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Extra-galactic sources of high-energy neutrinos

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Abstract. The existence of extra-galactic high-energy neutrino sources is implied by observations of ultra-high energy, $>10^{19}$ eV, cosmic-rays (UHECRs). Phenomenological, model-independent constraints imposed on the characteristics of the extra-galactic neutrino sources are presented. It is argued that high-energy neutrino telescopes under construction may reach the sensitivity required for detecting the extra-galactic neutrino signal. Such detection will allow to identify the sources of UHECRs and to test models of these sources. It will also provide information on fundamental neutrino properties.

Contents

1. Introduction and summary

The detection of MeV neutrinos from the Sun enabled direct observations of nuclear reactions in the core of the Sun, as well as studies of fundamental neutrino properties [1]. Existing MeV

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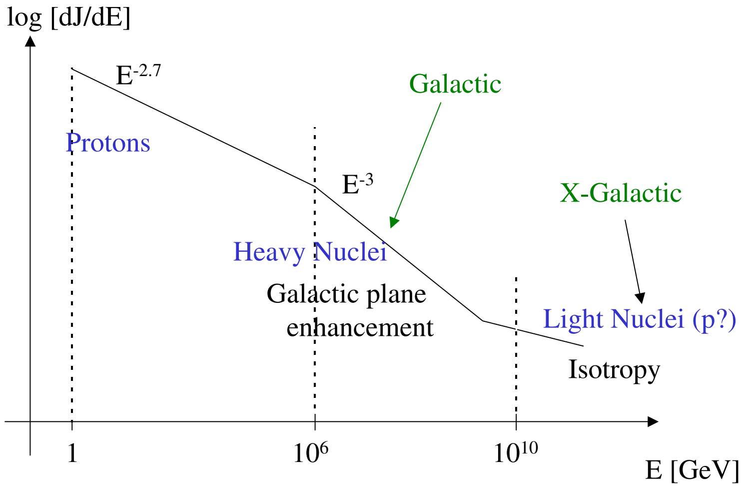

Figure 1. A schematic description of the differential spectrum and of the composition of cosmic rays observed on Earth.

neutrino 'telescopes' are also capable of detecting neutrinos from supernova explosions in our local galactic neighbourhood, at distances <100 kpc, such as supernova 1987A. The detection of neutrinos emitted by SN1987A provided a direct observation of the core collapse process and constraints on neutrino properties [2]. The main goal of the construction of high energy, >1 TeV, neutrino telescopes [3] is the extension of the distance accessible to neutrino astronomy to cosmological scales.

The existence of extra-galactic high-energy neutrino sources is implied by cosmic-ray observations. The cosmic-ray spectrum extends to energies $\sim 10^{20}$ eV [4] (see figure 1), and is likely dominated beyond $\sim 10^{19}$ eV by extra-galactic sources of protons. The flattening of the cosmic-ray spectrum at $\sim 10^{19}$ eV, accompanied by the evidence for a composition change from heavy nuclei to light ones at this energy and the lack of any anisotropy signal, suggest that a heavy nuclei galactic component, dominant below $\sim 10^{19}$ eV, is overtaken by an extra-galactic proton component at higher energy. The origin of the highest energy, $>10^{19}$ eV, cosmic rays (UHECRs) is a mystery. However, irrespective of the sources some fraction of the protons are expected to produce pions as they escape their source by either hadronic collisions with ambient gas or photoproduction with source photons, leading to electron and muon neutrino production through the decay of charged pions.

In section 2 a phenomenological, model-independent discussion of extra-galactic high-energy neutrino sources is presented. In section 2.1 we show that the stringent constraints, which are imposed on the properties of possible UHECR sources by the high energies observed, rule out almost all source candidates and also suggest that the UHECR sources may be detectable at ~ 1 TeV to ~ 1 PeV neutrino energies by km-scale (i.e. Gt scale) neutrino telescopes. These constraints suggest that γ-ray bursts and active galactic nuclei are the most plausible sources of UHECRs, and may be detectable by km-scale neutrino telescopes. The required large effective volume will be achieved by optical Cerenkov detectors being constructed under ice (AMANDA [5] and IceCube [6]) and water (ANTARES [7], NESTOR [8] and NEMO [9]).

In section 2.2 we discuss the constraints imposed by cosmic-ray observations on the extra-galactic high-energy neutrino intensity produced by sources which, like γ-ray bursts and jets of active galactic nuclei, are optically thin for high-energy nucleons to p, γ and p–p(n) interactions. For sources of this type, the energy generation rate of neutrinos cannot exceed the energy generation rate of high-energy protons implied by the observed cosmic-ray flux, setting an upper bound of $E_\nu^2\Phi_\nu < 2\times10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ to the extra-galactic high-energy neutrino intensity [10, 11] (figure 4, equation (7)). This upper bound, which came to be known in the literature as the Waxman–Bahcall (WB) bound, implies that km-scale (i.e. Gt) neutrino telescopes are needed to detect the expected extra-galactic flux in the energy range of ∼1 TeV to ∼1 PeV, and much larger effective volume is required to detect the flux at higher energy. We note that the WB bound may be evaded by postulating the existence of sources which are optically thick for protons to p, γ or p–p(n) interactions [10]–[12]. However, the existence of such 'hidden' or 'neutrino only' factories is not motivated by measurements of the cosmic-ray flux or by any electromagnetic observations.

