High energy astrophysical neutrinos: The upper bound is robust

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We elucidate the physical basis for the upper bound on high energy neutrino fluxes implied by the observed cosmic ray flux. We stress that the bound is valid for neutrinos produced either by p, γ reactions or by $p - p(n)$ reactions in sources which are optically thin for high energy protons to photo-meson and nucleon-meson interactions. We show that the upper bound is robust and conservative. The Waxman-Bahcall bound overestimates the most likely neutrino flux by a factor $\sim 5/\tau$, for small optical depths τ. The upper limit cannot be plausibly evaded by invoking magnetic fields, optically thick active galactic nuclei (AGNs), or large hidden fluxes of extragalactic protons. We describe the implications of the bound for future experiments including the AMANDA, ANTARES, Auger, ICECUBE, NESTOR, and OWL/AIRWATCH detectors.

I. INTRODUCTION

The observed cosmic ray flux at high energies implies an upper bound on the high energy neutrino flux produced in astronomical sources that are, like gamma ray bursts and the observed jets of active galactic nuclei, optically thin to photo-meson interactions on protons [1]. The upper bound also applies to $p - p$ or $p - n$ collisions that create neutrinos via pion production in sources that are optically thin to nucleon-meson interactions. For simplicity, we shall refer in the following only to $p - p$ collisions when we really mean either $p - p$ or $p - n$ collisions.

The high energy protons that produce neutrinos by $p - \gamma$ or by $p - p$ interactions contribute to the observed cosmic ray flux after they leave the site where the neutrinos are created. Since they have maintained a high energy in spite of the possibility of interactions with the cosmic microwave background, protons that are detected at Earth with energies greater than 10^{18} eV must originate at redshifts $z < 1$. Therefore, the observed flux of high-energy cosmic rays determines the rate at which particles of those energies are being created in the relatively local universe. One can obtain an upper limit to the cosmic ray production rate in the whole universe by assuming that the rate increases with redshift like the fastest known population of astronomical sources, quasistellar sources (QSOs). Knowing an upper limit to the universal proton production rate, one can readily compute, by standard particle physics techniques, an upper limit to the rate of production of neutrinos by the same protons.

The conservative upper bound derived in this way has come to be known in the literature as the Waxman-Bahcall upper bound [1].

The upper bound exceeds what one can reasonably expect to measure. As we shall see in Sec. III, the limit is derived numerically by assuming that all of the energy of the high

energy protons produced in the astronomical sources is transferred to pions by photo-pion or nucleon-proton interactions. Each time that a π^+ is produced by photo-pion interactions it receives only about 20% of the initial proton energy [1]. For $p - p$ collisions at very high energies, the explicit calculation of the fraction of energy that is transferred to pions has not yet been done but is likely to be even less than for $p - p$ interactions. Thus, at the very least, the Waxman-Bahcall upper bound is conservative by a factor of five, and the most likely neutirno flux is about $5/\tau$ smaller than the Waxman-Bahcall limit for small optical depths.

The Waxman-Bahcall bound is consistent with our prediction of the expected flux of high energy neutrinos from gamma-ray bursts (GRBs) [1,2]. Naturally, the flux expected from GRBs is less than the maximum allowed by the bound. For the GRB calculation, we estimated that $\sim 20\%$ of the total proton energy is transferred by photo-mesonic interactions to pions (proton-nucleon interactions are less efficient [3]). As described in the previous paragraph, we assumed, in deriving our upper bound, that 100% of the proton energy is transferred to pions.

The upper bound we set from the observed cosmic ray flux is two orders of magnitude lower than the intensity predicted in some previously published models for the production of neutrinos in active galactic nuclei (AGN) jets, implying that a km² neutrino detector would record at most 1 neutrino from AGN jets per year. The same argument also rules out models in which most or all of the gamma-ray background is produced by photo-meson interactions in AGN jets.

Can the upper bound on the high energy neutrino flux be evaded? This is an important question since very large neutrino detectors are being designed for installation in the ocean or a deep lake (see, e.g., Refs. [4–6]), under Antarctic ice (see, e.g., Ref. [7]), in space (see, e.g., Ref. [8]), and large area ground arrays (see, e.g., Refs. [9,10]). The design characteristics for these neutrino detectors are being determined in part by the best available theoretical models. It is therefore necessary to examine carefully the justifications for different

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predictions of high energy neutrino fluxes. We do so in this paper.

The goal of this paper is to clarify how the Waxman-Bahcall upper bound follows from the measured cosmic ray flux and, in the process of the clarification, to demonstrate that the upper bound is robust and conservative. We emphasize the implications of the bound for future neutrino and gamma-ray observations.

