High Energy Neutrino Astronomy –the cosmic-ray connection[1]

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Abstract. Several of the models for origin of the highest energy cosmic rays also predict significant neutrino fluxes. A common factor of the models is that they must provide sufficient power to supply the observed energy in the extragalactic component of the cosmic radiation. The assumption that a comparable amount of energy goes into high-energy neutrinos allows a model-independent estimate of the neutrino signal that may be expected.

I INTRODUCTION

An important argument in favor of supernova explosions as the power source for galactic cosmic rays is the fact that kinetic energy of the ejecta supplies the right amount of power. The energy content of the cosmic radiation is

$$\rho_E = \frac{4\pi}{c} \int E\,\phi(E)\,dE \;\approx\; 10^{-12}\,\mathrm{erg/cm^3}, \tag{1}$$

where $\phi(E) = dN/dE$ is the measured local flux of cosmic rays corrected for the effect of solar modulation. In the source region the average energy density in cosmic rays is related to the average production rate per unit volume, $q(E)$, by

$$\rho_E \;=\; q(E) \times \tau_{esc}(E), \tag{2}$$

where τ_{esc} is the characteristic residence time of cosmic rays in the source region (for example the disk of the galaxy). The characteristic time, $\tau_{esc}(E)$, decreases with energy [1] so that the observed spectrum is somewhat steeper than the source spectrum.

Given an estimate of τ_{esc} and the rate of supernova explosions, it is possible to estimate the fraction of energy of supernova explosions needed to maintain the galactic cosmic rays in steady state, assuming that supernovae provide the power, $q(E)$. Assuming a rate of three supernovae per century with a kinetic energy of 10^{51}

1) Research supported in part by NASA grant NAG5-7009

ergs per supernova, the conclusion is that an efficiency of $\sim 10\%$ for conversion of kinetic energy of supernova ejecta into relativistic cosmic rays would suffice. In the years since this coincidence was pointed out [2], a theory of cosmic-ray modified shocks with a high efficiency for particle acceleration has been developed [3]. A compelling feature of this theory is that it produces a spectral index that fits in well with what is observed after energy dependence of propagation is accounted for.

Here we want to apply a similar analysis of energetics to cosmic rays of extragalactic origin The reason to focus on the high energy end of the cosmic ray spectrum in connection with high energy neutrino astronomy is that several models have been suggested as sources of ultra-high energy cosmic rays which would also be likely sources of high energy neutrinos. These include some models of active galactic nuclei (AGN) and some models of gamma-ray burst (GRB) sources.

In the case of galactic cosmic rays, if the production rate of neutrinos is proportional to that of cosmic rays, $q_\nu(E) = f \times q(E)$, we would expect a flux of neutrinos related to the cosmic-ray flux by

$$\phi_\nu \propto \frac{V_D}{c} \times f \times \phi_{cr}, \tag{3}$$

where f is the efficiency with which the cosmic rays interact to produce neutrinos (either in the source region or in the interstellar medium) and V_D is the velocity of diffusion of cosmic rays out of the galaxy. $V_D \sim R_{galaxy}/\tau_{esc}$ depends on the model of cosmic-ray propagation in the galaxy, but in any case $V_D \ll c$. Thus the galactic neutrino flux should be suppressed by a large factor relative to the parent cosmic rays because of their straight-line propagation out of the galaxy. For the same reason, neutrinos, like gamma-rays, would be expected to show the structure of the galactic disk.

For a cosmological distribution of sources of ultra-high energy cosmic rays we assume initially, for the rough estimates discussed below, that

$$V_D \;\sim\; R_H/\tau_H \;\sim\; \frac{3000\,\mathrm{Mpc}}{10^{10} yrs} \;\approx\; c. \tag{4}$$

This approximation neglects evolution and assumes that the intergalactic magnetic fields are weak enough so that charged particles can reach us from distant sources in less than the age of the universe. The situation for super-GZK particles, where the maximum distance of propagation is limited to $R \ll R_H$ by photo-pion production, needs a separate discussion. The possibility of large inter-galactic magnetic fields and local concentrations of sources [4,5] would also have to be considered for a full treatment of the cosmic-ray spectrum. We use the approximation of Eq. 4 primarily to derive an estimate of the diffuse flux of high energy neutrinos that may be associated with the sources of extragalactic cosmic rays.

