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Ultra-high-energy cosmic rays / Rayons cosmiques d'ultra-haute énergie

Cosmogenic neutrinos and gamma rays

Neutrinos et photons cosmogéniques

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ABSTRACT

We describe the photoproduction interactions of ultrahigh energy protons on the universal photon backgrounds and the production of very high-energy neutrinos and γ-rays in such interactions. We compare the production in propagation in the microwave background to that in the extragalactic background light. The propagation of heavy nuclei is discussed only briefly. We show the extreme models for cosmogenic neutrino production and the limits set on them by different experiments.

RÉSUMÉ

Nous décrivons la production de neutrinos et rayons gamma de très haute énergie lors des interactions de photo-production des protons d'ultra haute énergie sur les fonds diffus de photons. Nous comparons la production sur le fond diffus cosmologique à celle sur le fond diffus de lumière extragalactique. La propagation des noyaux massifs est brièvement évoquée. Nous présentons les modèles extrêmes de production de neutrinos et les comparons aux limites obtenues par différentes expériences.

1. Introduction

A couple of years ago we were expecting to detect two types of extremely high-energy neutrinos: the neutrinos generated at the acceleration sources of high-energy cosmic rays and the neutrinos produced in the propagation of the high-energy cosmic rays from their sources to us. Now our expectations have changed, since the IceCube neutrino observatory at the South Pole has published [1] the detection of very high-energy neutrinos that come from unknown Galactic or extragalactic sources.

Since we do not expect to have large amounts of matter in the vicinity of the extragalactic cosmic ray sources (see however Ref. [2] where the matter density around the sources is high), such as Active Galactic Nuclei (AGN), the expectations are that cosmic rays accelerated there would interact with the intense radiation fields and produce γ-rays and neutrinos. Such interactions are called *photoproduction*. The threshold energy for photoproduction in the center of mass system of the interaction $\sqrt{s}$ should be at least equal to the sum of the proton and pion masses $m_\pi + m_\mathrm{p}$, which is 1.08 GeV. The center of mass energy squared s in photoproduction interactions is

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1631-0705/

$$s = m_p^2 + 2E_p\epsilon(1 - \beta_p \cos\theta) \quad (1)$$

where E_p is the proton energy in the Laboratory system, ϵ is the energy of the photon, and θ is the angle between the two interacting particles. When the particles go exactly against each other, $\cos\theta = -1$ and this defines the lowest proton energy. Photoproduction interactions have been extensively studied in the 1960s and later and their cross section is well established to quite high CMS energy. The accelerator experiments were performed with γ-rays interacting on proton target in the so-called Nucleon Rest Frame (NRF) system. The minimum photon energy for photoproduction in the NRF is 145 MeV.

For $\epsilon = 1$ eV (optical radiation), the minimum proton energy is slightly higher than 7×10^{16} eV, i.e. all extragalactic objects that are seen with optical telescopes and can accelerate protons to 10^{17} eV would produce γ-rays and neutrinos. Waxman and Bahcall [3] were the first authors to use photoproduction interactions and calculate the maximal neutrino fluxes generated by the extragalactic cosmic ray sources. Using the average fraction of the proton energy that the generated neutrinos carry, they obtained the maximum ν_μ and $\bar{\nu}_\mu$ neutrino flux generated by extragalactic sources to be

$$E_\nu^2 \Phi_\nu = 1.5 \times 10^{-8}\ \mathrm{GeV\,cm^{-2}\,srad^{-1}\,s^{-1}} \quad (2)$$

Including a $(1+z)^3$ cosmological evolution (where z is the redshift) of the sources, they obtained a limit of $E_\nu^2 \Phi_\nu$ of 4.5×10^{-8} GeV/(cm^2 srad s). Although we disagree with many assumptions in this calculation (including the assumption that all cosmic rays are accelerated on an E^{-2} spectrum), this provides us with a useful straight line in $E_\nu^2 \Phi_\nu$ to compare to observations and more sophisticated models. Such a calculation also requires an estimate of the proton emissivity of all extragalactic cosmic ray sources. The number above corresponds to a proton energy flow of 5×10^{44} erg/Mpc^3/yr.