There are two special types of sources for which the Waxman-Bahcall bound does not apply; these sources could in principle produce a neutrino flux exceeding the Waxman-Bahcall limit. The first special type of source is one in which neutrinos are produced by processes other than photo-meson or proton-nucleon interactions; the second type of special source is one for which the photo-meson (or proton-nucleon) optical depth is high. We begin by summarizing in Sec. II various speculations regarding the existence of such sources, for which we have no observational evidence to date. This section is particularly relevant for future neutrino observational programs. We then turn to a detailed discussion of the derviation of the bound and of its validity and robustness.

In Sec. III and Fig. 1, we summarize the existing data on the cosmic energy spectrum, including the limited information at very high energies that is derived from the Fly's Eye [11], AGASA [12], and Yakutsk [13] experiments. We show in this section that cosmic-ray observations imply a robust upper limit on neutrino fluxes in the energy range of $\sim 10^{16}$ eV to $\sim 10^{20}$ eV. What is expected at very high energies, $> 10^{20}$ eV, and at relatively low energies, $< 10^{16}$ eV? We argue in Sec. IV that it is plausible to extrapolate the Waxman-Bahcall bound to neutrino energies that correspond to protons more energetic than the expected Greisen-Zatsepin-Kuzmin cutoff at 5×10^{19} eV. In Sec. V, we summarize the observational evidence for the conventional viewpoint that most cosmic rays below 10^{18} eV are heavier particles of Galactic origin. Thus, the proton flux that is to be used in deriving the upper limit to the neutrino flux is much less than the total observed cosmic ray flux at energies below 10^{18} eV. We discuss the important question of whether sources that are not included in the Waxman-Bahcall bound derivation may exist in this energy range.

It has been common practice for some time to motivate proposed observatories to search for high energy neutrinos by considering the predictions of AGN models for neutrino production for photo-meson interactions that also produce the gamma-ray background. We show in Sec. VI that the large set of previously published AGN models for neutrino production exceed the Waxman-Bahcall bound by typically two orders of magnitude and therefore are not appropriate theoretical models upon which to base proposed observatories. We present estimates for the upper limit neutrino event rates photo-meson and nucleon-meson interactions that may be observed in the AMANDA, ANTARES, Auger, ICECUBE, NESTOR, and OWL detectors. The previously published AGN models based upon photo-meson interactions are also inconsistent with gamma-ray observations that show rapid time variability. We also discuss in this section the question of whether some AGN's models may have a high photo-meson optical depth.

Can one increase the rate at which high energy protons are generated beyond the value contemplated in the Waxman-Bahcall bound? If so, one could obviously raise the experimentally important bound on the neutrino flux. The only way of exceeding the bound is by hypothesizing the existence of high energy proton accelerators which exist in environments that do not allow protons to escape. Can one fine-tune the conditions in which luminous astronomical sources are imagined to exist so that neutrinos and photons escape, but protons do not leave the system? Strong magnetic fields obviously provide a potential way of confining protons, but not neutrons, and we discussed this possibility briefly in Ref. [1]. In Sec. VI, we consider a recently proposed *ad hoc* scenario for avoiding the Waxman-Bahcall limit by invoking strong mangetic fields and show that even this scenario does not evade the limit. We summarize our results in Sec. VII.

II. EXCEED, NOT VIOLATE, THE WB BOUND

Does the Waxman-Bahcall bound imply that neutrino fluxes from all conceivable astronomical sources must lie below this limit? Are all possible neutrino sources that will be searched for with very large area neutrino telescopes subject to this bound?

As we discussed in the Introduction, there are two (speculative) ways to exceed the limit without violating the constraint imposed by the observed cosmic ray background. The WB bound refers, see Sec. III, only to sources that are optically thin to proton photo-meson and proton-nucleon interactions and from which protons can escape. Thus, the first ''way out'' which was also discussed in our original paper [1], is to assume the existence of sources which are optically thick to proton photo-meson or proton-nucleon interactions. We referred in [1] to such sources as ''neutrino only factories'' or ''hidden core models'' since they are not motivated by measurements of the cosmic-ray flux or by any electromagnetic observations.

Examples of optically thick scenarios include neutrinos produced in the cores of AGNs (rather than in the jets) by photo-meson interactions [14], or via $p-p$ collisions in a collapsing galactic nucleus [15] or in a cocooned black hole [16]. The optimistic predictions of the AGN core model [14] have already been ruled out by the AMANDA experiment [17] (see Fig. 3).

