dN_\mu(E_\mu, z)}{dz} = -\frac{N_\mu(E_\mu, z)}{\lambda_\mu(E_\mu)} + \int_{E_\mu^{\text{min}}(E_\mu)}^{\infty} \frac{N_\pi(E_\pi, z)}{\Lambda_\pi(E_\pi)} P_{\pi\mu}^{\text{decay}}(E_\pi, E_\mu) dE_\pi, \quad (23)$$

where $N_\pi(E_\pi, z)$ is given by (15) and where the minimum pion energy to produce a muon (or neutrino) of energy E is

$$E_\pi^{\text{min}}(E) = E(1 - m_\mu^2/m_\pi^2)^{-1}. \quad (24)$$

In the first term of (23) we have anticipated that muon decay will be much more likely than interaction at the matter densities of interest. The muon neutrino transfer equation becomes

$$\frac{dN_{\nu_\mu}}{dz} = \int_{E_{\nu_\mu}^{\text{min}}(E_{\nu_\mu})}^{\infty} \frac{N_\pi(E_\pi, z)}{\Lambda_\pi(E_\pi)} P_{\pi\nu_\mu}^{\text{decay}}(E_\pi, E_{\nu_\mu}) dE_\pi + \int_{E_{\nu_\mu}}^{\infty} \frac{N_\mu(E_\mu, z)}{\lambda_\mu(E_\mu)} P_{\mu\nu}^{\text{decay}}(E_\mu, E_{\nu_\mu}) dE_\mu. \quad (25)$$

This must be numerically integrated to give $N_{\nu_\mu}(E_{\nu_\mu}, z)$. In these equations the decay probabilities are simple kinematic functions:

$$P_{\pi\nu_\mu}^{\text{decay}}(E_\pi) = \frac{1}{E_\pi} \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-1} \quad (26)$$

and, for $\bar{\nu}_\mu$ from μ^+ ,

$$P_{\mu\nu_\mu}^{\text{decay}}(E_\mu, E_{\nu_\mu}) = \frac{1}{E_\mu} \left[\frac{5}{3} - 3\left(\frac{E_{\nu_\mu}}{E_\mu}\right)^2 + \frac{4}{3}\left(\frac{E_{\nu_\mu}}{E_\mu}\right)^3 \right]. \quad (27)$$

In equation (25) the first term is the contribution from pion decay, with $N_\pi(E_\pi, z)$ given by formula (15). The second term gives the neutrinos from the tertiary process of muon decay with $N_\mu(E_\mu, z)$ obtained by numerically integrating (23). Even though there is one muon neutrino from muon decay for every muon neutrino from pion decay, the former is generally of lower energy and, because of the falling power-law spectrum, contributes only slightly to the resulting neutrino spectrum. The production by kaons and other particles has been neglected since such contributions will be less than the accuracy of this calculation, which cannot be expected to be better than 20%.

III. DISCUSSION OF RESULTS

Equations (22) and (25) above can be used to estimate the photon and neutrino fluxes which would occur at Earth from various sources, assuming particular models for these sources. It is more instructive, however, to ask what general conditions emerge which are independent of specific models, and whether these conditions may realistically be expected to exist in astronomical bodies.

a) Conditions for Maximum Photon and Neutrino Production

The quantitative results of our calculation will depend strongly on four basic parameters: the proton intensity at 1 TeV, $N_p(1)$; the proton spectral index α ; the matter density ρ ; and the integrated path length z . Before discussing the requirements for a detectable flux at Earth, let us first determine the