Ultrahigh-Energy Cosmic Rays (UHECR) are the highest energy fraction of the cosmic rays that we assume are accelerated at extragalactic cosmic ray sources. They can have photoproduction interactions on the most universal Cosmic Microwave Background (CMB), the leftover from the beginning of the Universe, which currently has a temperature of 2.725 K. This temperature corresponds to an average energy of the CMB of 6.34×10^{-4} eV. Using the same simple calculation for the minimum proton energy for interactions in CMB, we obtain 10^{20} eV in the current epoch. The actual minimum energy is lower (3×10^{19} eV), as the CMB energy distribution extends in a blackbody spectrum above 10^{-3} eV. In earlier cosmological epochs, for redshifts z higher than 0, the CMB temperature was higher by $1+z$ and the proton threshold energy is correspondingly lower.

The existence of such neutrinos, usually called *cosmogenic*, was suggested by Berezinsky and Zatsepin in 1969 [4] and independently by Stecker [5]. There have been quite many calculations of the expected fluxes of cosmogenic neutrinos since then. Among the older ones, the most interesting work is that of Ref. [6], which was done with the aim to use the limit on the ultrahigh-energy neutrino flux set by the Fly's Eye experiment to estimate the cosmological evolution of the cosmic ray sources. The current question is not if the cosmogenic neutrinos exist, we believe they do, but what is their flux. This depends on a large number of astrophysical parameters that we will define later.

2. Neutrino production by UHECR on propagation

The first step in all proton propagation calculations in the CMB is the calculation of the mean free path λ of the protons as a function of their energy. It is given by

$$\lambda_{p\gamma}^{-1}(E_p) = \frac{1}{8E_p^2} \int_{\epsilon_{thr}}^{\infty} d\epsilon\, \frac{n(\epsilon)}{\epsilon^2} \int_{s_{min}}^{s_{max}} ds\, (s - m_p^2)\sigma_{p\gamma}(s) \quad (3)$$

where ϵ is the photon energy in eV and $n(\epsilon)$ is the photon number density in cm^{-3} eV^{-1}. The mean free path in the current Universe has a minimum of 3.8 Mpc at E_p about 5×10^{20} eV and slightly increases at higher energy. At relatively small $\sqrt{s}$, the cross section is dominated by the Δ^+ production $p\gamma \to \Delta^+$, which is more than 500 μb. The resonance Δ^+ decays either to $p\pi^0$ or to $n\pi^+$ with a ratio of 2 between these two decay channels. Then heavier resonances follow with lower cross section and the multiparticle production starts at about $\sqrt{s}$ of about 5 GeV. It increases with the center of mass energy and is roughly 1% of the p–p cross section.

Another very important photoproduction interactions parameter is the proton *inelasticity* K_{inel} which defines the average fraction of its energy which the proton loses in the interaction and which goes in the production of secondary particles. At low $\sqrt{s}$, this fraction is small and K_{inel} is 0.17 for 10^{20} eV protons interacting now in the CMB. The distribution of this quantity is between 0 and 0.4, i.e. there are no cases where the proton loses more than 40% of its energy. Above 10^{20} eV, K_{inel} increases and at 10^{21} eV it grows to 0.27. The distribution becomes flatter, reaching inelasticities of 60% at higher $\sqrt{s}$.

The mean free path $\lambda_{p\gamma}$ and K_{inel} define the mean loss length. It is

$$L_{loss} = \frac{E_p}{dE_p/dx} = \frac{\lambda_{p\gamma}(E_p)}{K_{inel}(E_p)} \quad (4)$$

The minimum of L_{loss} coincides with the position of the minimum $\lambda_{p\gamma}$ and at $E_p = 5 \times 10^{20}$ eV it is about 16 Mpc and remains roughly constant as K_{inel} increases. Because of the increasing CMB temperature at higher redshifts, all these parameters have a relatively strong redshift dependence.