The outline of the paper is as follows. First we discuss the transition from galactic to extragalactic cosmic radiation in order to define an extragalactic component.

Then we compare the power needed for the extragalactic cosmic radiation with that available from various potential sources. We conclude with a review of the predictions for detection of high energy neutrinos.

II EXTRAGALACTIC COMPONENT OF COSMIC RAYS

It is generally believed that sources of the highest energy cosmic rays are extragalactic, or at least not confined to the plane of the galaxy. Indeed, there is some evidence for a transition from one particle population to another somewhere above 10^{18} eV. There is a trend from heavy toward lighter composition in the measurements of $X_{\max}$ versus energy (see Fig. 1) and a suggestion of a hardening of the spectrum between 10^{18} and 10^{19} eV (see Fig. 2). The picture is not as clear as it first appeared in the original stereo Fly's Eye result [6]. For example, the coincident measurements of the prototype HiRes Fly's Eye with the MIA ground array [7], as shown by the gray, filled circles in Fig. 2, have a steeper slope and trend toward the proton curve more quickly than the original Fly's Eye data (black triangles). This would indicate a stronger change of composition at a somewhat lower energy.

Another relevant piece of information is the anisotropy measurements from AGASA [13] and Fly's Eye [14], which can be interpreted as an enhancement of particles from near the direction of the galactic center in the energy bin around 10^{18} eV [15]. The anisotropy disappears at higher energy.

Although the experimental picture is still not entirely clear, in order to estimate the power 0 we assume in what follows that the transition to cosmic rays of extragalactic origin occurs between 10^{18} and 10^{19} eV.

III POWER FOR EXTRAGALACTIC COSMIC RAYS

Measurements of the cosmic-ray spectrum above 10^{17} eV are summarized in Fig. 2. There are at least three problems that must be dealt with to estimate the power required to supply the extragalactic cosmic radiation. First is where the transition to the extragalactic component occurs in the data. As discussed above, we assume that the particles with $E > 3 \times 10^{18}$ eV are mostly of extragalactic origin and normalize the extragalactic component at $E \geq 10^{19}$ eV. To set the scale for the uncertainty in this assumption, we investigate below the consequences of increasing or decreasing the crossover energy by half a decade. The second problem is to decide how to extrapolate to lower energy where the observed spectrum is likely dominated by cosmic rays from inside the galaxy. This is important because most of the energy content is likely to be in the lower energy particles. Finally, we must deal separately with the super-GZK particles whose sources must be relatively nearby. We deal with these points in turn.