The second type of source that may exceed the WB bound is one in which neutrinos are produced by some mechanism other than photo-meson or proton-nucleon interactions. We list below some of the hypothesized sources of this type.

Decays of supermassive, dark matter particles [18,19] might produce high energy neutrinos without violating the cosmic ray bound.

Topological defects (see, e.g., Refs. [20–25]) might produce particles which decay, among other channels, to neutrinos with only a small associated cosmic ray proton flux.

Superheavy relic neutrinos [26,27] which interact with the cosmic neutrino background have been proposed as one way of producing ultra-high energy cosmic rays.
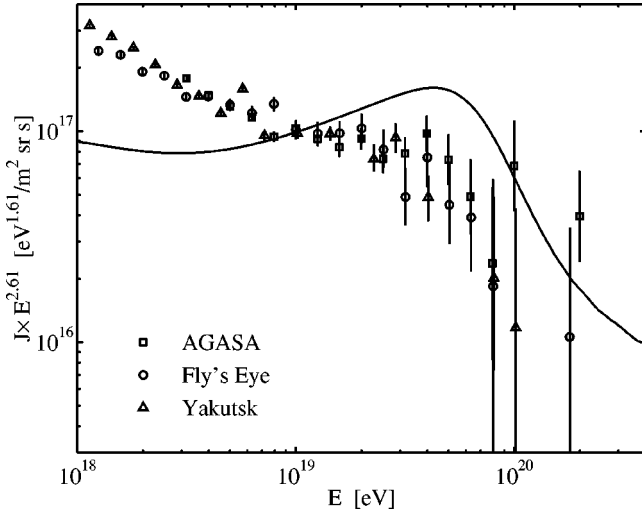
FIG. 1. The observed high energy cosmic ray flux. Measurements are shown from the Fly's Eye [11], AGASA [12], and Yakutsk [13] detectors. The smooth curve, computed from Eq. (1), was used by Waxman and Bahcall [1] to compute the upper bound on high energy astrophysical neutrino sources from $p-\gamma$ interactions.

Ultrahigh-energy photons at large redshifts [28] could in principle produce a flux of ultrahigh-energy neutrinos.

III. COSMIC RAY OBSERVATIONS AND THE WB BOUND

In this section, we summarize the observations and calculations that lead directly to the upper bound on high energy neutrino fluxes.

Figure 1 shows the cosmic ray fluxes measured by the Fly's Eye [11], AGASA [12], and Yakutsk [13] experiments. The smooth curve shown in Fig. 1 was used by us [1] in setting a conservative upper bound on the high energy neutrino fluxes. We now explain why the upper bound is robust and conservative.

The smooth curve was computed assuming that in the nearby universe ($z=0$) the energy production rate is

$$\left(E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}}\right)_{z=0} = 10^{44} \ \mathrm{erg\,Mpc^{-3}\,yr^{-1}}. \quad (1)$$

The energy generation rate given locally by Eq. (1) may increase with redshift. Cosmic rays observed at Earth with energies in excess of 10^{18} eV must have originated at small redshifts because of the large energy loss rate at these high energies. In order to establish a conservative upper limit, we assumed that the local rate given in Eq. (1) evolves with redshift at the maximum rate observed for any astronomical population, i.e., the evolutionary rate exhibited by the quasars [29–31]. We also included the adiabatic energy loss due to the expansion of the Universe.

Figure 1 shows that the smooth curve which we have used to estimate the cosmic ray flux above 10^{18} eV is a conservative (i.e., high) estimate of the observed rate. We note that Fig. 1 shows that the highest energy point measured by the AGASA experiment could be interpreted to suggest (with
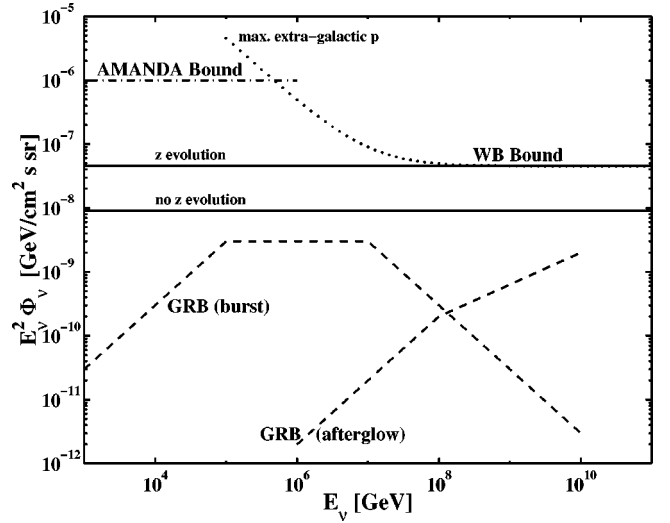