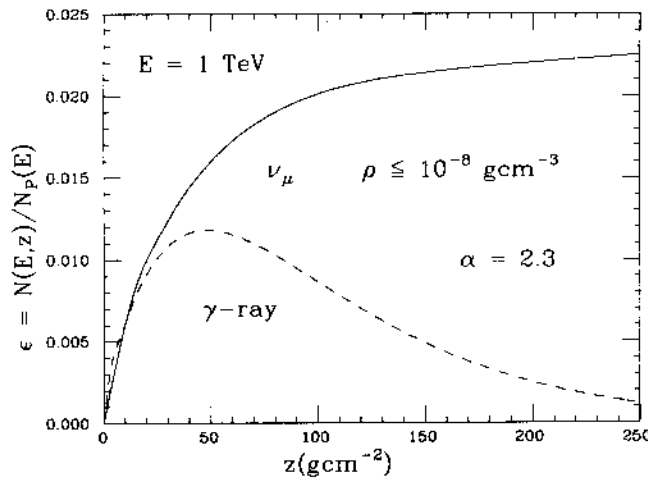


FIG. 1.—The efficiency for muon neutrino (solid) and γ -ray (dashed) emission at 1 TeV for a point source surrounded by a shell of matter density $\rho \leq 10^{-8} \text{ g cm}^{-3}$, as a function of the integrated path length z . The proton spectral index $\alpha = 2.3$. The γ -ray emission is independent of ρ .

conditions which must exist at the source for maximal production of γ -rays or neutrinos. For this purpose we define the efficiency for photon or neutrino production

$$\epsilon_{\gamma, \nu} = \frac{N_{\gamma, \nu}(E, z)}{N_p(E, 0)}, \quad (28)$$

that is, the ratio of the rate of production of photons or neutrinos in a given energy band to the rate of incoming protons in the same energy band, after these protons have traversed a path length z . Note that this is not, strictly speaking, an efficiency since the output, a flux of particles of energy E , does not result from an input flux of protons of energy E , but rather all those above E . Nevertheless $\epsilon_{\gamma, \nu}$ is still a convenient measure of the effectiveness of the production process.

The cosmic ray spectrum observed at Earth has a differential spectral index $\alpha = 2.7$. It is likely that the spectrum at the source is somewhat flatter, being steepened by leakage from the Galaxy. Various acceleration mechanisms, such as shock

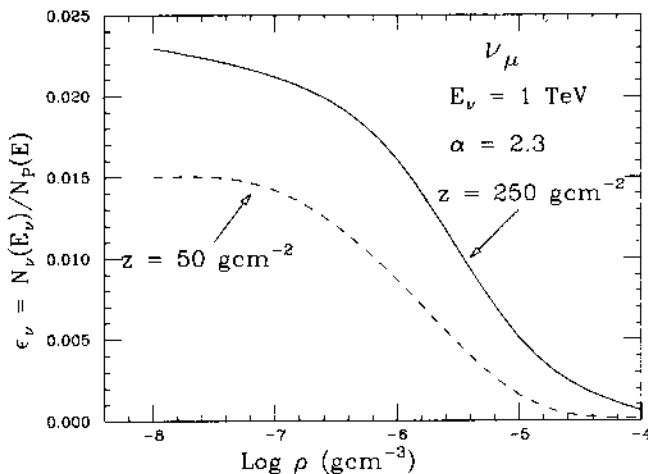


FIG. 2.—The efficiency for muon neutrino emission at 1 TeV for a point source surrounded by a shell of matter density ρ and integrated path length z , as a function of ρ , for two values of z . The proton spectral index $\alpha = 2.3$.

waves, can lead to a spectrum at the source as flat as $\alpha = 2$ (Blandford and Ostriker 1978; Bell 1978). There are several general observations which can be made which are not strongly dependent on α . We will illustrate these using the intermediate value $\alpha = 2.3$.

Plots of ϵ_γ and ϵ_ν as a function of z are given in Figure 1, for the energy band $1 < E < 2 \text{ TeV}$. A matter density $\rho \leq 10^{-8} \text{ g cm}^{-3}$ applies for the neutrino case (cf. Fig. 2). The γ -ray result is independent of density over any reasonable range. We see that the photon production efficiency peaks at about 50 g cm^{-2} , approximately the radiation length ($X_R = 60 \text{ g cm}^{-2}$ was used in the calculation). The dropoff at higher z results from the action of the first term on the right of equation (22), which crudely accounts for all the ways photons can lose energy by electromagnetic interactions with matter, e.g., Compton scattering and pair production.

The resulting redistribution of photons to lower energies by the electromagnetic cascade is beyond the scope of this work, which centers on energies above 1 TeV. Similarly, the role of accelerated electrons which, by synchrotron and other losses, will contribute to the lower energy photon spectrum is avoided, except to remark that with the magnetic fields and photon densities existing in the types of sources we are considering, electronic processes probably contribute little to the very high energy end of the observed γ -ray spectrum.