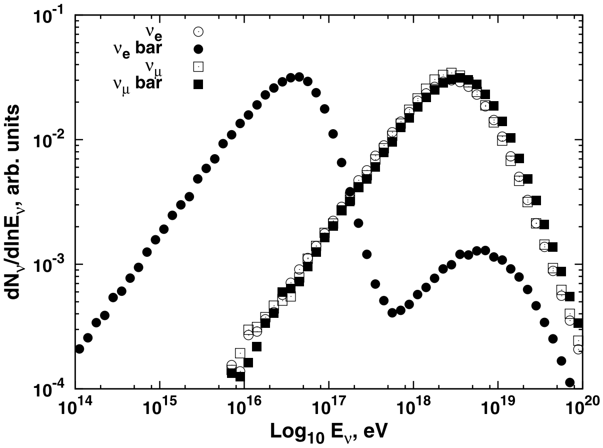

Fig. 1. Spectra of different neutrino types generated in proton propagation on 20 Mpc in CMB. The energy spectrum of the injected protons is $E^{-2.5}$. See text for different symbols.

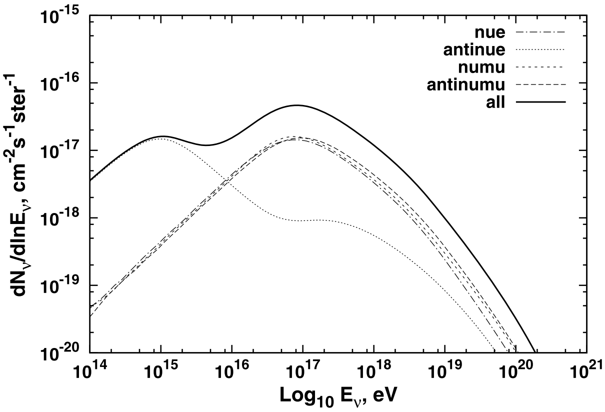

Fig. 2. Spectra of cosmogenic neutrinos integrated on propagation on redshifts from 0 to 8 in the CMB. The proton injection spectrum is $E_p^{-2.5}$ and extends to $10^{21.5}$ eV.

One also has to account for the other processes in which the protons lose energy in calculations of the γ-ray and neutrino fluxes from UHE protons propagating in the CMB and other universal photon backgrounds. The main such process is the pair production $p\gamma \rightarrow e^+e^-$. The energy loss length for this process is much larger, never below 100 Mpc. The mean free path is small, but the energy loss in the center of mass system is of the order of the electron mass. An additional energy loss is the adiabatic one due to the expansion of the Universe.

Fig. 1 shows the spectra of neutrinos generated by an $E^{-2.5}$ proton spectrum propagated at a distance of 20 Mpc. Electron neutrinos are indicated with open circles, $\bar{\nu}_e$ with filled circles, ν_μ with open squares, and $\bar{\nu}_\mu$ with closed squares. The spectra of ν_e, ν_μ and $\bar{\nu}_\mu$ are almost identical, so close to each other that the ν_e points are almost invisible in the graph. The electron antineutrinos have a very different spectrum that peaks slightly above 3×10^{16} eV. The reason is that such $\bar{\nu}_e$ are only generated in neutron decay ($n \rightarrow pe^-\bar{\nu}_e$). The neutron decay length is smaller than the neutron interaction length up to energy of 4×10^{20} eV. A small peak at about 5×10^{18} eV is created in neutron interactions in the CMB.

3. Energy spectra of cosmogenic neutrinos

The best way of calculating the cosmogenic neutrinos energy spectra is to propagate protons on different distances and then integrate the results of the propagation using the astrophysical assumptions [7]. Fig. 2 shows the result of the integration for a proton injection spectrum of $E^{-2.5}$ and a modest cosmological evolution of $(1+z)^3$. The thick solid line shows the sum of all neutrino types. It is interesting to understand what contributes the most to these energy spectra. The highest energy neutrinos are generated in the present Universe, close to $z = 0$ because neutrinos generate at large redshifts have their energy scaled down by $(1+z)$ by the adiabatic energy loss. The flux of $\bar{\nu}_e$ increases and its maximum moves to higher energy as higher-energy neutrons also decay in propagation on longer distances. There is a strong dependence of these effects on the cosmological evolution of the sources [8] and a moderate dependence on the cosmological model.