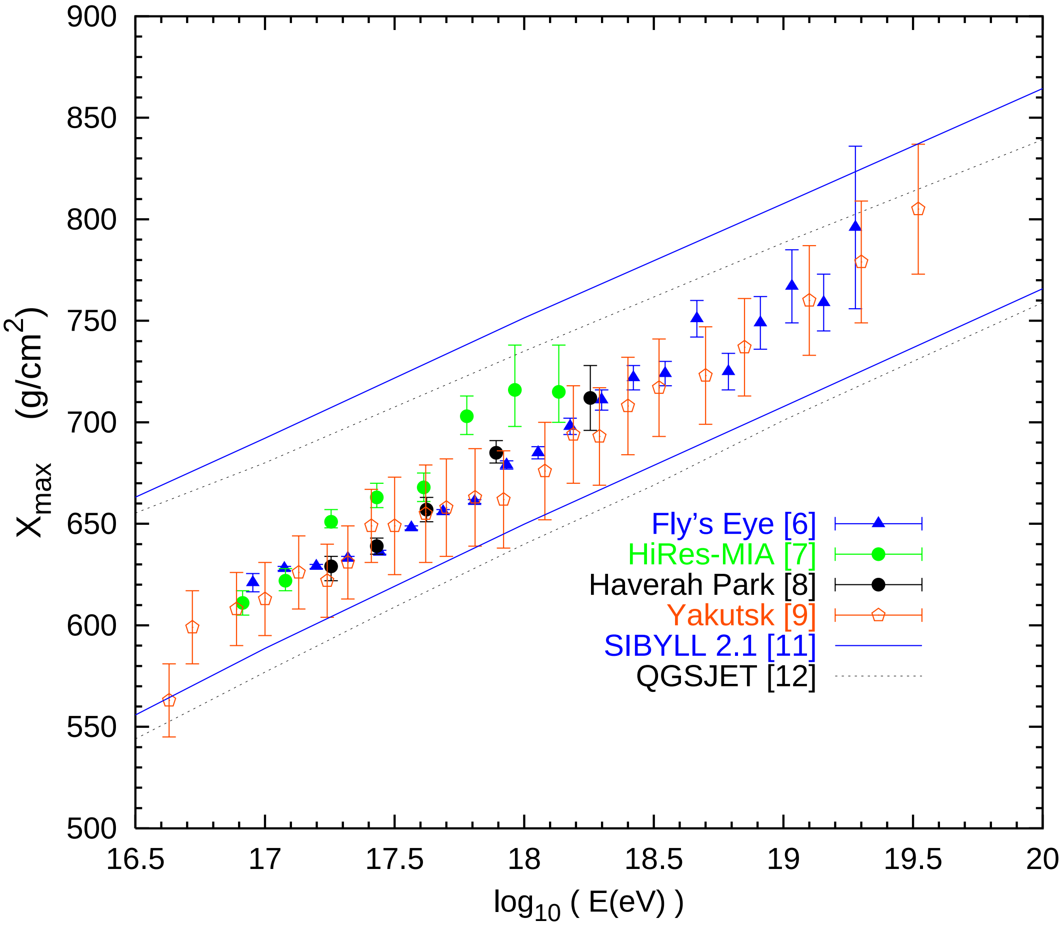

FIGURE 1. Average depth of shower maximum (X_{max}) vs. energy [6–9] compared to calculated [10] protons (upper curves) and iron primaries (lower curves) in two models [11,12].

A Normalization at high energy

Normalizing an E^{-2} differential spectrum, as is generally assumed for the sources of the highest energy cosmic rays [22,23], to a measured spectrum with a differential spectral index close to $\alpha = 3$ is a highly uncertain operation. The lower heavy line in Fig. 2 shows a spectrum with $\alpha = 2$ and an exponential cutoff at 5×10^{19} eV to represent the GZK effect. The excess of data above the curve for $E < 10^{19}$ eV may be attributed to the high energy tail of the galactic cosmic-ray spectrum. Another possibility could be that we live inside a cosmologically local concentration of extragalactic sources of cosmic rays which propagate with an energy-dependent τ_{esc} analogously to galactic cosmic rays.

Integrating the energy content under this curve as in Eq. 1 gives for the energy density in cosmic rays of extragalactic origin, $\rho_{EG} \sim 2 \times 10^{-19}$ erg/cm^3. Note that this result assumes the extragalactic spectrum extends down to ~ 1 GeV. Replacing