The photon density surrounding the source may also be large enough to play a role in further redistribution of the γ -rays to lower energy. This is also not considered here, so that the γ -ray results can be regarded as an upper limit and specifically the contribution from hadronic processes.

Unlike the γ -rays, the neutrino production builds up continuously as the protons pass through increasing amounts of matter, but an approximate plateau is reached above $z \approx 100 \text{ g cm}^{-2}$. Significant neutrino production, at least 1% of the proton flux, results for $z > 20 \text{ g cm}^{-2}$.

The dependence of neutrino production on matter density ρ is evident from Figure 2. For $\rho > 10^{-8} \text{ g cm}^{-3}$ we begin to see the effect of pions interacting before they have a chance to decay and produce neutrinos, the neutrino emission falling sharply as the density increases.

The expected spectra of γ -rays and neutrinos are illustrated in Figure 3. The γ -ray spectrum is found to have a spectral

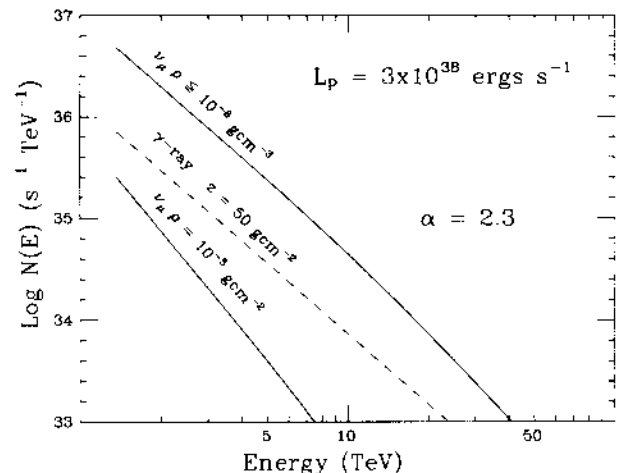


FIG. 3.—The muon neutrino (solid) $3 \times 10^{38} \text{ ergs s}^{-1}$ and γ -ray (dashed) emission spectra for a point source of proton luminosity $10^{38} \text{ ergs s}^{-1}$ surrounded by a shell of matter density ρ and integrated path length z . The proton spectral index $\alpha = 2.3$.

index equal to that of the incident proton, 2.3 in this case. To the extent that the assumptions made here apply, this implies that an observation of the γ -ray spectrum would directly give the shape of the source proton spectrum, information which is not readily available in the charged cosmic rays observed at Earth. Knowledge of the proton spectrum at the source would be invaluable in attempting to understand the acceleration mechanism. In fact, the observations of Cygnus X-3 γ -rays show an E^{-2} spectrum, as expected for efficient cosmic-ray acceleration and flatter than the cosmic rays observed at Earth (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983).

The neutrino spectrum steepens as the density increases. Although not shown, the spectral index eventually becomes one unit greater than the source index at higher densities. The analogous effect is observed for muons produced by cosmic ray protons hitting the Earth's atmosphere. We can conclude that a measurement of the neutrino spectrum provides information about the matter density surrounding the source. Gamma-ray and neutrino observations at very high energies are thus highly complementary, with measurements of their spectra and relative fluxes providing information on α , ρ , and z .

The dependence of the neutrino production efficiency on α is shown in Figure 4. We have assumed that the flattest source spectrum which can be expected has $\alpha = 2$. This would result, for example, from shock acceleration with negligible losses, and would lead to maximal neutrino production of 7% under optimum conditions. On the other hand, the efficiency drops below 2% for steep spectra.