FIG. 2. The Waxman-Bahcall (WB) upper bound on muon neutrino intensities ($\nu_\mu + \bar{\nu}_\mu$). The numerical value of the bound assumes that 100% of the energy of protons is lost to π^+ and π^0 and that the π^+ all decay to muons that also produce neutrinos. The WB upper bound exceeds the most likely neutrino flux by a factor of $5/\tau$ for small optical depths τ. The upper solid line gives the upper bound corrected for neutrino energy loss due to redshift and for the maximum known redshift evolution (QSO evolution, see text). In what follows, we will refer to this conservative upper curve as the "Waxman-Bahcall bound." The lower solid line is obtained assuming no evolution. The dotted curve is the maximum contribution due to possible extra-galactic component of lower-energy, $<10^{17}$ eV, protons as first discussed in [1] (see Sec. V for details). The dash-dot curve shows the experimental upper bound on diffuse neutrino flux recently established by the AMANDA experiment [17]. The dashed curves show the predictions of the GRB fireball model [2,1,32].

$\sim 1\sigma$ significance) that the cosmic ray generation rate at $E > 10^{20}$ eV is twice the rate obtained from our smooth curve generated by Eq. (1), implying that the upper bound might be underestimated by a factor of two at $\sim 10^{19}$ eV. However, the higher rate of generation is not observed by the Fly's Eye and Yakutsk experiments, and even if correct would imply only a small correction to the upper bound at this energy.

What is the neutrino bound that results from the observed cosmic ray flux? Figure 2 shows the numerical limit that is implied by the cosmic ray observations. The upper horizontal curve is computed by assuming that the cosmic ray sources evolve as rapidly as the most rapidly evolving known astronomical sources. This very conservative limit is what we shall mean when in the following we refer to the "Waxman-Bahcall bound." The lower curve is computed assuming that the number density of cosmic ray sources at large distances is the same as in the local universe. We will discuss the implications of the bound for previously published AGN models in Sec. VI.

IV. BEYOND 10^{20} eV

The theoretical curve in Fig. 1 shows the predicted decrease above 5×10^{19} eV in the observed cosmic ray flux due

to interactions with the cosmic microwave background [33]. The existing obervations do not clearly demonstrate this decrease and therefore many authors have speculated that there may be a new source of ultra-high energy neutrinos beyond 10^{20} eV.

In our original discussion (see Fig. 1 of Ref. [1] or Fig. 2 of the present paper), we did not extend the upper bound to energies beyond 10^{20} eV because we judged that too little is presently known about the cosmic ray flux in that region. However, as a useful guide to designing experiments, it is a reasonable expectation that the production rate will not exceed by a large factor the flux predicted by an extension of the E^{-2} production rate used in setting the limit at observed proton energies of 10^{19} eV.

In our view, it is reasonable to extend the Waxman-Bahcall limit beyond 10^{20} eV by simply extrapolating the horizontal line in Fig. 2 to higher energies. The validity of this extrapolation will be tested by future measurements of the spectrum of ultra-high energy cosmic rays, measurements that will determine observationally whether the spectrum exhibits the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff at high energies.

We have suggested elsewhere [34] that the clustering of sources of ultra-high energy ($>10^{20}$) cosmic rays may give rise to more events beyond the GZK cutoff than expected on the basis of a homogeneous distribution of sources. Other authors (see, for example, the references cited in Sec. II) have suggested exotic sources of ultra-high energy cosmic rays that are not described by the E^{-2} proton generation rate. If any of these scenarios is correct, then the upper bound shown in Fig. 2 will have to be raised above the simple extrapolation we currently advocate as a useful guide.

V. LOWER ENERGY: $E < 10^{18}$ eV

Figure 1 shows that our smooth curve for the extragalactic proton cosmic ray flux falls below the total observed flux for energies less than 10^{19} eV. We have assumed [see Eq. (1)] that the generation rate of extragalactic protons is proportional to E^{-2}, where E is the proton energy. This E^{-2} dependence is produced generically by the Fermi mechanism for accelerating high energy cosmic rays in shocks [35]. If the lower energy cosmic rays were protons from extragalactic sources, then (as we noted earlier [1]) one could raise the upper bound for astrophysical neutrinos at these lower energies.