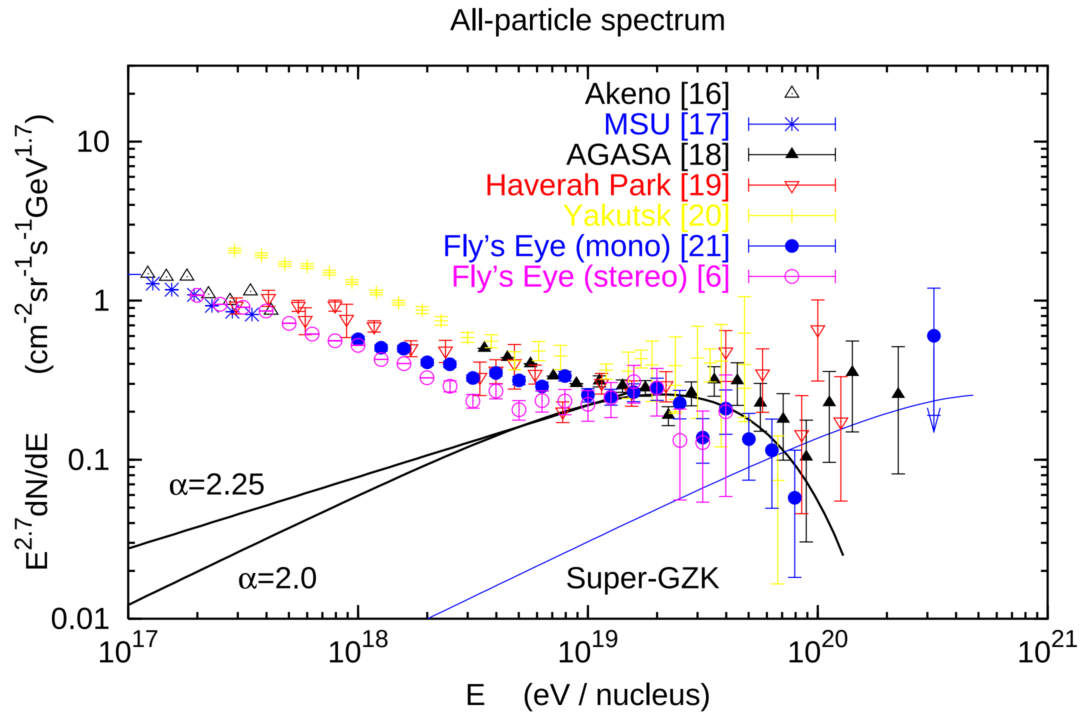

FIGURE 2. The high energy cosmic rays spectrum. See text for explanation of curves. Data are from Refs. [16–21,6]

$\tau_{esc} \to \tau_H \approx 10^{10}$ yrs in Eq. 2 then leads to the estimate $q_{EG} \sim 10^{37}$ erg/Mpc^3/s. Shifting the normalization point lower (or higher) by half a decade in energy would increase (decrease) this estimate by roughly a factor of two. This is comparable to the systematic differences among the different measurements of the spectrum.

Table 1 shows what this power requirement would imply for various classes of potential sources. In each case, these are comparable to observed luminosities. Therefore all are plausible potential sources provided a mechanism exists to achieve $E_{max} \sim 10^{20}$ eV. (For clusters of galaxies see Refs. [24,25]; for active galaxies [26] and for GRB [27,28].)

B Extrapolation to low energy

If the spectral index of the extragalactic source spectrum is steeper than $\alpha = 2$, then the power requirement will be greater. Both AGN and (especially) GRB involve relativistic shocks. Acceleration at relativistic shocks typically produces a spectral index $\alpha \approx 2.25$ [29–31]. The difference is particularly important in the case of GRB where the bulk Lorentz factor $\Gamma \sim 300$. Such a spectrum, with the same normalization at 10^{19} eV is shown by the upper heavy line in Fig. 2. In general

TABLE 1. Power per source for extragalactic cosmic rays

Source density (rate)	Power per source
3×10^{-3} galaxies/Mpc^3	3×10^{39} erg/s/galaxy
3×10^{-6} clusters/Mpc^3	3×10^{42} erg/s/cluster
10^{-7} AGN/Mpc^3	10^{44} erg/s/Active galaxy
1000 GRB/yr	3×10^{52} erg/GRB

$$\frac{q(\alpha)}{q(\alpha=2)} = \left(\frac{10^{19}\,\mathrm{eV}}{E_{min}}\right)^{(\alpha-2)} \times \frac{1}{(\alpha-2)\,\ln(E_{max}/E_{min})}, \tag{5}$$

where the normalization is fixed at 10^{19} eV. For $\alpha \approx 2.3$ and $E_{min} \approx 1$ GeV, the power requirement is a factor of ~ 100 greater than for $\alpha = 2.0$.

