Ultra high energy neutrinos: the key to ultra high energy cosmic rays

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Abstract

We discuss the relation between the acceleration spectra of extragalactic cosmic ray protons and the luminosity and cosmological evolution of their sources and the production of ultra high energy cosmogenic neutrinos in their propagation from the sources to us.

1 Introduction

High energy astrophysical neutrinos are produced in hadronic reactions of accelerated nucleons and the subsequent decay of the secondary meson and muons. In astrophysical environments all mesons and muons decay, so that the generated neutrino flux indicates the energy spectrum of the accelerated nucleons and the available target density in the neutrino production site, as it does for $\pi^0$ decay $\gamma$-rays. One of the best examples for this correlation is the prediction for diffuse $\gamma$-ray fluxes from the galactic plane. To fit the observations the EGRET group had to use the data on the matter density and the cosmic ray density in the galactic plane (Hunter et al. 1997).

Waxman&Bahcall (1999, 2001) did the same kind of calculation of the high energy neutrinos generated in extragalactic sources replacing the target density with a parameter $\eta$ that describes the fraction of the accelerated
cosmic rays at all extragalactic sources that interact at source and generate neutrinos. The process is photoproduction interactions of the accelerated protons in the ambient photon field. One very important parameter is the cosmic ray emissivity that was estimated (Waxman 1995) to be $4.5 \times 10^{44}$ erg/Mpc$^3$/yr with an error of about 30%. The acceleration proton spectrum is assumed to be $E_p^{-2}$ and the maximum proton energy is assumed to be $10^{21}$ eV. The emissivity above refers to the cosmic ray flux measured at $10^{19}$ eV, which is assumed to be of extragalactic origin. The calculation uses the average fraction of the proton energy that neutrinos carry - 15% in all neutrino flavors. The point made is that if $\eta = 1$, i.e. if all protons interact, this will give an upper bound of the astrophysical neutrino flux.

This bound was criticized by Mannheim, Protheroe & Rachen (2001) where a more detailed analysis of the assumptions made by Waxman&Bahcall (1999) was performed and a new, generally higher, limit that accounts for the energy loss horizon of cosmic rays and neutrinos was derived. The work of Waxman&Bahcall, right or wrong, is the first published direct connection of the flux of astrophysical neutrinos and of extragalactic cosmic rays.

We shall attempt to relate the flux of ultra high energy cosmic rays (UHECR) to UHE neutrinos created in the propagation of these particles from their sources to us in the photon fields present in the whole Universe. The main one is the microwave background radiation (MBR) where most of these cosmogenic neutrinos are generated. Neutrino production in the GZK interactions was first proposed by Berezinsky&Zatsepin (1969). Many other calculations were subsequently made and the most important of those is that of Hill&Schramm (1983) who attempted to limit the cosmological evolution of the cosmic ray sources by the lack of detection of such ultra high energy neutrinos.

The difference between the source neutrinos discussed by Waxman&Bahcall and the cosmogenic neutrinos is that the target for the latter is extremely well studied. While different astrophysical sources show various photon spectra the MBR energy spectrum is not only well known in the current epoch, but can be easily evolved for any value of the redshift $z$. Because of that we know exactly what the threshold proton energy $E_p^{\text{thr}}$ for photoproduction is:

$$E_p^{\text{thr}} = \frac{m_\pi (2m_p + m_\pi)}{2\varepsilon (1 - \cos \theta)},$$

where $\varepsilon$ is the photon energy and $\theta$ is the angle between the two interacting particles. $E_p^{\text{thr}}$ in the current epoch is above $2 \times 10^{20}$ eV for interactions
on the average energy MBR photon. The actual threshold is about $3 \times 10^{19}$ eV. For earlier cosmological epoch it decreases as $(1 + z)^{-1}$ because of the increase of the MBR temperature. In the following we shall assume that all extragalactic cosmic rays are protons and that their sources are isotropically and homogeneously distributed in the Universe.

The mean free path for proton photoproduction interactions in the contemporary Universe reaches a minimum of 3.8 Mpc (Stanev et al 2000) at proton energy of $5 \times 10^{20}$ eV and very slightly increases after that. The energy loss length for protons is 16 Mpc at the same energy (the inelasticity coefficient $K_{\text{inel}}$ for photoproduction interactions at threshold is below 0.2) and decrease at higher energy when $K_{\text{inel}}$ continues growing with $\sqrt{s}$.