The conclusion drawn from these results is that significant photon or neutrino production at very high energies will not occur, at least by the mechanisms considered, except when the source is a compact object surrounded by large amounts of matter or intense magnetic fields which trap very high energy protons. Gamma-rays will be suppressed when the column density exceeds 50 g cm^{-2} or when there is high photon density. The best candidate sources are neutron stars or black holes on the stellar scale, and massive black holes at the centers of galaxies.

b) Predicted Fluxes of Very High Energy Photons and Neutrinos

If $N_p(E)$ is the proton intensity in an energy band E , per TeV, then the proton energy luminosity per decade of energy in that

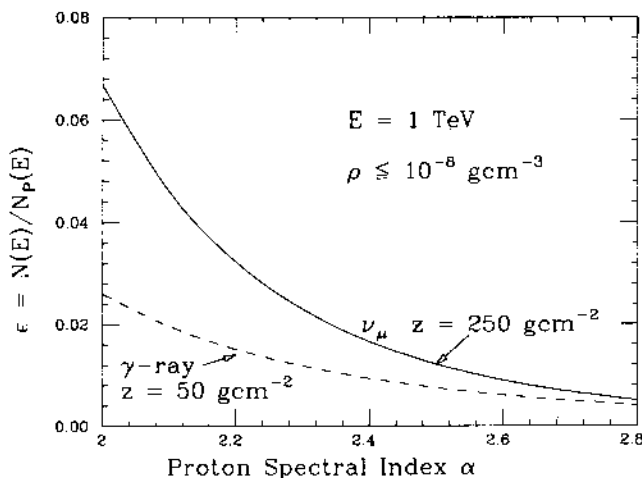


FIG. 4.—The efficiency for muon neutrino and γ -ray emission at 1 TeV for a point source surrounded by a shell of matter density ρ and column density z which are optimum in each case, as a function of the proton spectral index α .

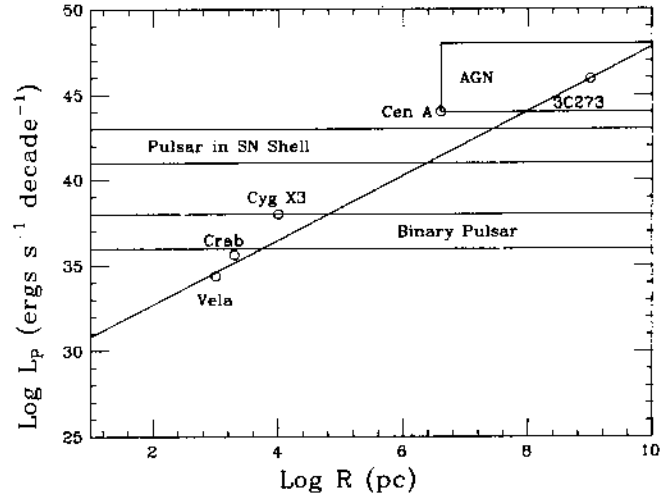


FIG. 5.—The solid line shows the proton energy luminosity per decade required to produce detectable neutrinos or γ -rays under optimum conditions for each, as a function of distance to the source. The points show the observed electromagnetic luminosities observed in X-rays and γ -rays for some specific sources inside and outside the Galaxy. The bands indicate the estimated luminosity range for three types of sources: binary pulsars, early stage supernovae, and active galaxies.

band is

$$L_p(E) = E^2 N_p(E), \quad (29)$$

and we can rewrite equation (1) as

$$N_p(E) = L_p(1) E^{-\alpha}. \quad (30)$$

The flux of photons or neutrinos above an energy E at a distance R , for an isotropic source,² is then

$$F_{\gamma, \nu}(>E) = \epsilon_{\gamma, \nu}(\alpha) \frac{L_p(1)}{4\pi(\alpha-1)R^2} E^{1-\alpha}, \quad (31)$$

where $\epsilon_{\gamma, \nu}(\alpha)$ is given in Figure 4. Let us consider the case when the best conditions exist for γ -ray or neutrino production. Then, from Figure 4, $\epsilon_\gamma = 0.026$ and $\epsilon_\nu = 0.067$ with $\alpha = 2$.

The typical flux sensitivity for the detection of γ -rays using the atmospheric Cerenkov technique is $10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ above 1 TeV (Grindlay 1982). For neutrinos above 1 TeV, the Deep Undersea Muon and Neutrino Detector (DUMAND) has estimated minimum detectable flux, for $\alpha \approx 2$, of $10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ (DUMAND 1982). Let us define fluxes at this level to be detectable.

In Figure 5 we plot the proton luminosity $L_p(1)$ which is required to produce a detectable flux of γ -rays or neutrinos above 1 TeV from a source at a distance R . Since the neutrino production efficiency is about 3 times the γ -ray production efficiency, while the flux sensitivities are in approximately the inverse ratio, both are coincidentally represented by approximately the same line.