Vietri [32] argues, however, that in the case of a relativistic shock accelerating particles from swept up material, $E_{min} \sim \Gamma^2 \times m_p$, which corresponds to $E_{min} \sim$ 100 TeV for GRB with $\Gamma \sim 300$. In this case the enhancement factor in Eq. 5 is only about a factor of 3, and the power requirement increases from 3×10^{52} to 10^{53} erg/GRB.

C Super-GZK particles

One possibility is that the particles above the GZK cutoff may be due to a local concentration of the same type of sources that produce a universal component [33,34]. The line labelled *Super-GZK* in Fig. 2 represents a possible contribution from such nearby sources, assuming $\alpha = 2$. The energy integral for this component is approximately a factor of four lower than for the corresponding universal contribution, but the power density to supply it is higher by a factor of five or ten because the distance from which sources can contribute is limited by energy loss due to photo-pion production. A factor of 5-10 local overdensity of sources of ultra-high energy cosmic rays is difficult to reconcile with other considerations. For example, Ref. [35] points out that most of the GRB rate comes from sources with $z \sim 1$. (See Ref. [36] for a different GRB scenario.) A local overdensity of more than a factor ~ 2 would also be difficult to reconcile with data on the large scale distribution of matter in our vicinity of the universe [37]. Given the limited statistics, however, this explanation cannot be ruled out if the source spectrum is hard enough ($\alpha \leq 2$ [37]).

Another possibility is that the super-GZK particles have a different origin altogether, being products of parton cascades generated by decay or annihilation of GUT-scale objects, such as topological defects [38] or massive relic particles [39]. In both cases the cascade consists of hadronization of partons at extremely high mass scale. Thus the ratio of photons and neutrinos to protons at production is large because pions dominate the hadronic cascade. However, in the case of a cosmological distribution of sources, the photons will initiate electromagnetic cascades during propagation in the microwave background, reducing their contribution to the observed super-GZK events [40]. In the model of decaying massive relics, however, the predominant contribution comes from relatively nearby – particles concentrated in the halo of the galaxy. In this case, electromagnetic cascading will be negligible, and the highest energy events would, for the most part, have to be photon-initiated showers. It has been known for some time that the big Fly's Eye event [41], for which the profile is measured, looks more like a shower initiated by a proton or nucleus than a photon [42]. Recently, an analysis of horizontal air showers [43] showed that most of the observed events above the GZK cutoff cannot be initiated by photons.

IV EXPECTED NEUTRINO FLUXES

A standard technique to search for high energy neutrinos of astrophysical origin is to look for upward-moving muons induced by ν_μ that have penetrated the Earth. The signal is the convolution

$$Signal \;\sim\; Area \otimes R_\mu \, N_A \otimes \sigma_\nu \otimes \phi_\nu, \tag{6}$$

where R_μ is the muon range in g/cm^2 and N_A is Avogadro's number. The range and cross section both increase linearly with energy into the TeV region, after which the rate of increase slows. Neutrinos with $E_\nu < 100$ TeV are not strongly attenuated by the Earth, and much of the solid angle away from the nadir remains accessible up to 1 PeV [44]. Thus the optimum range for ν_μ-induced upward muons is from a TeV to a PeV. Also in this energy range the muon energy loss is greater than minimum ionizing, which is a potential way to discriminate against the background of atmospheric neutrinos, which have a steeply falling spectrum. In what follows, I use the cross sections from Ref. [44], taking account of absorption by the Earth, to estimate ν_μ-induced signals in a kilometer-scale detector. A minimum pathlength of 0.5 km inside the detector is required, which corresponds to a threshold of approximately $E_\mu \geq 100$ GeV in water.