Could the lower energy cosmic rays be primarily extragalactic protons? Unfortunately, the answer is no. The available observational evidence suggests that only a small fraction of the cosmic-ray flux in the energy range of 10^{14} eV to 10^{17} eV is composed of protons. Direct (balloon) composition measurements at 10^{14} eV [36] show that the fraction of cosmic-ray flux composed of protons at this energy is $\sim 20\%$. Air-shower and cosmic-ray tracking detector measurements indicate [37] that the proton fraction decreases in the energy range of 10^{14} eV to 10^{16} eV. In fact, the Fly's Eye and AGASA experiments support [38] a composition strongly dominated by (consistent with 100%) heavy nuclei at 10^{17} eV. Moreover, both the Fly's Eye [39] and the

AGASA [40] Collaborations have reported, for energies less than 3×10^{18} eV, a small but statistically significant enhancement of the cosmic ray flux near the galactic plane. This enhancement is expected for a galactic, but not an extragalactic, origin for the cosmic rays in this energy domain.

In summary, the observational evidence is that most of the observed cosmic rays in the energy range 10^{14} eV to 10^{17} eV are not protons and therefore the total flux of cosmic rays cannot be used to raise the upper bound for neutrinos in the energy range 10^{14} eV to 10^{17} eV. The NASA satellite AC-CESS is expected to provide accurate measurements of the composition of the cosmic rays at energies up to $\sim 10^{15}$ eV sometime in the next decade.

Assuming, conservatively, that $\sim 10\%$ of the cosmic rays in this energy region are protons, the neutrino bound may be raised at energies $E_\nu < 10^{16}$ eV (since the cosmological model we have used, see Eq. (1) and Fig. 1, accounts for $\sim 10\%$ of the total cosmic ray flux at 10^{17} eV, and a progressively larger fraction at higher energies, one cannot increase the upper bound on neutrino fluxes at energies $\geqslant 10^{16}$ eV). Since the energy density in cosmic rays is approximately proportional to E^{-1} for energies less than 10^{18} eV, the actual extragalactic neutrino flux could exceed the most stringent Waxman-Bahcall limit by a factor of 10^{16} eV$/E_\nu$ for neutrino energies $E_\nu < 10^{16}$ eV.

Figure 2 illustrates with a curved dotted line the maximum contribution from unrecognized extragalactic sources of protons, i.e., sources of extragalactic protons that do not contribute significantly to the observed cosmic ray flux at 10^{19} eV. The ''unknown source'' contribution is obtained by multiplying the proton generation rate that is proportional to E^{-2} by an analytic approximation to the maximum additional contribution allowed at lower energies by the existing experiments. Thus

$$\text{max. proton rate} \propto E^{-2}[1 + 0.1((10^{17}\,\text{eV})/E)], \quad (2)$$

where E is the proton energy. The recent experimental bound established by the AMANDA experiment already rules out a contribution from unrecognized extragalactic sources of protons at the maximum level allowed by present cosmic-ray observations.

We note that including a contribution to the neutrino flux due to neutrino production by photo-meson interactions on heavy nuclei will not affect the neutrino bound. For heavy elements, the cross section for photo-dissociation is higher than, and its energy threshold is lower than, for photo-meson production. Thus, heavy elements will dissociate before losing a significant fraction of their energy to neutrino production.

VI. AGN MODELS

There are two classes of models that have been considered as explanations for the emission of radiation from AGN jets, ones in which radiation is due to electromagnetic processes [41] and others in which emission of radiation involves the acceleration of very high energy protons [42–44]. For the first class of models, no significant flux of high en-

ergy neutrinos is expected. The second class of models has been normalized by postulating that the jets produce the observed gamma-ray background via photo-meson processes on high energy protons, which produce π^0's that decay into gamma rays. The photo-meson process, if it produces the gamma-ray background, would also produce a large flux of high energy neutrinos via charged meson decay. Therefore, the second class of models, involving photo-meson interactions on high energy protons, has received a lot of attention.

Figure 3 compares the Waxman-Bahcall upper bound to predictions by various proton acceleration models for AGN jets. The previously published models illustrated in Fig. 3 are inconsistent with the cosmic ray limit; they typically predict fluxes one to two orders of magnitude above the Waxman-Bahcall upper bound.

The expected detection rate in a km^2 detector (e.g., ANTARES, ICECUBE, or NESTOR) is less than one event per year from AGNs with spectral neutrino energy shapes like the models P97, HZ97, and M95B shown in Fig. 3 if a neutrino flux consistent with the Waxman-Bahcall bound is assumed. This rather pessimistic result can be obtained from Tables III–VI of Ref. [45] by dividing by 30 the detection rate given in those tables for the model denoted by AGN-M95. The same model is labeled ''M95B'' in Fig. 3, where one can see that the flux predicted from M95B is about a factor of 30 above the cosmic ray upper bound.