To obtain the flux of cosmogenic neutrinos we calculate the neutrino production yield at $z = 0$ and then scale it for (Engel, Seckel & Stanev 2001) arbitrary redshift values. The flux is obtained by folding the neutrino yield with the proton injection spectrum and integration in time or redshift in a cosmological model. The $z$ dependence of the proton injection spectrum can include the cosmological evolution of its sources which in the current work is assumed to be of the form $(1 + z)^m$ with different $m$ values in various cosmological epochs. We use $H_0$ of 75 km/s/Mpc. $\Omega_\Lambda$ dominated Universe enhances the cosmogenic neutrino fluxes by about 75% in comparison with the matter dominated Universe ($\Omega_M = 1$).

2 Fits of the UHE cosmic ray spectrum

One of the current problems in ultra high energy astrophysics is the derivation of the extragalactic UHECR acceleration spectrum which for the purposes of propagation studies we also call injection spectrum. Fig. 1 shows two extreme fits. The left hand one is a fit with $E_p^{-2}$ extragalactic injection spectrum (Bahcall&Waxman 2003) and two different cosmological evolutions with $m=3$ and 4 up to a $z_{\text{max}} = 1.9$. The small difference between $m = 3$ and 4 is explained with the fact that only readshifts smaller than 0.4 contribute to the UHECR flux above $10^{19}$ eV. Since the contribution of extragalactic protons below $10^{19}$ eV is small one has to assume that the galactic cosmic ray spectrum extends up to and above that energy. The experimental points shown are these of AGASA (Takeda et al 1998) and HiRes (Abbasi et al 2004) normalized to each other at $10^{19}$ eV to emphasize the shape of the UHECR spectrum. Except for the AGASA events above $10^{20}$ eV the two spectra agree quite well in shape. The preliminary data of the Auger Observatory (Sommers 2005) have a flux normalization close to
Figure 1: Left hand panel: Fit of the observed cosmic ray spectrum with flat injection spectrum ($\gamma = 1$) and cosmological evolutions of the cosmic ray sources with $m = 3$ and 4 (bottom and top of the shaded area). The galactic cosmic ray spectrum is shown with a dashed line. Right hand panel: Fit with steep injection spectrum ($\gamma = 1.7$) and no cosmological evolution.

that of HiRes and a similar energy spectrum.

The right hand figure shows a different fit (Berezinsky, Gazizov & Grigorieva 2005) - the extragalactic injection spectrum is $E_p^{-2.7}$ and there is no cosmological evolution of the UHECR sources ($m = 0$). The fit describes quite well the cosmic ray spectrum down to at least $10^{18}$ eV. The wide feature in the spectrum around $10^{19}$ eV is explained with the second most important energy loss process in proton propagation - the Bethe-Heitler production of $e^+ e^-$ pairs (Berezinsky & Grigorieva 1988). According to this fit the end of the galactic cosmic rays is at $10^{18}$ eV or below.

In addition to the different ends of the galactic cosmic ray spectrum (and respectively the cosmic ray chemical composition as a function of the energy) the major difference between the two fits is the cosmological evolution of the cosmic ray sources that they require. Fits with flat injection spectrum ($E_p^{-2}$, $\gamma = 1$) require a strong cosmological evolution of the cosmic ray sources, similar to that of star forming regions. The fit of Berezinsky et al (2005) on the other hand does not need any cosmological evolution of the sources. Our own fits have shown that if cosmological evolution is assumed the best value for the injection spectrum index $\gamma$ decreases by 0.05 to 0.15 (DeMarco & Stanev, 2005).
3 Redshift dependence of the cosmogenic neutrino production

Since neutrinos do not lose energy in propagation their production follows well the cosmological evolution of the cosmic ray sources. To illustrate that point we briefly discuss calculation of the cosmogenic neutrino flux. The neutrino flux at Earth due to GZK process is

$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \int dt d\epsilon_p \frac{d\Gamma}{d\epsilon_p} E_\nu \frac{dy}{dE_\nu}(E_\nu, \epsilon_p, t) \quad (1)$$

where $\Gamma$ is the injection rate of UHECR and $y$ is the neutrino yield per proton injected with energy $\epsilon_p$, and $E_\nu$ is the neutrino energy today. Equation 1 can be put into a more convenient form by defining $q = 1 + z$ and integrating over redshift. For simplicity in this example we assume matter dominated Universe.

After scaling the neutrino yield from photoproduction interactions in MBR as a function of redshift, including a cosmological evolution as $q^m$, and changing the variable to $\ln q$ the neutrino flux becomes (Seckel & Stanev 2005)

$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \frac{3A}{2} \int_0^{q_{max}} d(\ln q) q^{(m+\gamma-\frac{3}{2})} E_\nu \frac{dY_{\gamma\nu}}{dE_\nu}(q^2 E_\nu) \quad (2)$$

It is now clear that for values of $(m+\gamma)$ greater than 3/2 higher redshifts generate more neutrinos, while for values below that the neutrino production diminishes with redshift. Fig. 2 shows three illustrative examples where the same cosmological evolution is assumed to $q = 10$.