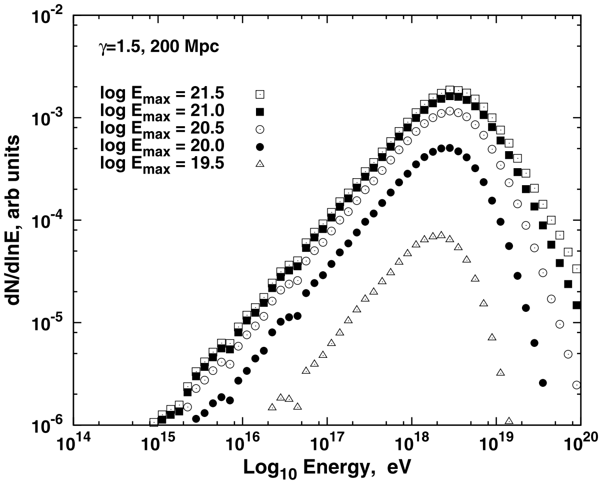

Fig. 3. Spectra of cosmogenic ν_μ and $\bar{\nu}_\mu$ produced on propagation on 200 Mpc (redshift z of 0.05) of proton spectra with different maximum energies.

Here is the list of all parameters one needs to perform a calculation.

- The total proton emissivity of the Universe in UHE cosmic rays, usually expressed in erg/Mpc^3/yr. This is a coefficient that normalizes the calculation to the assumed proton flux in the Universe.
- The average acceleration spectrum of these particles. The flatter the spectrum is, more UHECR can interact in the CMB.
- The chemical composition of UHECR. This relates to the spectrum of protons because nuclei interact in the CMB in a different way that we will briefly discuss later.
- The maximum acceleration energy in the UHECR sources. It is obvious that the higher the maximum energy is, the more photoproduction interactions there are and the more (and higher energy) neutrinos are generated.
- The cosmological evolution of the UHECR sources.

Many of these parameters are related. High maximum acceleration energy and a flat acceleration spectrum generate higher emissivity of UHECR, for example. A strong cosmological evolution can compensate for a low current emissivity because at high redshifts the energy of the CMB was higher and lower energy protons were able to photoproduce. It is difficult to describe all relations between these five parameters.

Fig. 3 shows the spectra of muon neutrinos and antineutrinos generated on propagation in 200 Mpc in the CMB as a function of the maximum acceleration energy of the protons. The proton injection spectrum is $E_p^{-2.5}$. The difference between $\log(E_p^{max})$ of $10^{21.5}$ and 10^{20} eV is not big because of the relatively flat injection spectrum and the same energy flux used in this calculation. If the acceleration spectrum were flatter, the difference would increase. Less neutrinos are generated when the maximum energy decreases and the neutrino spectrum also changes. It is impossible to produce neutrinos of energy higher than E_p^{max}, of course, and for this reason the energy spectrum is narrower for the lowest maximum energy. If the maximum acceleration energy is less than $10^{19.5}$ eV protons do not interact in the contemporary Universe and there are only neutrinos generated at higher redshifts.

3.1. Production of cosmogenic gamma rays

It is not easy to estimate the ratio of cosmogenic neutrinos to γ-rays, except in the dominating Δ^+ production cross section. Δ^+ decays in $n\pi^+$ or $p\pi^0$. Positively charged pions decay generates three neutrinos (ν_μ, ν_e, $\bar{\nu}_\mu$) and π^0 decays in two γ-rays. There are twice as many π^0s in the Δ^+ decay. For this reason, the energy spectra of neutrinos and gamma rays are slightly different. Fig. 4 compares the production spectra of all neutrinos and of γ-rays and electrons in propagation on 200 Mpc. This calculation includes all photoproduction processes, not only Δ^+ production. The peak of the neutrino flux is higher, but the γ-ray flux extends to higher energy. The charged pions decay chain contributes to the electromagnetic cosmogenic component through the neutron decay to electrons. Since the decay electron has much higher energy than the $\bar{\nu}_e$, electrons peak at higher energy.