In section 2.3, we discuss 'GZK neutrinos'. If the sources of UHECRs are extra-galactic and the particles are indeed protons, then these particles lose energy by interacting with the cosmic microwave background photons [13]. Protons of energy exceeding the threshold for pion production, $\sim5\times10^{19}$ eV, lose most of their energy over a time, short compared to the age of the universe (the 'GZK effect'). The decay of the pions generates a background of high-energy neutrinos ([14]; for detailed updated discussion see [15] and references therein). The intensity of this background, at neutrino energies $\sim10^{19}$ eV, should be similar to the WB bound, $E_\nu^2\Phi_\nu\sim2\times10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$. Coherent radio Cerenkov detectors (ANITA [16] and RICE [17]), and possibly large air-shower detectors (Auger [18] and OWL-AIRWATCH [19]), may provide the large effective volume required for the detection of the 'GZK neutrinos'. Their detection will help to determine the identity of the cosmic-ray particles and will constrain the redshift evolution of UHECR sources.

The rapid energy loss of $>5\times10^{19}$ eV protons implies, in addition to the generation of high-energy neutrinos, a strong suppression of UHECR flux above 5×10^{19} eV (the 'GZK suppression'). The flux measurements of all UHECR experiments are in agreement below 10^{20} eV, and consistent with the expected GZK suppression [20] (figure 3). At higher energy, $\sim2\times10^{20}$ eV, the flux reported by one experiment is higher by a factor of ∼3 than that reported by other experiments, which report a flux consistent with the GZK suppression. At still higher energy, $>3\times10^{20}$ eV, the exposure of all experiments is insufficient to derive a reliable estimate of the flux. The uncertainty in the experimental determination of the UHECR flux at energies $>10^{20}$ eV lead many authors to speculate that there may be a new source of ultra-high-energy cosmic rays and neutrinos beyond 10^{20} eV, producing a neutrino intensity higher than the WB bound at these neutrino energies (see section 2.3). Since, however, we do not have direct experimental evidence for a rapid increase beyond 3×10^{20} eV of the cosmic-ray energy generation rate with cosmic-ray energy, it is reasonable in our view to extend the WB limit beyond 10^{19} eV by simply extrapolating the horizontal line in figure 4 to higher energies. The validity of this extrapolation will be tested by future measurements of the spectrum of ultra-high-energy cosmic rays and neutrinos.

In section 3, we discuss high-energy neutrino emission from gamma-ray bursts (GRBs). This discussion illustrates the applicability of the phenomenological, model-independent arguments presented in section 2 through a discussion of (a model of) a particular, plausible extra-galactic source of UHECRs and high-energy neutrinos (for discussion of AGN models, see [21] and references therein). In section 3.1 we present a brief discussion of the fireball model of GRBs, which has recently gained strong support from 'afterglow' observations (for more complete discussions see [22]–[24]), and in section 3.2 we briefly present the arguments suggesting a connection between GRBs and UHECR sources (see [23, 24] for more detailed discussion). In section 3.3 we show that the production of 100 TeV neutrinos in the region where GRB in γ-rays are produced is a generic prediction of the fireball model. It is a direct consequence of the assumptions that energy is carried from the underlying engine as kinetic energy of protons and that γ-rays are produced by synchrotron emission of shock accelerated particles. The predicted neutrino intensity is $\approx$20% of the WB intensity bound, implying a detection of $\sim$20 muon induced neutrino events per year in a km-scale neutrino detector [25, 26] (since these events should be correlated in time and direction with GRB in γ-rays, the search for GRB neutrinos is essentially background-free). Neutrinos may also be produced in other stages of fireball evolution, at energies different than 100 TeV. The production of these neutrinos is dependent on additional model assumptions. As an example, we discuss in section 3.4 the production of TeV neutrinos expected in the 'collapsar' scenario, where GRB progenitors are associated with the collapse of massive stars. (A more detailed and comprehensive discussion can be found in [23, 24].)

The discussion of GRB neutrino emission demonstrates that in addition to identifying the sources of UHECRs, high-energy neutrino telescopes can also provide a unique probe of these sources. Moreover, the detection of high-energy neutrinos from extra-galactic sources may also provide information on fundamental neutrino properties [25]. High-energy neutrinos are expected to be produced in astrophysical sources by the decay of charged pions, which lead to the production of muon and electron neutrinos. However, oscillation to ν_τ's [27] implies that neutrino telescopes should detect equal numbers of ν_μ's and ν_τ's. Up-going τ's, rather than μ's, would be a distinctive signature of such oscillations. The detection of neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of $\sim$1 s, checking the assumption of special relativity that photons and neutrinos have the same limiting speed. These observations would also test the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential. With 1 s accuracy, a burst at 1 Gpc would reveal a fractional difference in limiting speed of 10^{-17}, and a fractional difference in gravitational time delay of order 10^{-6} (considering the galactic potential alone). Previous applications of these ideas to supernova 1987A (see [28] for a review), yielded much weaker upper limits of orders 10^{-8} and 10^{-2}, respectively.