The electromagnetic luminosity of a source powered by gravitation cannot be appreciably greater than the Eddington-limited value: $L_{\text{Ed}} = 1.38 \times 10^{38} (M/M_\odot) \text{ ergs s}^{-1}$ for a source of mass M . This limit does not apply in the case of the processes being considered here, but we can still regard it as a familiar benchmark. From Figure 5 it would appear that a stellar-size object within $\sim 50 \text{ kpc}$ radiating near the Eddington limit at

² Any beaming effects would of course enhance the flux along the line of sight and deplete it at large angles.

TeV energies would be sufficiently energetic to produce detectable very high energy γ -rays or neutrinos, if the other conditions discussed above are met. Supermassive objects as high as $10^9 M_\odot$, such as the black holes which may exist at the centers of active galaxies, could have sufficient energy to be detectable at quasar distances.

Let us ask whether there is any evidence for proton luminosities at very high energies adequate to produce detectable photons and neutrinos. Note from equation (29) that an E^{-2} proton spectrum implies a constant energy luminosity per decade. That is, if the source of particle acceleration is highly efficient, such as in the case of strong shocks (Blandford and Ostriker 1978; Bell 1978), it will produce equal luminosities in all energy bands. Remarkably, this effect seems to be approximately consistent with observations in the electromagnetic spectrum, from the optical to γ -rays, for two main classes of compact objects we consider to be potential sources: pulsars and active galaxies. For example, the Crab has an electromagnetic luminosity of $\sim 10^{37}$ ergs s^{-1} over the nine orders of magnitude in energy from 1 to 10^9 eV. On a vaster scale, quasar 3C 273 emits $\sim 10^{46}$ ergs s^{-1} over the same range in photon energy. Assuming that the electromagnetic spectrum results ultimately from the acceleration of protons and electrons in the source, we might expect L_p to be of the order of the measured L_{em} .

In our Galaxy, the Crab and Vela pulsars have been observed in both the low (Kniffen *et al.* 1974; Thompson *et al.* 1975) and very high (Grindlay 1982) energy γ -ray bands. The electromagnetic luminosities implied by X-ray and γ -ray observations of these sources are shown in Figure 5. Both fall about on the line for detectable TeV γ -rays or neutrinos. We must hasten to add, however, that this does not constitute a prediction of measurable neutrino fluxes from the Crab and Vela, but rather simply that we have at least two examples of pulsars with adequate energy production. The fact that these pulsars are visible in the optical would seem to rule them out specifically as likely neutrino sources, given the requirement of ≥ 10 g cm^{-2} of matter along the line of sight. However, we can take the Crab as a prototype neutron star and imagine other situations where there may be large amount of matter in the vicinity.

For example, it has been suggested (Berezinsky and Prilutsky 1976) that during the early stages of a supernova the remnant neutron star is surrounded by a sufficiently thick shell of matter (~ 100 g cm^{-2} for ~ 1 month) to produce neutrinos. Another suggestion (Eichler and Schramm 1978) is that a pulsar in a binary system could produce γ -rays and neutrinos by accelerating particles which collide with the companion star. Bands indicating the expected range of luminosities from these types of sources are shown in Figure 5. The results of the present paper indicate that they are indeed good possibilities for detectable neutrino sources in our Galaxy and possibly other galaxies in our Local Group.

The quasar 3C 273 has also been observed to emit low-energy γ -rays (Swanenburg *et al.* 1978), but only an upper limit flux has been set at 1 TeV (Weekes *et al.* 1972). As seen in Figure 5, if the 1 TeV photon luminosity is the same as observed at lower energies, then TeV γ -rays are marginally detectable and neutrinos may be as well. This important result is consistent with independent calculations (Protheroe and Kazanas 1983). To the extent that nearer objects, such as Seyferts and radio galaxies, are similar in nature, they may be observable. Since the power sources for quasars and active

galaxies are possibly supermassive compact objects in their nuclei, these represent perhaps the most interesting candidates for neutrino sources. Several authors (Berezinsky and Ginzburg 1981; Kafatos, Shapiro, and Silberberg 1981) have emphasized that a combination of neutrino and γ -ray observations may be a powerful way to distinguish between models of these power sources, and have made estimates of the column density which are of the order of 100 g cm^{-2} . Even if the line-of-sight column density is small, there may be adequate magnetic fields to trap protons so that they still have a high probability of interacting. A band indicating the possible range of luminosities from active galaxies is given in Figure 5.