A Generic estimate

Using the normalization of § III-A and assuming $\alpha \sim 2.0$ for the neutrinos as well as the cosmic rays, one estimates a signal of $f \times 30$ events/km^2/yr [45], where f is the efficiency for production of neutrinos relative to cosmic rays. For $f = 1$ this is essentially the Waxman-Bahcall upper bound [22], which applies for sources that are transparent to neutrons. If evolution is included, this estimate may be increased by factor of about five if sources are assumed to evolve similarly to the rate of star formation [22,46]. This is because the ultra-high energy protons from high redshift would be attenuated by photoproduction and pair production while the neutrinos would not. Thus the neutrino flux would be greater for a given cosmic-ray flux at the normalization point. In addition, if the spectrum of extragalactic cosmic rays to which the normalization is made has $\alpha > 2.0$, then the corresponding estimated neutrino flux in the TeV to PeV range and the corresponding signal could also be larger.

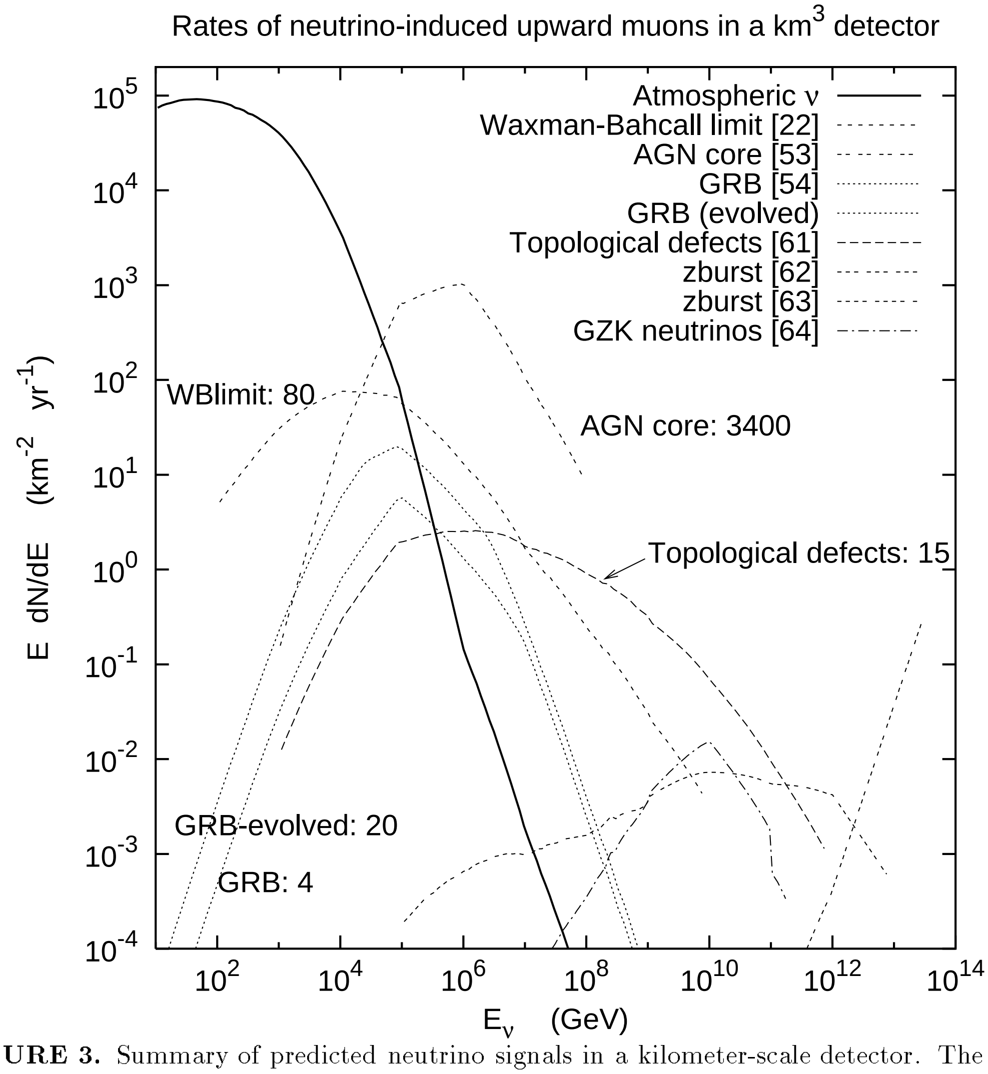

FIGURE 3. Summary of predicted neutrino signals in a kilometer-scale detector. The diffuse signal per year per steradian per logarithmic energy interval is plotted as a function of E_ν. Numbers indicate events per year above atmospheric background (see text).

B Predictions of models

Fig. 3 shows the rates of neutrino-induced upward muons predicted in various specific models. These are diffuse fluxes summed over 2π sr with absorption in the Earth accounted for. The background induced by atmospheric ν_μ is shown as the heavy solid line. The flattening of the atmospheric background at 1 PeV is due to an assumed prompt component of neutrinos from charm decay [47], the level of which is rather uncertain [48]. The numbers indicate events per year above atmospheric background, which I have estimated by taking the integral of the signal flux above the energy where it crosses the atmospheric background. This crossover is generally in the range of 100 – 300 TeV. Present upper limits from Frejus [49], Baikal [50] and AMANDA [51] rule out one of the original AGN core models [52], and the model of Ref. [53] (shown as AGN core in Fig. 3) is marginally allowed [49] or marginally ruled out [51]. The GRB curves in Fig. 3 are calculated from Eq. 6 starting from the unevolved GRB neutrino flux plotted in Ref. [22]. I assumed source evolution from Ref. [22] to obtain the GRB-evolved neutrino spectrum.