2. Phenomenological considerations

2.1. The luminosity constraint for UHECR sources and its implications for high-energy neutrino telescopes

A detailed discussion of particle acceleration is beyond the scope of this paper. However, the essence of the challenge of accelerating particles to $>10^{19}$ eV can be understood using the following simple arguments. Consider an astrophysical source driving a flow of magnetized plasma, with characteristic magnetic field strength B and velocity v. Imagine now a conducting wire encircling the source at radius R, as illustrated in figure 2. The potential generated by the moving plasma is given by the time derivative of the magnetic flux Φ and is therefore given by $V = \beta BR$ where $\beta = v/c$. A proton which is allowed to be accelerated by this potential drop would reach energy $E_p \sim \beta eBR$. The situation is somewhat more complicated in the case

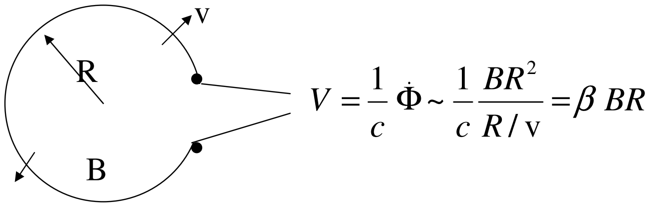

Figure 2. Potential drop generated by an outflow of magnetized plasma.

of a relativistic outflow, where $\Gamma \equiv (1-\beta^2)^{-1/2} \gg 1$. In this case, the proton is allowed to be accelerated only over a fraction of the radius R, comparable to R/Γ. To see this, one must realize that as the plasma expands, its magnetic field decreases, so the time available for acceleration corresponds, say, to the time of expansion from R to $2R$. In the observer frame this time is R/c, while in the plasma rest frame it is $R/\Gamma c$. Thus, a proton moving with the magnetized plasma can be accelerated over a transverse distance $\sim R/\Gamma$. This sets a lower limit to the product of the magnetic field and source size, which is required to allow acceleration to E_p,

$$BR > \Gamma E_p/e\beta. \tag{1}$$

Equation (1) also sets a lower limit to the rate L at which energy should be generated by the source. The magnetic field carries with it an energy density $B^2/8\pi$, and the flow therefore carries with it an energy flux $>vB^2/8\pi$ (some energy is also carried as plasma kinetic energy), which implies $L > vR^2B^2$. Using equation (1), we find

$$L > \frac{\Gamma^2}{\beta}\left(\frac{E_p}{e}\right)^2 c = 10^{45.5}\frac{\Gamma^2}{\beta}\left(\frac{E_p}{10^{20}\,\mathrm{eV}}\right)^2 \mathrm{erg\,s^{-1}}. \tag{2}$$

Only two types of sources are known to satisfy this requirement. The brightest steady sources are active galactic nuclei (AGN). For them Γ is typically between 3 and 10, implying $L > 10^{47}\,\mathrm{erg\,s^{-1}}$, which may be satisfied by the brightest AGN.[1] The brightest transient sources are GRBs. For these sources $\Gamma \simeq 10^{2.5}$ implying $L > 10^{50.5}\,\mathrm{erg\,s^{-1}}$, which is generally satisfied since the typical observed MeV-photon luminosity of these sources is $L_\gamma \sim 10^{52}\,\mathrm{erg\,s^{-1}}$.[2]

It is instructive to compare equation (2) to the constraints imposed on a neutrino source by requiring it to be detectable by a km-scale neutrino telescope. Consider the minimum flux of a source that can be detected by a neutrino telescope with effective area A (in the plane perpendicular to the source direction) and exposure time T. The probability that a muon

[1] Phenomenological arguments similar to those used here were applied by Lovelace [29] to a specific model of AGN jets, in which the relation between proton energy and source luminosity may be written as $L \sim 10^{46}(E_p/10^{20}\,\mathrm{eV})^2\,\mathrm{erg\,s^{-1}}$, consistent with equation (2). The derivation given here is more general, as it does not assume a specific model and includes the dependence on characteristic plasma velocity.

[2] It was recognized earlier (see [30] and references therein) that while highly magnetized neutron stars may also satisfy equation (1), it is hard to utilize the potential drop in their electromagnetic winds for proton acceleration to ultra-high energy. The mechanisms recently proposed for acceleration in 'magnetars' (see [31] and references therein) also face serious difficulties. In [31], for example, the electromagnetic wind must penetrate through a supernova envelope shell without losing energy to acceleration of the shell and without 'contaminating' the wind with baryons. The mechanism by which such penetration may be achieved is unclear.

produced by the interaction of a muon neutrino with a nucleon will cross the detector is given by the ratio of the muon and neutrino mean free paths.[3] For water and ice, this probability is $P_{\nu\mu} \approx 10^{-4}(E_\nu/100\,\mathrm{TeV})^{\alpha}$, with $\alpha = 1$ for $E_\nu < 100\,\mathrm{TeV}$ and $\alpha = 0.5$ for $E_\nu > 100\,\mathrm{TeV}$ (see e.g. [32]). Thus, the neutrino flux required for the detection of N events is

$$f_\nu \approx 5\times 10^{-12} N \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{1-\alpha} \left(\frac{AT}{\mathrm{km}^2\,\mathrm{yr}}\right)^{-1} \mathrm{erg\,cm^{-2}\,s^{-1}}. \tag{3}$$