While the produced neutrinos have only adiabatic energy loss, the generated γ-rays and electrons interact with the universal photon background in $\gamma\gamma \to e^+e^-$ and inverse Compton collisions. The high-energy electrons also quickly lose energy on synchrotron radiation in the extragalactic magnetic fields. In the first paper that discusses the ultrahigh energy γ-rays and electrons cascading in the photon background [9], the conclusion is that the GeV–TeV γ-ray diffuse flux can correspond to the ultrahigh energy γ-ray production if the average magnetic field in the extragalactic space is less than

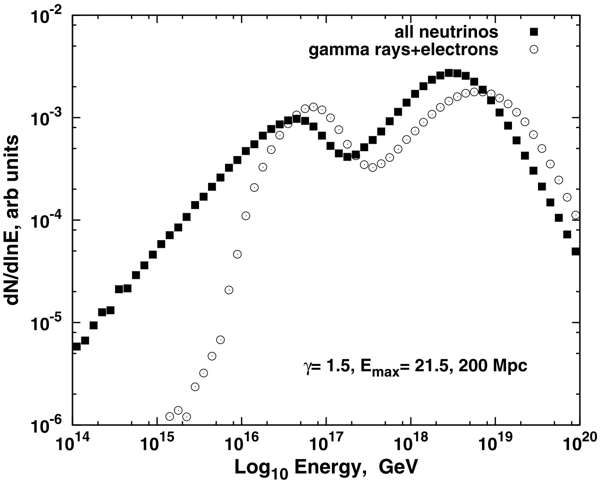

Fig. 4. Spectra of all neutrino types and of γ-rays and electrons in propagation on 200 Mpc.

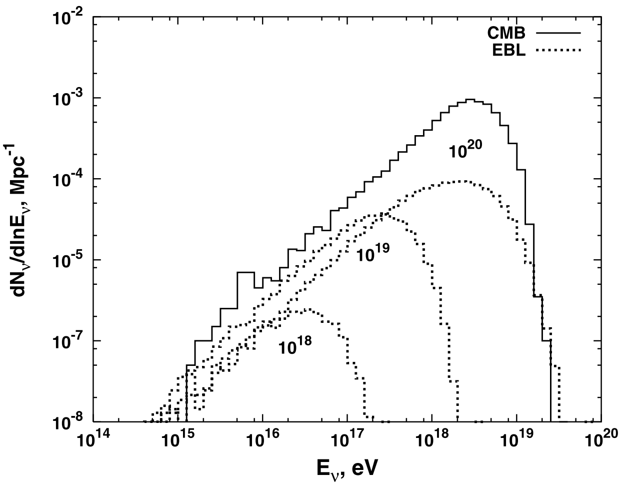

Fig. 5. Spectra of cosmogenic ν_μ and $\bar{\nu}_\mu$ generated on propagation on 1 Mpc in the contemporary Universe. The proton energy is marked by the histograms.

10^{-12} G, but not if it is of the order of 10^{-9} G. Such dependence on the magnetic field strength can generate anisotropy of the diffuse high-energy γ-ray background.

3.2. The other universal photon background

The cosmic microwave background is not the only universal photon background. There is also the radio and extragalactic background light (EBL) that covers wavelengths between the microwave and optical radiation. The latter exhibits two peaks—one at the maximum of the optical light close to energy of one eV, and another above wavelengths of 100 μm that represents the scattered and thermalized optical light. The total number density of EBL is about 1 cm^{-3}, more than 400 times lower than that of the CMB, but even the far infrared range has energy much higher than that of the CMB. That means that much lower energy protons would photoproduce in the EBL and also generate neutrinos. The energy spectra of the cosmogenic neutrinos generated in EBL will have roughly the same shape but will be shifted to lower energy than these generated in the CMB. While the lowest energy protons interacting in the CMB is 3×10^{19} eV, even 10^{17} eV protons occasionally interact in the EBL—see the estimates in Section 1 for photons of energy 1 eV.

Fig. 5 compares the production of $\nu_\mu + \bar{\nu}_\mu$ of protons of different energy in the propagation on 1 Mpc in the EBL with the production of 10^{20} eV protons on the CMB. At this energy, the production in interactions with the CMB photons is much higher, but even 10^{18} eV protons generate neutrinos in the EBL. Since even for very flat proton acceleration spectra (E_p^{-2}), there are 10 000 more 10^{18} eV protons than there are 10^{20} eV ones, the contribution of the EBL may turn to be important for cosmogenic secondaries.