In understanding the importance of Fig. 2 one should remember that redshifts above 0.4 do not contribute to the extragalactic cosmic ray spectrum.
above $10^{19}$ eV independently of the maximum acceleration energy. For this reason the cosmological evolution of the sources affects the observed cosmic ray spectrum only slightly, as visible in Fig. 1.

4 Cosmogenic neutrinos from the two extreme fits of the UHECR spectrum.

It is now obvious that the two fits of the cosmic ray spectrum will generate different fluxes of cosmogenic neutrinos. In the flat injection spectrum case we have $m + \gamma = 4$, which provides for a strong cosmological evolution of the neutrino production. In the steep injection spectrum fit we have practically no cosmological evolution. Fig. 3 shows the spectra from the both fits assuming the same cosmic ray flux at $10^{19}$ eV, which corresponds to the emissivity derived by Waxman (1995). The cosmological evolution for the flat injection spectrum model $H(z)$ used is from the same paper and is

$$ H(z) = \begin{cases} (1 + z)^3 & : z < 1.9 \\ (1 + 1.9)^3 & : 1.9 < z < 2.7 \\ (1 + 1.9)^3 \exp\{(2.7 - z)/2.7\} & : z > 2.7 \end{cases} \quad (3) $$

The two models indeed generate very different cosmogenic neutrino spectra, which are shown in Fig. 3 for dark energy dominated cosmology and $H_0 = 75$ km/s/Mpc. The flat injection spectrum model generates about 1.5 orders of magnitude more neutrinos in the peak that is at about $10^{17.6}$ eV. The steep spectrum contains a smaller faction of above threshold protons and the neutrino flux peaks at slightly lower energy. This will influence also the detection probability as the neutrino-nucleon cross section grows with the neutrino energy.

The flat injection spectrum model generates about $10^{-19}$ muon neutrinos and antineutrinos per cm$^2$.s.ster above $10^{20}$ eV which brings it in the range that could be detected by the Auger observatory (Abraham et al 2004) and RICE (Kravchenko et al. 2006) and ANITA-like (Barwick et al 2006) radio detection experiment. The steep injection spectrum model with no cosmological evolution goes below $10^{-20}$ per cm$^2$.s.ster shortly above $10^{19}$ eV.

In practice this means that the cosmogenic neutrinos from the flat injection spectrum model could be detected by the neutrino telescopes in construction, including IceCube (Ahrens et al 2004) while the steep injection spectrum model would not allow us to detect cosmogenic neutrinos in the foreseeable future.
Figure 3: Sum of muon neutrinos and antineutrinos generated by the two extreme fits of the UHECR spectrum

It is indeed very difficult to estimate the detection rate in different experimental arrangements without the use of a proper detection montecarlo code that can estimate the detection probability as a function of the neutrino energy and direction. Roughly speaking, the IceCube neutrino telescope should be able to see about one event per year with energy above $10^6$ GeV from the flat injection spectrum model. The large majority of these events will come from above, as most neutrinos coming from the lower hemisphere will be absorbed in propagation through the Earth. The cosmogenic neutrinos generated by the steep injection spectrum model will generate detection rates smaller by more than an order of magnitude.

The possible future detection even of a very small number of neutrino events of extremely high energy could serve as a powerful tool for solving the problem of the acceleration spectrum of UHECR and the cosmological evolution of their sources.

5 Cosmogenic neutrinos from proton interactions in other universal photon fields

The microwave background radiation is by far not the only universal photon field - it is only the best known. For this reason we performed a calculation (DeMarco et al 2006) of the neutrino production on the infrared and optical background (IRB). This background has been measured several times,
directly and indirectly by the TeV gamma ray absorption, but its exact number density is a matter of dispute. We use the model of Stecker, Malkan & Scully (2005) which also follows the cosmological evolution of the infrared background. We are mostly interested in the far infrared background (FIR) that has the highest number density and provides a denser target for high energy proton interactions.