A lower limit to the source flux is also set by the requirement that the signal would exceed the background produced by atmospheric neutrinos. The flux of atmospheric neutrinos, averaged over zenith angle, is approximately given by $\Phi_\nu^A \approx 5\times 10^{-8}(E_\nu/100\,\mathrm{TeV})^{-\beta}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, with $\beta = 1.7$ for $E_\nu < 100\,\mathrm{TeV}$ and $\beta = 2.0$ for $E_\nu > 100\,\mathrm{TeV}$. For a neutrino detector with angular resolution $\Delta\theta$, the source flux for which the signal constitutes a 5σ detection over the atmospheric background flux is

$$f_\nu \approx 3\times 10^{-12} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\beta/2} \left(\frac{\Delta\theta}{1^\circ}\right) \left(\frac{AT}{\mathrm{km}^2\,\mathrm{yr}}\right)^{-1/2} \mathrm{erg\,cm^{-2}\,s^{-1}}. \tag{4}$$

Comparing equations (3) and (4), we find that for km-scale detectors, the atmospheric neutrino background poses a less stringent constraint on source flux than the requirement of a detectable signal, except at low energies $\ll$100 TeV.

The luminosity of a cosmologically distant source which corresponds to the flux of equation (3) is

$$L_\nu \approx 10^{46} N d_{L,28}^2 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{1-\alpha} \left(\frac{AT}{\mathrm{km}^2\,\mathrm{yr}}\right)^{-1} \mathrm{erg\,s^{-1}}. \tag{5}$$

Here, $d_L = 10^{28} d_{L,28}$ cm is the luminosity distance and $d_{L,28} \sim 1$ for sources at redshift $z = 1$. The neutrino luminosity is, of course, a lower limit to the total energy output rate from the source. The lower limit set by equation (5) to the luminosity of a steady source that may be detectable at $\sim 10^{1\pm 1}$ TeV neutrino energies by a km-scale neutrino detector, $L > 10^{46}\,\mathrm{erg\,s^{-1}}$, is similar to the constraint of equation (2) imposed by requiring proton acceleration to $\sim 10^{20}$ eV. As mentioned following equation (2), the only steady sources bright enough to possibly satisfy these constraints are AGN. Equations (2) and (5) also imply similar luminosity constraints on GRBs. For a typical GRB duration of $10^{1.5}$ s, equation (5) implies $L > 10^{52}\,\mathrm{erg\,s^{-1}}$, similar to the constraint imposed by equation (2) for the typical Lorentz factor appropriate for these sources, $\gamma \simeq 10^{2.5}$.

The phenomenological arguments presented above imply that the luminosity that must be produced by a source of UHECRs, equation (2), may allow such a source to be detectable by a km-scale neutrino detector at $\sim 10^{1\pm 1}$ TeV neutrino energy (see equation (5)). Equation (5) also implies that the detection of sources at $\gg 10^2$ TeV neutrino energy would require detectors with effective volume $\gg 1\,\mathrm{km}^3$. The most plausible sources of UHECRs, GRBs and AGN, are therefore also the most likely to be detectable neutrino sources. Such detection would be possible only if the neutrino luminosity of the source constitutes a significant fraction of the total source luminosity. For GRBs, this issue is discussed in some more detail in section 3, within the context of current GRB models.

[3] Note that the mean free path of muons of energy >0.3 TeV is of order 1 km. Thus, a detector with effective cross-sectional area A corresponds to a detector with an effective volume $\sim A \times (1\,\mathrm{km})$.

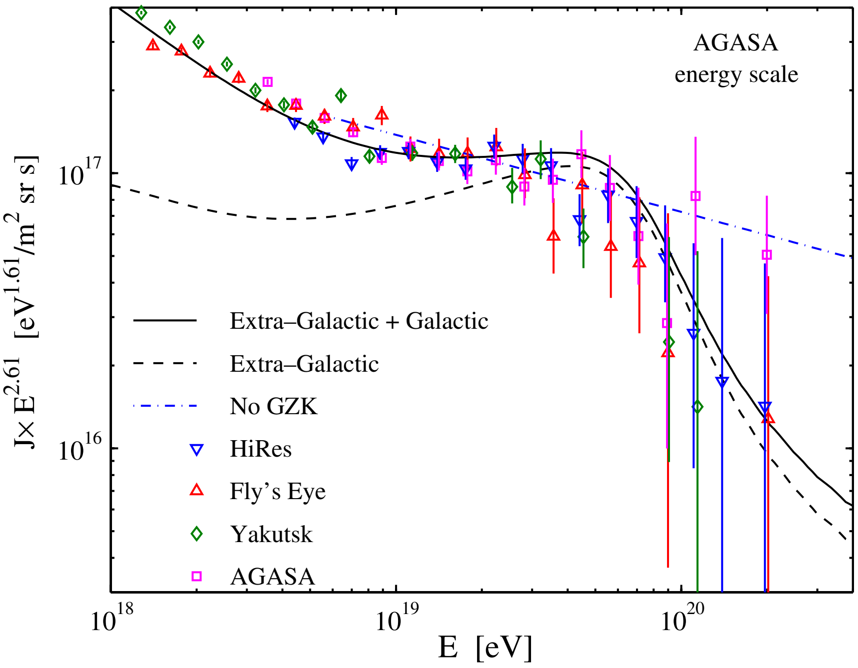

Figure 3. The solid curve shows the energy spectrum derived from the two-component model discussed in section 2.2 (the energy generation rate of the extra-galactic component, equation (6), was assumed to evolve rapidly, $\phi(z) \propto (1+z)^3$ up to $z = 2$, following the evolution of QSOs [40] and star formation rate [41]). The dashed curve shows the extra-galactic component contribution. The 'No GZK' curve is an extrapolation of the $E^{-2.75}$ energy spectrum derived for the energy range 6×10^{18}–4×10^{19} eV [4]. Data taken from [35]–[38] (AGASA's energy scale was chosen).

