Ultrahigh Energy Cosmic Rays and Neutrinos

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We discuss the relation between the highest energy cosmic rays (UHECR) and UHE neutrinos. The neutrinos produced in the sources of optically thin astrophysical sources have been linked to the UHECR emissivity of the Universe. The fluxes of cosmogenic neutrinos, generated in propagation by UHECR, also reflect the acceleration of these particles, the maximum acceleration energy, and the cosmological evolution of their sources.

1. Introduction

It is now a time when both subjects in the title are of high scientific interest in the field of particle astrophysics. The interest is related to the emergence of new set of experiments that are obviously of much better quality than what we know from the past.

The Southern Auger Observatory \cite{1} in Argentina is almost fully completed and is operating during construction. The Telescope Array (TA) is under construction in Utah. Both these giant air shower arrays are designed and constructed to operate in hybrid mode, i.e. they employ both methods of air shower detection: surface array plus optical detectors that follow the fluorescent light generated by the giant air shower in the atmosphere. The optical detectors operate about 10% of the time but the energy assignment by integration over the shower longitudinal profile seems to be less model dependent than the classical method of relating the primary energy to the shower particle density on the ground. The latter depends much more on the hadronic interaction model used in Monte Carlo studies of the shower development. The fraction of showers detected in hybrid mode by both detectors can be used for a better calibration of the surface array. The sizes of the surface arrays, 3,000 km\textsuperscript{2} for Auger and 1,000 km\textsuperscript{2} for TA are very impressive, more than one order of magnitude higher than the previous largest array - Agasa.

There are also big news on the neutrino front. The IceCube neutrino observatory \cite{3} on the South Pole is in the middle of successful construction. Twenty two of the eighty underice strings are deployed and the deployment is now faster than initially expected. The Antares \cite{4} detector in the Mediterranean is also successfully close to completion and the km\textsuperscript{3}net \cite{5} is working on the design of a cubic kilometer under water neutrino telescope in the Northern hemisphere. With these cubic kilometer neutrino detectors we approach for first time the dimensions needed for detection of astrophysical neutrinos - a gigaton of target matter or $6 \times 10^{38}$ target nucleons.

Experiments of this size and quality can certainly make the objects of their studies fashionable. The first high statistic results of the Auger observatory were posted on ArXive.org and reported at the 20th International Cosmic Ray Conference in Merida, Mexico in front of a huge audience. Auger has set \cite{1} a strict limit of 2\% on the gamma-ray contribution to the UHECR flux above $10^{19}$ eV and in the following we shall assume that the highest energy cosmic rays originate in acceleration in powerful astrophysical objects.

IceCube has not yet detected any astrophysical neutrino signals but the limits already obtained have led to revisions of many models.
2. Relation and differences between UHE cosmic rays and neutrinos

The connection between ultrahigh energy cosmic rays (UHECR) and neutrinos was first emphasized by Waxman & Bahcall [7]. This paper used an estimate of the cosmic ray emissivity of the Universe [8] above $10^{19} \text{eV}$ to calculate the maximum neutrino fluxes generated at the acceleration sites of UHECR. The calculation has to assume an energy spectrum for these particles. It was taken to be a flat $E^{-2}$ acceleration spectrum. Accounting for the cosmological evolution of the UHECR sources (and assuming that the same acceleration spectrum is followed to much lower energy) the maximum isotropic neutrino flux was calculated to be $E^2 dF/dE = 5 \times 10^{-8}$ per cm$^2$.ster/s and was called the upper bound of the isotropic neutrino fluxes. This bound applies to optically thin sources where the accelerated nuclei can leave the astrophysical source and does not limit the neutrino production in optically thick ones.

A better calculation emphasizing the simplifications in this approach was published by Mannheim, Protheroe & Rachen [9]. Their upper bound touches the W&B one at $E_\nu = 10^{18} \text{eV}$ and is higher than it at all other neutrino energies. A comparison between the two calculations is shown in Fig. 1. Neither of these calculation include the neutrinos that are generated by the UHECR on propagation to us - the cosmogenic neutrinos.