The neutrino event rate in the Auger detector [9,10] is less than or of order 1 event per year above a neutrino energy of 10^{19} eV for optically thin sources, i.e., sources that satisfy
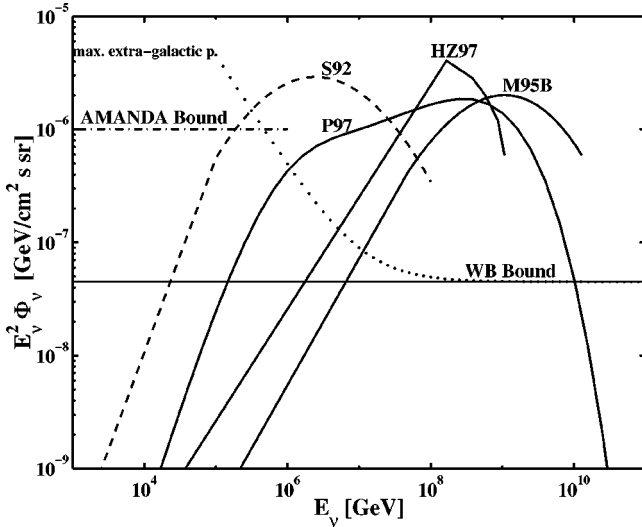

FIG. 3. The Waxman-Bahcall (WB) upper bound on muon neutrino intensities ($\nu_\mu + \bar{\nu}_\mu$) (solid line) compared to predictions of representative AGN jet models, taken from the earlier papers of Mannheim [42] (marked M95B in the figure), Protheroe [43] (P97), and Halzen and Zas [44] (HZ97). The AGN models were normalized so that the calculated gamma-ray flux from π^0 decay fits the observed gamma-ray background. The AGN hidden-core conjecture (S92), to which the WB upper bound does not apply due to high photo-meson optical depth of the source, is taken from [14]. Note that this conjecture is already ruled out by the AMANDA upper bound [17].

the WB bound. The rate may be two orders of magnitude larger if the OWL/AIRWATCH detector is built according to the preliminary specifications [8].

Mannheim, Protheore, and Rachen (MPR) [46] have recently argued that one might be able to avoid the Waxman-Bahcall limit by considering optically thick AGNs or by involving very strong magnetic fields. We consider both possibilities in the following two sections and show that they do not succeed in evading the limit.

A. Are AGNs optically thick to photo-meson interactions?

We first explain why published AGN models predict a small optical depth, and then discuss whether new, high optical depth models can be constracted.

The optical depth to photo-messon interactions for protons of energy ϵ_p can be related to the optical depth for pair production of photons of much lower energy, ϵ_γ. The threshold relation for photon-meson interactions is $\epsilon_p \epsilon_\gamma \approx m_\pi m_p$ and the threshold relation for pair production is $\epsilon'_\gamma \epsilon_\gamma = 2m_e^2$. Thus, as first pointed out in [1], a photon of energy ϵ_γ that causes a photon-meson interaction with a proton of energy ϵ_p could also pair-produce with a photon of energy $[2m_e^2/(m_\pi m_p)]\epsilon_p = 4 \times 10^{-6}\epsilon_p$. Taking account of the ratio between photo-meson and pair production cross sections, one finds that

$$\tau_{\gamma p}(\epsilon_p) \approx 5 \times 10^{-4} \tau_{\gamma\gamma}(\epsilon_\gamma = 4 \times 10^{-6}\epsilon_p). \qquad (3)$$

Observed AGN photon energy distributions typically follow a power-law, $dn_\gamma/d\epsilon_\gamma \propto \epsilon_\gamma^{-2}$. For such photon spectra, one can easily show [1] that $\tau_{\gamma\gamma} \propto \epsilon_\gamma$, and hence that

$$\tau_{\gamma p}(\epsilon_p) \approx 2\tau_{\gamma\gamma}(\epsilon_\gamma = 10 \text{ GeV})\left(\frac{\epsilon_p}{10^{19} \text{ eV}}\right). \qquad (4)$$

Emission of ~ 1 TeV photons from ''blazars,'' AGN jets nearly aligned with our line of sight, is now well established [48], and there is evidence that the high-energy photon spectrum extends as a power-law at least to ~ 10 TeV [49]. The high energy photon emission is the main argument used [50] in support of the hypothesis that high-energy emission from blazars is due to pion decay rather than inverse Compton scattering. However, the observation of >1 TeV photons implies, as shown by Eq. (3), that the jet optical depth to photo-meson interaction is very small. Indeed, one can readily see from Fig. 4 of Ref. [51] that high-energy photon data of northern hemisphere blazars requires small pair-production optical depth at photon energy <0.1 TeV. All protons blazar models shown in the figure have $\tau_{\gamma\gamma}<1$ at this energy, i.e., $\tau_{\gamma p}<1$ for $\epsilon_p<10^{19}$ eV.