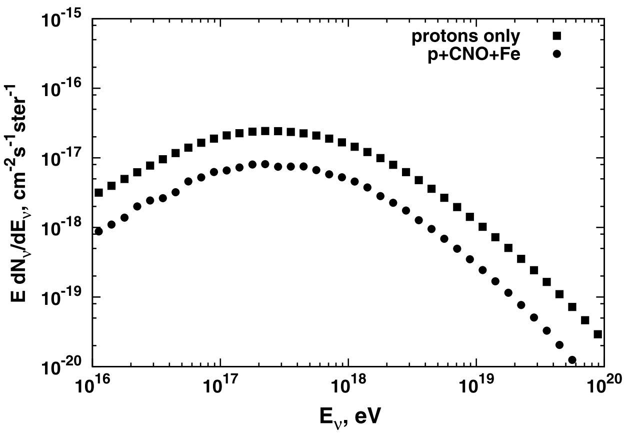

Fig. 6. Spectra of cosmogenic ν_μ and $\bar{\nu}_\mu$ from interactions in the CMB of a purely proton composition and the toy UHECR composition discussed in the text.

The fact that lower-energy protons interact in EBL has an interesting effect on the neutrino production: while in interactions on the CMB flatter injection spectra generate more neutrinos, in interactions in EBL steeper proton spectra have the same effect, since there are more lower energy protons for the same energy flux. The steeper the proton spectrum is, the bigger the contribution of the EBL target is.

3.3. *Interactions of nuclei in photon fields*

Nuclei heavier than protons have also another source of energy loss: photodisintegration. The dominant process is the giant dipole resonance induced in the nuclei by the microwave background or any other photon field. The giant dipole resonance cross-section peaks in the ϵ' energy range 10–30 MeV. The nucleus absorbs the photon and forms an excited state, which decays, releasing one or two nucleons. The photoabsorption cross-section roughly obeys the Thomas–Reiche–Kuhn sum rule. It is usually defined as

$$\sigma_{\text{phabs}} \equiv \int_0^\infty \sigma\left(\epsilon'\right) \mathrm{d}\epsilon' \simeq 60 \frac{NZ}{A} \tag{5}$$

The photoabsorption cross-section σ_{phabs} is measured in mb MeV. In Eq. (5), A is the mass number, Z is the charge, and N is the number of neutrons.

This is only a rough approximation of the real cross-section that depends on the stability of the nucleus. At energies ϵ' lower than about 30 MeV, the disintegration is dominated by the emission of one or two nucleons. At higher energy, the emission of more than two nucleons is possible.

Generally, because of its charge, it appears easier to emit a proton than a neutron. Stable nuclei are more difficult to disintegrate, although there are no absolute rules. It is even more important to account for the e^+e^- pair production energy loss since it scales as the nucleus charge Z^2.

It is obvious that a nucleus of total energy 10^{20} eV will have energy per nucleon A times smaller and iron nuclei of that energy will never suffer photoproduction and generate high-energy cosmogenic neutrinos. On the other hand, many of the neutrons released in the photodisintegration will decay and generate $\bar{\nu}_e$. For that reason, the fluxes of electron antineutrinos increase significantly if the composition of the UHECR is heavy or mixed, while the fluxes of high-energy neutrinos decrease.

If the UHECR composition was constant with energy, one could scale the cosmogenic neutrino flux down with the fraction of protons in the UHECR flux. As an illustration, we show in Fig. 6 the fluxes of cosmogenic $\nu_\mu + \bar{\nu}_\mu$ generated by protons with a differential spectral index $E^{-2.5}$ and by the toy UHECR composition consisting of 50% H, 20% CNO and 30% Fe nuclei at 10^{19} eV. The fraction of H nuclei declines to 10% at 10^{21} eV, where the injection spectrum ends and the fraction of heavy nuclei increases to compensate for the proton decline. This composition easily generates all nucleon spectrum that was used for this illustration. Note that this toy composition does not fit well the UHECR spectrum.