The current upper limits provided by the AMANDA experiment on neutrino fluxes from steady point sources, $\sim 10^{-10}$ erg cm^{-2} s^{-1} [33], indicate that the sensitivity required to detect the fluxes expected from cosmological sources will be achieved by km-scale detectors.

2.2. The WB bound

As explained in section 1, cosmic-ray observations suggest that the cosmic-ray flux is dominated above 10^{19} eV by extra-galactic sources of protons (and at lower energy by galactic heavy nuclei sources). Under the assumption that the UHECRs are extra-galactic protons, the observed flux of UHECRs allows one to determine the rate (per unit time and volume) at which high-energy protons are produced. Such analysis was carried out in [34], based on Fly's Eye [35] and AGASA [36] data available at the time, constraining the rate of energy production in protons in the energy range of 10^{19} eV $< E_p < 10^{21}$ eV to $4.5 \pm 1.5 \times 10^{44}$ erg Mpc^{-3} yr^{-1}. Assuming the production spectrum to follow a power-law, $\mathrm{d}N/\mathrm{d}E_p \propto E_p^{-n}$, the same analysis constrained n to $1.8 < n < 2.8$. A recent analysis, with larger AGASA exposure and including data from Yakutsk [37] and new data from HiRes [38], gives consistent results [20]. Figure 3 presents a comparison of available UHECR data with the predictions of a model, where extra-galactic protons in the energy range 10^{19}–10^{21} eV are produced by cosmologically distributed sources at a rate and spectrum given by

$$E_p^2 \frac{\mathrm{d}\dot{N}_p}{\mathrm{d}E_p} = 0.65 \times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}\phi(z), \tag{6}$$

corresponding to energy production rate of $3 \times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ in protons in the energy range of $10^{19}\,\mathrm{eV} < E_p < 10^{21}\,\mathrm{eV}$ and spectral index $n = 2$.[4] Here, $\phi(z)$ accounts for redshift evolution and $\phi(z = 0) = 1$. The spectrum above 10^{19} eV is only weakly dependent on $\phi(z)$ since proton energy loss limits their propagation distance. For the heavy nuclei component dominating at lower, $<10^{19}$ eV, energy we have taken the Fly's Eye experimental fit [35], $\mathrm{d}N/\mathrm{d}E \propto E^{-3.50}$.

Figure 3 demonstrates that model predictions are in good agreement with the data of all experiments in the energy range 10^{19}–10^{20} eV. The uncertainty in the derived energy production rate, equation (6), due to systematic uncertainties in the absolute energy calibration of the experiments is ≈20% [20].[5] Above 10^{20} eV the Fly's Eye, HiRes and Yakutsk experiments are in agreement with each other and with the model, while the AGASA experiment reports a flux higher by a factor ∼3.

The energy production rate, equation (6), sets an upper bound to the neutrino intensity produced by sources which, like GRBs and AGN jets, are optically thin for high-energy nucleons to p, γ and p–p(n) interactions. For sources of this type, the energy generation rate of neutrinos cannot exceed the energy generation rate implied by assuming that all the energy injected as high-energy protons is converted to pions (via p, γ and p–p(n) interactions). The resulting upper bound (for muon and anti-muon neutrinos, neglecting mixing) is [10]

$$E_\nu^2 \Phi_\nu < 2 \times 10^{-8} \xi_z \left[\frac{(E_p^2\, \mathrm{d}\dot{N}_p/\mathrm{d}E_p)_{z=0}}{10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}} \right] \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}. \tag{7}$$

ξ_z is (a dimensionless parameter) of order unity, which depends on the redshift evolution of $E_p^2\, \mathrm{d}\dot{N}_p/\,\mathrm{d}E_p$ (see equation (6)). In order to obtain a conservative upper bound, we adopt $(E_p^2\, \mathrm{d}\dot{N}_p/\,\mathrm{d}E_p)_{z=0} = 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ and a rapid redshift evolution, $\Phi(z) = (1 + z)^3$ up to $z = 2$, following the evolution of QSOs [40], which exhibit the fastest (known) source evolution. This evolution, which also approximately describes the evolution of star formation rate [41], yields $\xi_z \approx 3$.

Below $\sim 10^{19}$ eV, the extra-galactic proton flux is dominated by the galactic cosmic-ray background. In our derivation of the neutrino intensity bound, we have assumed that the generation rate of extragalactic protons extends to energies lower than $\sim 10^{19}$ eV as $\mathrm{d}\dot{N}_p/\mathrm{d}E_p \propto E_p^{-2}$. The energy generation rate at these energies may, however, be higher, since part of the

[4] An energy spectrum similar to the assumed $\mathrm{d}N/\mathrm{d}E_p \propto E_p^{-2}$ has been observed for both non-relativistic [4] and relativistic [39] shocks. It is believed to be due to Fermi acceleration in collisionless shocks [4, 39], although a first principles understanding of the process is not yet available.