![Figure 4: Ratio of the proton mean free path in the total photon field to this in the infrared background.](image)

Figure 4 shows the ratio of the proton interaction length in the ratio of the proton mean free path in all photon fields with photon energy below 1 eV to that in the infrared background as a function of the proton energy. There are three curves corresponding to redshifts of 0, 2, and 4, i.e. covering almost the whole redshift range important for cosmogenic neutrino production. Since the proton threshold energy for interactions in MBR at \( z = 0 \) is about \( 3 \times 10^{19} \) eV at lower energy all interactions are in the IRB. One question is how IRB with number density of less than \( 1 \text{ cm}^{-3} \) can compete with the MBR with number density of \( 430 \text{ cm}^{-3} \) above the threshold energy. The answer is simply that only a small fraction of the MBR photons provide above threshold targets for photoproduction while almost all IRB photons do.

At higher redshifts the dominance of the IRB photon extends to lower energy. The main reason is the different cosmological evolution of the two backgrounds. MBR photons energy grows as \((1 + z)\) and their number density as \((1 + z)^3\) while IRB photons have slower cosmological evolution.
- they are emitted by astrophysical objects and we suspect that the IRB number density at redshifts higher than 6 is close to zero.

Figure 5: Sum of muon neutrinos and antineutrinos generated by the two fits of the extragalactic cosmic ray spectrum generated in both MBR and IRB.

Figure 5 shows the cosmogenic neutrino fluxes generated by the two fits of the UHECR spectrum with account for the interactions in the infrared background. The difference between the two models now is much smaller. Since the UHECR emissivity is normalized to the flux at $10^{19}$ eV the IRB neutrinos in the steep injection spectrum model are much larger fraction of those generated in the MBR than those in the flat injection spectrum model. In addition, the strong cosmological evolution of the cosmic ray sources in the flat injection spectrum case is not enhanced by equally strong cosmological evolution of the photon target density.

Up to about $10^{15}$ eV the two spectra are almost identical. The steep injection spectrum model generates neutrinos that peak at about $10^{16.3}$ eV and has a spectrum with relatively narrow width. The flat injection spectrum with cosmological evolution peaks as in the MBR only case and has a much wider spectrum. The difference in the peak values is now smaller, about a factor of 3. The ratio in the detection rates has most likely not changed much because the higher energy neutrinos interact with matter with correspondingly higher cross section.

It is worth noting that we have not calculated the neutrino production by protons of energy below $10^{18}$ eV and photons of energy exceeding 1 eV were neglected. In the calculation presented by Allard et al (2006) not only all
optical photons, but also UV ones, are included. Nucleons of energy lower than $10^{18}$ eV also interact and generate neutrinos. Their lower neutrino yield is weighted by the much higher number of lower energy nucleons and the neutrino fluxes have wider distributions and peak at lower energy.

6 Discussion

We have shown that the fluxes of cosmogenic neutrinos generated by extragalactic protons depend very strongly on the cosmological evolution of the UHECR sources. The detection of even a small number of such neutrinos will be an important input in the solution of the origin of these particles. Currently the observed UHECR spectrum can be equally well be fitted with vastly different cosmic ray acceleration spectra. Fits with flat ($\gamma = 1$) acceleration spectra require strong cosmological evolution, while steep ($\gamma = 1.7$) do not require any cosmological evolution of the sources. The acceleration spectrum could be derived if the cosmological evolution of the sources were determined by observations of cosmogenic neutrinos.

The traditional way to study the same question is through studies of the chemical composition of these particles. Cosmogenic neutrinos give one more parameter that should be consistent with the changes of the composition if all extragalactic cosmic rays are light (H and He) nuclei. The steep injection spectrum model predicts changes of the cosmic ray composition when approaching $10^{18}$ eV and a very low flux of cosmogenic neutrinos. In the flat acceleration spectrum model the composition changes continue up to and exceeding $10^{19}$ eV.

The calculations and estimates presented here assume that ultra high energy cosmic rays are protons. We have not accounted even for a small He contribution in the flux of UHE particles. There are, however, in the literature papers that do similar calculations in the assumption that UHECR have the same chemical composition as the galactic cosmic rays (Allard 2005). Under this assumption the injection spectrum of UHECR comes out to be intermediate between the two fits discussed above. Cosmogenic neutrinos are also produced (Hooper, Taylor & Sarkar 2005; Ave et al 2005) but they are mostly electron antineutrinos from the decay of neutrons from nuclear photodisintegration. These neutrinos are also strongly correlated with the cosmological evolution of the UHECR sources.
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DISCUSSION

FRANCESCO VISSANI: You estimated the number of neutrino events in IceCube to 1.5 per year. What is the expected number of events in ANITA and Auger?

TODOR STANEV: In principle Auger has 30 times more volume than IceCube, but the number of events is probably smaller. I would guess it does not exceed 5 events per year depending on the exact energy threshold and efficiency. Even for IceCube I gave you my own estimate.