TeV emission is observed from the nearest blazars, which are hence relatively low-luminosity blazars. It had recently been argued by MPR [46] that the emission of high energy, ~ 1 TeV, photons may be suppressed in high luminosity blazars, for which models with high optical depth may therefore be constructed. The most intense high-energy gamma-ray source is 3C 279. Figure 6 of Ref. [47] shows that the measured optical depth for pair production is at most $\tau_{\gamma\gamma}$

~ 1 at $\epsilon_\gamma = 10$ GeV. Combining this observation with Eq. (4) we see that $\tau_{\gamma p}(\epsilon_p) < 1$ for $\epsilon_p < 10^{19}$ eV. Making the *ad hoc* assumption, that the pair-production optical depth for high luminosity blazars like 3C 279 exceeds unity for photons above 10 GeV, i.e., just above the highest energy for which data are available, MPR concluded that the AGN neutrino flux may slightly exceed the WB bound at $\sim 10^{18}$ eV (see dotted curve in their Fig. 5a).

In order to avoid the constraint given in Eq. (4), and construct AGN models with significant optical depth to photomeson interaction, one must argue that the spectral distribution of the background photons (for photo-meson and pair-production interactions) deviates from a $dn_\gamma/d\epsilon_\gamma \propto \epsilon_\gamma^{-2}$ power-law. Since the observed spectral distribution does follow an ϵ_γ^{-2} power-law, one must argue that the background radiation with which high energy photons and protons may interact is not the radiation associated with the observed photon flux. This may indeed be the case for jets which expand with high Lorenz factor Γ. In this case, an ambient isotropic radiation field, u_{amb}, through which the jet expands, will dominate pair-production and photo-meson interactions as long as its energy density exceeds a fraction Γ^{-4} of the energy density associated with the observed radiation, u_{obs}, which is produced within the jet. The presence of such a radiation field cannot be ruled out. However, the energy density of such ambient radiation is limited to values not much exceeding $u_{amb}/u_{obs} = \Gamma^{-4}$, since for $u_{amb}/u_{obs} > \Gamma^{-4}$ inverse Compton scattering emission of jet electrons would dominate over the synchrotron emission which produces the observed radiation in the radio to UV bands.

In order to obtain the maximum possible optical depth, MPR have therefore adopted [46] the following *ad hoc* assumptions: (1) The pair production optical depth in luminous blazars, e.g. 3C 279, exceeds unity for photons above 10 GeV; (2) The optical depth is due to ambient radiation (which is not detected); (3) The spectrum of the ambient radiation deviates from a ϵ_γ^{-2} power law in such a way that its energy density increases by an order of magnitude at photon energies just below those corresponding to the pair-production threshold of 10 GeV photons. Adopting these implausible assumptions, MPR concluded that the AGN neutrino flux may exceed the WB bound by a factor ~ 2 at $\sim 10^{18}$ eV (see thick dashed curve in their Fig. 5a).

B. Can one evade the upper bound with the aid of magnetic fields?

Recently, it has been argued by MPR that while high energy protons cannot be confined to the vicinity of their sources by magnetic fields, adiabatic losses of protons escaping magnetic halos surrounding AGN jets may lead to significant decrease in proton energy for $\epsilon_p < 10^{18}$ eV, which may lead to modification of the bound for $\epsilon_\nu < 10^{17}$ eV. Clearly, even if this claim is correct, proton AGN models are still in contradiction with the Waxman-Bahcall bound, since the bound is not affected at $\epsilon_\nu > 10^{17}$ eV (see Fig. 3). Moreover, the key arguments made by MPR in deriving the claimed adiabatic energy loss are flawed. First, the magnetic field model adopted by MPR is in conflict with observations.