At neutrino energies below 10^{18} eV, the toy composition generates a few times less cosmogenic neutrinos, but at the highest neutrino energy the ratio between these two models is a factor of more than 10. The $\nu_\mu + \bar{\nu}_\mu$ spectrum appears more irregular than the purely proton one. This might be explained by the contribution of the high-energy nuclei: the highest energy CNO nuclei ($A = 14$) increase a bit the nucleons of energy 7.1×10^{19} eV that interact in the CMB. If interactions in the EBL were included in the calculation, the influence of such nucleons would be higher. The biggest difference between these models in a real calculation would be in the vastly increased $\bar{\nu}_e$ flux.

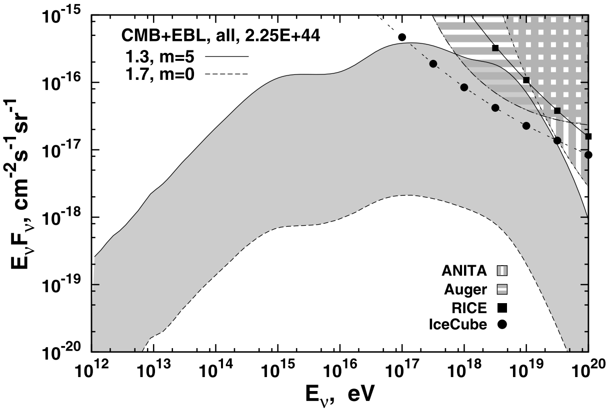

Fig. 7. Spectra of all cosmogenic neutrinos generated by the two extreme models described in the text. Both models have purely proton chemical composition. All interactions on the CMB and in the EBL are included in the neutrino production. The figure also shows the limits on the cosmogenic neutrino flux set by different experiments.

The cosmogenic neutrino fluxes generated by different cosmic ray compositions and the corresponding maximum energies are very well described and discussed in Ref. [10], which explores the possible range of the cosmogenic neutrino fluxes in dependence of the cosmic ray chemical composition, as interpreted by different experiments.

4. Expected fluxes of cosmogenic neutrinos

The expected fluxes of cosmogenic neutrinos are very different depending on the interpretations on the cosmic ray energy spectrum and composition detected by the UHECR detectors, such as the Auger observatory [11], the High-Resolution Fly's Eye [12] and the Telescope array [13]. While the energy estimates of Auger and the other two detectors are only different by about 20% (with difference decrease reported at the International Cosmic Ray Conference in 2013), they do measure different cosmic ray composition above 10^{18} eV. HiRes and TA measure a very light cosmic ray composition that would generate cosmogenic neutrinos. The Auger observatory claims a mixed composition above 10^{18} eV that becomes increasingly heavier above 10^{19} eV. The statistics is insufficient to have a better model of the chemical composition as a function of the primary energy, but the tendency is to observe more heavier nuclei at the highest energies. Since this energy range coincides with threshold energy for neutrino production in the CMB, the expected flux of cosmogenic neutrinos is low.

In addition, the models for the generation of the UHECR energy spectrum also strongly influence the neutrino production. In classical models where the dip of the spectrum at about 3×10^{18} eV is due to the emergence of extragalactic cosmic rays, the extragalactic injection spectrum would be about $E^{-2.3}$ and may require a strong cosmological evolution of the sources. On the other hand, the *dip* model of Ref. [14], which explains a proton-dominated spectrum that fits the observations down to 10^{17} eV, uses injection spectrum with power law index -2.7 and requires no cosmological evolution of the sources.

Fig. 7 compares the prediction of the two extreme interpretations of the energy spectrum—the fit of the Auger spectrum [15] with protons accelerated to a -2.3 spectral index with $(1+z)^5$ cosmological evolution and that of Ref. [14] with $E^{-2.7}$ acceleration and no cosmological evolution. The latter model fits well the spectrum measured by the HiRes experiment [16]. The UHE proton emissivity above 10^{19} eV used in the calculation in both models is 1/2 of that defined in Ref. [3]. One can easily see that the difference in the neutrino flux is more than two orders of magnitude in almost the whole energy range. It is true that the maximum ($\gamma = 1.3$, $m = 5$) model is not very realistic. We show it here to emphasize the huge difference in the expectations.