[5] As explained in detail in [20], the various experiments are consistent with each other when systematic errors in the absolute energy scale of the events are taken into account. The relative systematic shifts in absolute energy calibration between Fly' Eye and the other experiments, required to bring into agreement the fluxes measured at 10^{19} eV by the different experiments, are {−11%, +7.5%, −19%} for {AGASA, HiRes, Yakutsk}, respectively. All shifts are well within the published systematic errors.

cosmic-ray flux below $\sim 10^{19}$ eV may be produced by extra-galactic sources of protons. The available observational evidence suggests that only a small fraction of the cosmic-ray flux in the energy range 10^{14}–10^{17} eV is composed of protons. Direct (balloon) composition measurements at 10^{14} eV [42] show that the fraction of cosmic-ray flux composed of protons at this energy is $\sim$20%. Air-shower and cosmic-ray tracking detectors measurements indicate [43] that the proton fraction decreases in the energy range 10^{14}–10^{16} eV. In fact, the Fly's Eye and AGASA experiments support [44] a composition strongly dominated by (consistent with 100%) heavy nuclei at 10^{17} eV. 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 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 extra-galactic neutrino flux could exceed the most stringent WB limit by a factor of $(10^{16}\,\mathrm{eV}/E_\nu)$ for neutrino energies $E_\nu < 10^{16}$ eV [10, 11].

The WB upper bound is compared in figure 4 with current limits of the lake Baikal and of the AMANDA experiments on the diffuse neutrino intensity, and with the expected sensitivity of planned neutrino telescopes.

The figure indicates that km-scale (i.e. Gt) neutrino telescopes are needed to detect the expected extra-galactic flux in the energy range of $\sim$1 TeV to $\sim$1 PeV, and that much larger effective volume is required to detect the flux at higher energy.

2.3. GZK neutrinos

Protons of energy exceeding the threshold for pion production, $\sim 5 \times 10^{19}$ eV, lose most of their energy over a time, short compared to the age of the universe: $>10^{20}$ eV protons, for example, lose most of their energy over $<3 \times 10^{8}$ yr. Assuming that high-energy protons are produced by extra-galactic sources at the rate implied by UHECR observations (equation (6)), the proton energy loss to pion production produces a neutrino intensity similar to the WB bound. The expected GZK neutrino intensity is schematically shown in figure 4. Since most of the pions are produced in interactions with photons of energy corresponding to the Δ-resonance, each of the resulting neutrinos carry approximately 5% of the proton energy. The neutrino background is therefore close to the WB bound above $\sim 5 \times 10^{18}$ eV, where neutrinos are produced by $\sim 10^{20}$ eV protons. The intensity at lower energies is lower, since protons of lower energy do not lose all their energy over the age of the universe. The GZK intensity in figure 4 decreases at the highest energies since it was assumed that the maximum energy of protons produced by UHECR sources is 10^{21} eV. The results of detailed calculations of the expected GZK neutrino intensity [15] are in agreement with the qualitative analysis presented above. Recently, it was pointed out that the GZK neutrino spectrum at the low energy end, $<10^{18}$ eV, is expected to be modified due to the interaction of high-energy protons with the infrared background [47].

The detection of GZK neutrinos will be a milestone in neutrino astronomy. Most important, neutrino detectors with sensitivity better than the WB bound at energies $>10^{18}$ eV will test the hypothesis that the UHECR are protons (possibly somewhat heavier nuclei) of extra-galactic origin. Measurements of the flux and spectrum would constrain the redshift evolution of the sources. The GZK neutrino intensity presented in figure 4 is obtained for rapidly evolving sources. For non-evolving sources the intensity is lower by a factor of $\approx$5.