While the jet magnetic field inferred from observations is high, tens of μG (e.g. [52]), depolarization measurements [53] imply a small halo magnetic field, 0.1–1 μG at the central halo region, $r \sim 10$ kpc, and much smaller at large distances, $r \sim 100$ kpc. MPR assume a spherically symmetric field structure with amplitude decreasing as r^{-2} from 30 μG $r = 10$ kpc to 0.3 μG at $r = 100$ kpc. Second, MPR assume that high energy protons are produced in the central region of the jet, where the magnetic field is high, and then are confined to jet plasma which expands adiabatically to the halo plasma conditions of low magnetic field. This is an implausible description of the plasma evolution and of proton confinement. Acceleration of protons to high energy is typically expected to occur at the outer edge of the jet at the strong shock. Moreover, since the jet is narrow, typical opening angles are 10 degrees, the typical jet structures are ~ 1 kpc in scale, and neutrons produced by photo-meson interactions leading to ν production escape the jet before decaying.

VII. DISCUSSION

In this paper, we have shown that the Waxman-Bahcall upper limit on neutrino fluxes is robust for neutrino energies above 10^{16} eV. Cosmic ray experiments set a firm upper limit on the flux of extragalactic protons, and hence on the flux of extragalactic neutrinos, that are produced by $p + \gamma$ or $p - p$ interactions in astronomical sources that are optically thin to photo-meson and nucleon-meson interactions on high energy protons. The upper solid curve in Fig. 2, which is labeled WB bound, is a conservative representation of the limit imposed by the cosmic ray observations and includes the maximum plausible redshift evolution of the sources of high-energy cosmic rays. The WB bound exceeds the most likely neutrino flux from $p + \gamma$ or $p - p$ interactions by a factor of $5/\tau$, for small optical depths, τ, to photo-meson and nucleon-meson interactions.

The Waxman-Bahcall upper bound is about two orders of magnitude less than published predictions [42–44] of neutrino fluxes expected from models for AGN jets that explain the gamma-ray background by photo-meson interactions on high energy protons (see Fig. 3). Given the neutrino upper limit, photo-mesonic interactions in optically thin sources like AGN jets can at most account for a few percent of the flux of the gamma-ray background [1].

The Waxman-Bahcall bound implies an upper limit to the expected event rate from optically thin sources that may be observed in the AMANDA, ANTARES, Auger, ICECUBE, NESTOR, and OWL/AIRWATCH detectors [4–10]. In km^2 detectors like ANTARES, ICECUBE, or NESTOR, one expects to detect less than or of order 1 neutrino event per year from optically thin AGNs with neutrino spectral energy shapes like the AGN models P97, HZ97, and M95B shown in Fig. 3. For the Auger detector, one expects less than or of order 1 neutrino event per year above 10^{19} eV from all sources satisfying the WB bound. The event rate could be approximately two orders of magnitude larger for the OWL detector if it performs according to the preliminary specifications. These estimates are conservative upper limits, but

are much less than the estimates given in many published papers describing the capabilities of the neutrinos detectors, since in those papers AGN models like those shown in Fig. 3 were assumed in the calculations.

At neutrino energies below 10^{16} eV, the flux of extra-galactic neutrinos from optically thin sources may reach as high as the dotted curve in Fig. 2. In order for this curve, labeled ''max. extra-galactic p'' in Fig. 2. to apply, a large fraction of the cosmic rays with energies below 10^{17} eV must be protons of extra-galactic origin [cf. Eq. (2)]. For cosmic rays more energetic than 10^{20} eV, there is not yet an accurate determination of the cosmic ray flux. Hence there is no way of rigorously extending the WB bound for neutrino energies $> 10^{19}$ eV. We propose that horizontal line in Fig. 2 simply be extrapolated to higher energies as a plausible bound if the source spectrum continues to fall off at ultrahigh-energies as E^{-2}.

The large area neutrino experiments [4–7] that are currently being constructed are designed to detect neutrinos with energies $<10^{15}$ eV, corresponding to protons with energies less than or of the order of 10^{16} eV. The WB limit is constructed by normalizing to the observed flux of cosmic ray protons at 10^{19} eV and extrapolating to lower energies using the E^{-2} source spectrum. The extrapolation is plausible but not rigorous for the neutrino energy domain

of the ANTARES, BAIKAL, ICECUBE, and NESTOR experiments.

There are two hypothetical ways of exceeding the Waxman-Bahcall limit without violating the constraint imposed by cosmic ray observations. First, the neutrinos could be produced in sources that are optically thick to photo-nucleon or nucleon-nucleon interactions. Second, the neutrinos could be produced by processes that do not give rise to high energy cosmic rays, such as the decay of dark matter particles, topological defects, superheavy relic neutrinos, or ultrahigh-energy photons. So far, there is no observational evidence supporting any of these possiblities.

We have investigated *ad hoc* scenarios involving magnetic fields that were invented to try to exceed the Waxman-Bahcall bound. We show that the scenarios do not successfully evade the bound.

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