There are two X-ray sources which have been fairly convincingly observed in the TeV γ -ray region or above, but not yet at lower γ -ray energies: Cygnus X-3 in our own Galaxy (Fomin *et al.* 1981) and the radio galaxy Cen A. The X-ray luminosities for these objects, which are comparable to the less-reliable atmospheric Cerenkov measurements, are also shown in Figure 5. Cygnus X-3 is a possibility for the binary pulsar process discussed above, its electromagnetic luminosity being more than adequate. Centaurus A, the nearest active galaxy, has a luminosity two orders of magnitude greater than that needed under optimum conditions.

Sources of the types discussed are candidates for hadronic production of γ -rays and neutrinos, although electronic sources of γ -rays with negligible neutrino production cannot be ruled out at this stage for the sources below a few TeV. Any γ -rays above that energy, such as those from Cyg X-3, almost certainly result from proton acceleration since magnetic fields will very likely prevent electrons from being accelerated to such energies. The observation of neutrinos from any source would convincingly confirm the existence of protons being accelerated to very high energies, help determine the acceleration mechanism, and provide information on the density of matter surrounding the source.

IV. SUMMARY AND CONCLUSIONS

From general and (fairly) model-independent considerations it has been shown that the production of measurable fluxes of very high energy photons and neutrinos by cosmic-ray protons from around compact objects is a viable possibility. Protons are being accelerated somewhere in the cosmos to energies far exceeding any earthbound particle accelerator. If these protons pass through sufficient matter, they can efficiently generate γ -rays and neutrinos by pion production and decay in sufficient numbers to be detected by feasible experiments.

The efficiency of production depends on the matter density ρ , integrated column density z , and proton spectral index α . The most efficient production occurs when the spectrum is flat, as is expected from general considerations in several proposed cosmic ray acceleration mechanisms such as strong shocks. The predicted spectrum, E^{-2} , is in fact suggested by observations over the entire electromagnetic spectrum for a wide class of objects from pulsars to quasars. Maximal γ -ray production occurs at $z \approx 50$ g cm^{-2} . Maximal neutrino production occurs when $\rho \leq 10^{-8}$ g cm^{-3} and $z \geq 100$ g cm^{-2} . While these column densities are large by usual astronomical standards, they cannot be ruled out of hand by conventional astronomical observations which see only a few g cm^{-2} into the matter. It is certainly possible to conceive of great thicknesses of matter in the vicinity of compact objects. It is also possible to conceive of the presence of high magnetic fields nearby which are capable

of trapping protons so that they have close to unit probability of interacting to produce pions.

The requirement of $\rho \leq 10^{-8} \text{ g cm}^{-3}$ for maximal neutrino production is not considered unreasonable in many cases, but may be exceeded near compact objects or when the proton beam passes through a companion object.

The fluxes of γ -rays above 1 TeV from three galactic objects and one extragalactic object, calculated on the basis of the most optimistic assumptions, are compatible with those observed using the atmospheric Cerenkov technique. However, since most of the considerations used in making these estimates are fairly general, similar flux levels might be expected from nonhadronic mechanisms; so this cannot be regarded as a verification but merely an encouraging suggestion that the mechanisms discussed here may play a major role.

If the predicted levels of neutrinos above 1 TeV are confirmed by future observations, then we would have strong and direct evidence that a major component of cosmic-ray proton

acceleration occurs in very localized regions of space buried deep in matter. Thus very high energy γ -ray and neutrino astronomy are highly complementary; electromagnetic observations by themselves can lead to ambiguous interpretations of the mechanisms involved. By a combination of observations on the fluxes and spectra of γ -rays and neutrinos from a particular source we obtain the spectrum of the primary protons at the site of acceleration and the nature of the matter around the object. In doing so we will peer far deeper into the object than is possible by any other known means.

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