The GRB model [54], has an interesting feature, which illustrates the important point that the neutrino spectrum need not have the same shape as the parent spectrum of accelerated protons [55]. In this case the target for pion production is assumed to be the X-ray/γ-ray photons in the expanding fireball, which have approximately an E_γ^{-2} differential spectrum above a characteristic energy ϵ_b and an E_γ^{-1} spectrum below the break. For protons with energy sufficiently high to photoproduce on photons with $E_\gamma < \epsilon_b$, the resulting neutrino spectrum follows the parent proton spectrum. For lower energy protons, the density of target photons above threshold for photo-pion production decreases as the proton energy decreases. The result of this convolution is a break (steepening) in the neutrino spectrum, which, for the parameters of Ref. [54] occurs at $E_\nu \sim 100$ TeV. Since both R_μ and σ_ν are increasing with energy, this is where the signal peaks.

The key to detecting a diffuse signal above the atmospheric background is to look for an excess of events of high energy. Typically, muons with energies of several TeV and higher will radiate one or two bursts per kilometer of water in which they deposit some 10% of their energy. Such bursting tracks may be a useful signature.

C Point sources

With point sources, the atmospheric background can be reduced to an extent that depends on the angular resolution of the detector. As an example, Fig. 4 shows the signal that would be generated by a neutrino flux normalized to the level of the TeV γ-ray emission during the extended high-state of Mrk501 in 1997 [56–58], assuming $\phi_{\nu_\mu+\bar{\nu}_\mu} = \phi_\gamma$, (specifically using the fit of Ref. [56]). The atmospheric background is calculated assuming that the detector has a pointing resolution of 1° space angle, and the angle between the detected muon and the neutrino that produced it has been accounted for. The integral of the signal shown in the figure would give $\sim$ 30 events per year above atmospheric background. Unfortunately, Mrk501 is not normally such an intense source [59] as it was for half of 1997.