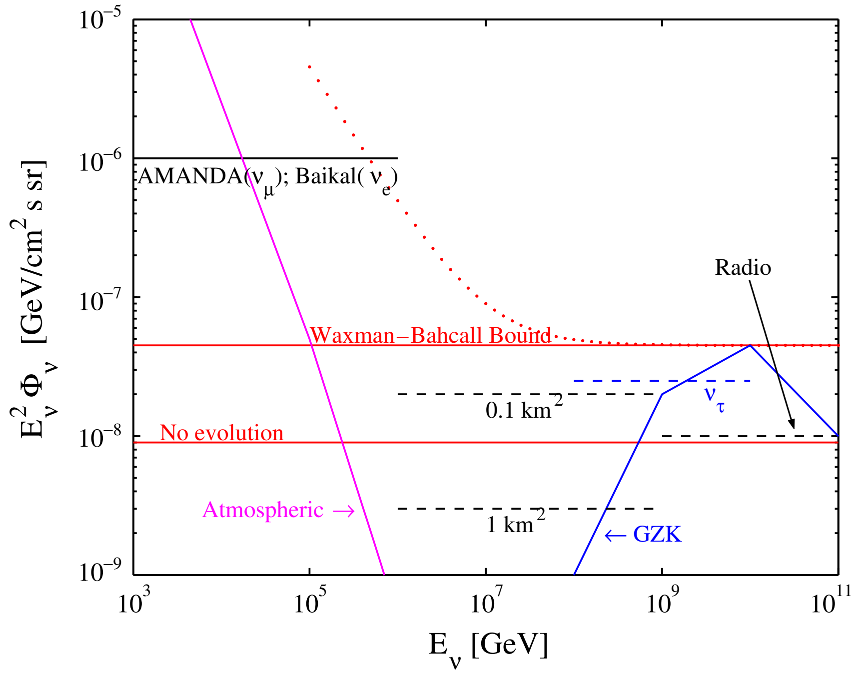

Figure 4. The upper bound imposed by UHECR observations on the extra-galactic high-energy muon neutrino intensity (lower-curve: no evolution of the energy production rate of equation (6); upper curve: assuming evolution following star formation rate), compared to the atmospheric neutrino background and to the experimental upper bounds of BAIKAL [45] and AMANDA [46]. The dotted curve is the maximum contribution due to possible extra-galactic component of lower-energy, $<10^{17}$ eV, protons as first discussed in [10] (see text). The curve labelled 'GZK' shows the intensity due to interaction with micro-wave background photons. Dashed curves show the expected sensitivity of 0.1 Gt (AMANDA, ANTARES, NESTOR) [5]–[8] and 1 Gt (IceCube, NEMO) [6, 9] optical Cerenkov detectors, of the coherent radio Cerenkov (balloon) experiment ANITA [16] and of the Auger air-shower detector (sensitivity to ν_τ) [18]. Radio Cerenkov detectors in ice (RICE [17]) and space air-shower detectors (OWL-AIRWATCH [19]) may also achieve the sensitivity required to detect fluxes lower than the WB bound at energies $>10^{18}$ eV.

The uncertainty in the experimental determination of the UHECR flux at energies $>10^{20}$ eV lead many authors to speculate that there may be a new source of ultra-high-energy cosmic rays and neutrinos beyond 10^{20} eV, producing a neutrino intensity higher than the WB bound at these neutrino energies. Most of these models involve 'new physics': decay of super-massive dark matter particles (see e.g. [48]) and topological defects (see e.g. [49]) have been proposed to produce ultra-high-energy neutrinos with small associated cosmic-ray proton flux, thus possibly producing a flux of neutrinos exceeding the WB bound. Other models postulate the existence of 'neutrino-only' sources, producing ultra-high-energy neutrinos with small associated proton or γ-ray flux, without specifying a model for such sources [50]. In our view, it is reasonable to extend the WB limit beyond 10^{20} eV by simply extrapolating the horizontal line in figure 4 to

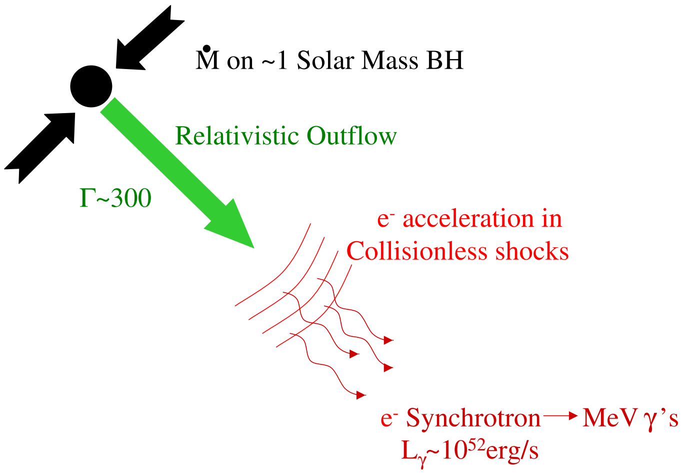

Figure 5. The fireball scenario of GRB production.

higher energies. The validity of this extrapolation will be tested by future measurements of the spectrum of ultra-high-energy cosmic rays and neutrinos.

3. GRBs

3.1. The fireball model

GRBs are short, typically tens of seconds long, flashes of γ rays, carrying most of their energy in >1 MeV photons. The detection in the past few years of 'afterglows', delayed x-ray, optical and radio emission from GRB sources, proved that the sources lie at cosmological distances, and provided strong support for the scenario of GRB production described in figure 5 [22]–[24]. The energy source is believed to be rapid mass accretion on a newly formed solar-mass black hole (or, possibly, neutron star). Recent observations suggest that the formation of the central compact object is associated with type Ib/c supernovae [51].

The energy release drives an ultra-relativistic, $\Gamma \sim 10^{2.5}$, plasma outflow. The emission of γ-rays is assumed to be due to internal collisionless shocks within the relativistic wind, the 'fireball,' which occur at a large distance from the central black hole due to variability in the wind emitted from the central 'engine'. It is commonly assumed that electrons are accelerated to high energy within the collisionless shocks, and that synchrotron emission from these shock accelerated electrons produces the observed γ-rays. At still larger distances, the wind impacts on surrounding medium. Here too, the collisionless shock driven into the ambient gas is believed to accelerate electrons to high energy, leading to synchrotron emission which accounts for the 'afterglow'.

3.2. The association of GRBs and UHECRs

GRBs were suggested to be UHECR sources in [52, 53]. The GRB–UHECR association was based on two major arguments in [52]: (i) the constraints imposed on the relativistic wind by requiring that it would produce the observed γ-rays are remarkably similar to those imposed by

Table 1. Constraints on GRB wind parameters from photon observations and from the requirement for proton acceleration to 10^{20} eV.