A very good discussion of the dependence of the cosmological neutrino flux on the UHECR composition is made in Ref. [17], which describes the *disappointing* model in which the highest energy cosmic rays are iron nuclei. In such a model, its authors say, the maximum energy of the accelerated protons is between two and five EeV $(2\text{–}5) \times 10^{18}$ eV and the highest energy iron nuclei are 2.8×10^{20} eV. Therefore no neutrinos would be produced in current interactions with the CMB photons. There would still be some production at high redshifts, in the EBL and, of course, $\bar{\nu}_e$ from neutron decay. If the disappointing model is true, there is no chance that IceCube [18] will ever detect high-energy cosmogenic neutrinos.

The interest in detecting cosmogenic neutrinos rose substantially last year when IceCube announced the detection of two 10^{15}-eV neutrino-induced cascades [19] and after more very high-energy neutrinos were detected [1]. Since 10^{15} eV is significantly lower than 10^{18} eV, the main question was if the two events are not $\bar{\nu}_e$ interacting with electrons to generate the Glashow resonance $\bar{\nu}_e + e^- \rightarrow W^-$. The resonant cross section reaches 0.47 μb at 6.4×10^{15} eV but the width of the resonance is very narrow 2.1 GeV. The W^- decays in six hadronic and three leptonic channels, but all of them would create significantly higher-energy cascades in IceCube. Eventually the conclusion was that these are not likely to be $\bar{\nu}_e e^-$ interactions.

Limits of the cosmogenic neutrinos of energy above 10^{17} eV have been set by the Auger air shower array [20], the RICE experiment at the South Pole [21], by the ANITA experiment [22], and by IceCube [23]. Auger has updated the neutrino limit (set on τ neutrino interactions) on the basis of six years of observations using different air shower techniques. IceCube has set the lowest limits in the vicinity of 10^{18} eV, while Auger and ANITA have the strongest limits at energies exceeding 10^{20} eV. At 10^{17} eV the IceCube limit equals the Waxman and Bahcall limiting neutrino flux.

At lower energies, all limits are well above the cosmogenic neutrino models. It is, however, difficult to believe that the cosmogenic neutrino fluxes do not follow the shape predicted by all calculations and the new limits seem to exclude the highest predicted neutrino fluxes.

There are some limits on the extremely high-energy γ-rays in our neighborhood. Both the Auger experiment and the Telescope Array limited the fraction of γ-rays in very high-energy air showers. The best limit is at 10^{19} eV, where the surface detector of the Auger experiments limits the integral flux of gamma rays to less than 2% of the cosmic ray flux [24]. This limit is just above the limited prediction of cosmogenic γ-rays calculated in Ref. [25]. The Telescope Array limit [26] is less stringent.

Ref. [25] uses the diffuse γ-ray flux detected by the Fermi/LAT detector to restrict the cosmogenic secondaries from the UHECR propagation and the cosmological evolution of highest-energy cosmic ray sources. The conclusion is that the cosmogenic neutrino flux can be two or three times higher than the lower limit shown in Fig. 7 if all highest energy cosmic rays are protons. If a fraction of them consists of heavier nuclei the flux of cosmogenic neutrinos should be lower.

Not everybody who used the Fermi/LAT diffuse γ-ray flux agrees fully with this statement. Ref. [27] has also attempted to limit the cosmogenic neutrino flux using the diffuse γ-ray background. They study the cosmogenic neutrino and gamma ray production as a function of the *cross-over* energy where the extragalactic cosmic rays dominate over the Galactic ones. The cross-over range is between $10^{17.5}$ and 10^{19} eV. There may be a better account for the electron energy loss to synchrotron radiation in this paper. As a result the cosmogenic neutrino flux could be a factor of 30 above the $\gamma = 1.7$, $m = 0$ model shown in Fig. 7. Such flux can be detected by the IceCube experiment with several years of exposure. The new IceCube limit presented in Fig. 7 does not allow the fluxes at 10^{18} eV to grow that much, but it can be a factor of ten higher than the minimal value.

A possible detection of cosmogenic neutrinos by one of the experiments that set the current limits would not only benefit neutrino astronomy. It will contribute to many general astrophysical communities dealing with cosmic ray acceleration, possible sources of UHECR, and the details of their propagation in the Universe. It may also provide a basis for a confirmation for the models of the neutrino interaction cross section.

Acknowledgements

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