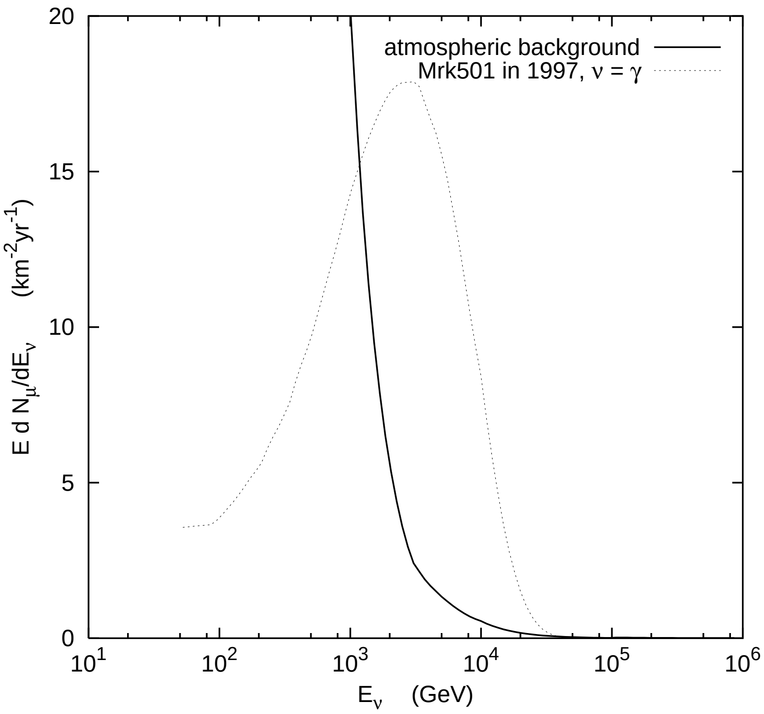

FIGURE 4. Predicted signal of ν-induced muons from a source with $\phi_\nu = \phi_\gamma$(Mrk 501, high). (See text.)

It is interesting that there is at least one AGN-blazar model in which a neutrino flux comparable to the γ-ray flux would be expected [60]. In this model the high energy photons and neutrinos come from decay of pions produced when blobs of ultra-relativistic gas collide with the interstellar medium of the host galaxy near the central engine of the AGN. Farther out the material slows down and merges into the jets that extend to large distance.

D Ultra-high energy neutrinos

Some of the "top-down" models for the ultra-high energy cosmic rays [61–63] predict an intensity of neutrinos with energies in the PeV range and higher that is somewhat above the neutrinos photo-produced by ultra-high energy cosmic rays on the microwave background (GZK neutrinos). The rates of ν_μ-induced upward neutrinos shown for those models in Fig. 3 are strongly attenuated by absorption in the Earth (although regenerated ν_τ could emerge with degraded energy [65]). However, the energy is high enough so that charged-current interactions of ν_e from above could be identified by the large electromagnetic cascades they would produce inside a kilometer-scale detector [66]. For example, the rate of downward events predicted by the model from Ref. [63] would be ~ 10 per year per km^3 even though the integrated rate of upward ν_μ-induced muons shown in Fig. 3 is $\ll 1$.

E Concluding comment

Estimates of the type discussed here – either based on energetics and a generic relation to extra-galactic cosmic rays, or on specific models – set the scale for a high energy neutrino telescope. The estimates are of the order of tens of events per year in a kilometer-scale detector. While the hope is that new kinds of "hidden" neutrino sources [67] will be discovered, the detector should be designed to find signals from likely known sources at this level.

ACKNOWLEDGEMENTS. I am grateful for helpful conversations with Jaime Alvarez-Muñiz, Todor Stanev and Mario Vietri.

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