Wind property	MeV γ-rays	10^{20} eV protons
u_B/u_e	$\geqslant 0.1$	$\geqslant 0.02$
Γ	$\geqslant 300$	$\geqslant 100$
$\mathrm{d}N/\mathrm{d}E$	$\mathrm{d}N_e/\mathrm{d}E_e \propto E_e^{-2}$	$\mathrm{d}N_p/\mathrm{d}E_p \propto E_p^{-2}$

the requirement that the wind would allow proton acceleration to 10^{20} eV; (ii) the rate (per unit volume) at which energy is generated by GRBs in γ-rays is similar to the rate at which energy should be generated in high-energy protons in order to account for the observed UHECR flux. Both arguments have been strengthened by more recent GRB and UHECR observations [54].

The constraints on wind parameters are summarized in table 1 (for a pedagogical discussion see [23, 24]). γ-ray observations require the ratio of magnetic field and electron energy densities, u_B/u_e, to exceed 0.1 in order to produce electron synchrotron emission in the MeV range, $\Gamma > 300$ to avoid pair production by high-energy photons which would make the wind opaque, and $\mathrm{d}N_e/\mathrm{d}E_e \propto E_e^{-2}$ to account for the synchrotron spectrum. Acceleration of protons to 10^{20} eV requires $u_B/u_e > 0.02$ to satisfy equation (1); $\Gamma > 100$ to avoid synchrotron losses of protons on a time scale shorter than the acceleration time; and $\mathrm{d}N_p/\mathrm{d}E_p \propto E_p^{-2}$ to reproduce the observed UHECR spectrum (see equation (6)). The constraints on wind parameters imposed by requiring proton acceleration to $>10^{20}$ eV are largely independent of the details of the assumed acceleration process (as illustrated, e.g., by the analysis of [55]).

The fact that similar constraints are obtained from independent arguments, related to γ-ray emission and to proton acceleration, suggests that GRBs and UHECRs are associated. The association is further supported by the similarity of energy generation rates. The energy generation rate of GRBs (at $z = 0$) is $\approx 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ [54], comparable to the energy generation rate in UHECRs (equation (6)).

We note that GRBs have also been suggested as the sources of galactic cosmic rays above the 'knee', i.e. above $\sim 10^{15}$ eV [56]. The discussion of this issue is beyond the scope of this paper.

3.3. 100 TeV neutrinos

Protons accelerated in the fireball to high energy lose energy through photo-meson interaction with fireball photons. The decay of charged pions produced in this interaction results in the production of high-energy neutrinos. The key relation is between the observed photon energy, E_γ, and the accelerated proton's energy, E_p, at the threshold of the Δ-resonance. In the observer frame,

$$E_\gamma E_p = 0.2\,\mathrm{GeV}^2\,\Gamma^2. \tag{8}$$

For $\Gamma \approx 10^{2.5}$ and $E_\gamma = 1$ MeV, we see that characteristic proton energies $\sim 10^{16}$ eV are required to produce pions. Since neutrinos produced by pion decay typically carry 5% of the proton energy, the production of $\sim 10^{14}$ eV neutrinos is expected [25].

The fraction of energy lost by protons to pions, f_π, is $f_\pi \approx 0.2$ [23]–[25], [57]. Assuming that GRBs generate the observed UHECRs, the expected GRB muon-neutrino flux may be estimated using equation (7) [10, 25],

$$E_\nu^2 \Phi_\nu \approx 0.3 \times 10^{-8} \frac{f_\pi}{0.2} \,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}. \tag{9}$$

This neutrino spectrum extends to $\sim 10^{16}$ eV, and is suppressed at higher energy due to energy loss of pions and muons [10, 25, 58]. Equation (9) implies a detection rate of ~20 neutrino-induced muon events per year (over 4π sr) in a cubic-km detector. Since GRB neutrino events are correlated both in time and in direction with γ-rays, their detection is practically background-free.

3.4. TeV neutrinos

The 100 TeV neutrinos discussed in the previous section are produced at the same region where GRB γ-rays are produced. Their production is a generic prediction of the fireball model. It is a direct consequence of the assumptions that energy is carried from the underlying engine as kinetic energy of protons and that γ-rays are produced by synchrotron emission of shock accelerated particles. Neutrinos may be produced also in other stages of fireball evolution, at energies different than 100 TeV. The production of these neutrinos is dependent on additional model assumptions. We discuss below some examples related to the GRB progenitor. For a more detailed discussion see [23, 24] and references therein.

The most widely discussed progenitor scenarios for long-duration GRBs involve core collapse of massive stars. In these 'collapsar' models, a relativistic jet breaks through the stellar envelope to produce a GRB. For extended or slowly rotating stars, the jet may be unable to break through the envelope. Both penetrating (GRB producing) and 'choked' jets can produce a burst of ~5 TeV neutrinos by interaction of accelerated protons with jet photons, while the jet propagates in the envelope [59]. The estimated event rates may exceed $\sim 10^2$ events yr^{-1} in a km-scale detector, depending on the ratio of non-visible to visible fireballs. A clear detection of non-visible GRBs with neutrinos may be difficult due to the low-energy resolution for muon-neutrino events, unless the associated supernova photons are detected. In the two-step 'supranova' model, interaction of the GRB blast wave with the supernova shell can lead to detectable neutrino emission, either through nuclear collisions with the dense supernova shell or through interaction with the intense supernova and backscattered radiation field [60].

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