Ultrahigh energy cosmic rays are not well understood for two reasons: it is indeed very difficult to appreciate how charged particles can be accelerated to energies as high as $10^{20} \text{eV}$ in any astrophysical object, and because of their high energy loss in interactions on the microwave background (MBR) and other universal photon fields, such as the infrared/optical background (IRB). Although we are discussing interactions of particles exceeding $10^{19} \text{eV}$ in the Lab the physics involved is very well known. Because of the low energy of the photon background fields the center of mass energy is in the 1-10 GeV range and the cross sections are well known from accelerator experiments. There are two important processes: photoproduction interactions and $e^+e^-$ pair production. The photoproduction process that generates the GZK [10] effect has in the MBR a threshold of about $3 \times 10^{19} \text{eV}$ for protons. There are lower energy proton interactions in the IRB but they do not seem to be important for the proton spectrum evolution in propagation. The minimum interaction length is at proton energy of $5 \times 10^{20} \text{eV}$ and is below 4 Mpc. At higher energy the energy loss length is about 14 Mpc, which for Hubble constant $h_0 = 0.75$ corresponds to redshift $z=0.0035$. A large fraction of the proton energy loss in photoproduction interactions goes into neutrinos. Every time a charged pion is produced three neutrinos (muon neutrino and antineutrino and an electron neutrino) are produced.

At lower energy (smaller CM energy needed) the main energy loss process is the electron-positron pair production. This process has a threshold of $2 \times 10^{18} \text{eV}$. The cross section increases with proton energy, but the energy loss per interaction decreases. The combination leads to a minimum energy loss distance of 1.2 Gpc ($z = 0.3$) at about $2 \times 10^{19} \text{eV}$. Berezinsky & Grigorieva [11] first discussed the importance of this process for the UHECR spectrum after propagation.

At energies lower than $2 \times 10^{19} \text{eV}$ the main energy loss process is the adiabatic energy loss from
the expansion of the Universe. The energy loss length for $h_0 = 0.75$ is 4 Gpc.

Both the UHECR spectra from isotropically distributed cosmic ray sources and the neutrinos generated by them depend on the cosmic ray acceleration spectrum and on the maximum acceleration energy. There is, however, a big difference related to the very different energy loss of cosmic rays and neutrinos. Neutrinos only suffer adiabatic energy loss and easily propagate to us from all redshifts while protons of arbitrary energy can propagate from large redshifts. Figure 2 shows the proton spectrum after propagation at different redshifts, from 0.025 to 0.4. The maximum energy in this graph is $10^{22}$ eV with exponential cutoff at $10^{21.5}$ eV. Still, after propagation on $z = 0.4$, no protons of energy above $10^{19}$ remain in the cosmic ray flux. This fact shows that the influence of the cosmological evolution of the UHECR sources is not very significant for the highest energy cosmic rays.

The cosmogenic neutrino fluxes, on the other hand, are very sensitive to the cosmological evolution of the sources. Figure 2 shows a similar graph for cosmogenic neutrinos. The contribution of different redshifts is shown on a logarithmic scale of $z$ for the same cosmological evolution model as in Fig. 2 - $(1 + z)^3$ to $z = 1.9$ and then constant to 2.8 with exponential decline at higher redshift. Because of the small energy loss of neutrinos the contribution continues growing after redshift of 2.5. Without cosmological evolution of the sources the highest contribution would have come from the contemporary Universe. If we succeed in the detection of cosmogenic neutrinos we can understand the cosmological evolution of the extragalactic cosmic ray sources and create a better model of the highest energy cosmic rays [12].

**3. Ultrahigh Energy Cosmic Rays**

In this section we will present the newest set of data, compare it to older ones and to some of the available models. Figure 3 shows the data from all experiments. The new Auger data come from the surface array normalized to the fluorescent detector energy assignment in hybrid events [13]. At lower energy only showers detected in hybrid mode are included [14]. Another energy spectrum, consistent with the shown ones, was derived from inclined showers. At $10^{19}$ eV the difference in the energy assignment between the highest and lowest flux (Agasa [15] and Auger) is about 40%. Auger supports the measurement of HiRes [16,17] that shows a strong decrease of the cosmic ray
flux above $5.6 \times 10^{19}$ eV. The total number of events higher than $10^{20}$ eV is two. These two data sets change our expectations for such events - it appears that expect to see 0.5 event in 1,000 km$^2$.ster.yr of exposure, about 10 times less than the Agasa estimate. The Auger energy assignment seems to be somewhat lower than that of HiRes, maybe by about 20% averaged over the whole energy range shown. There are also some minor differences in the exact shape of the spectrum: the dip at $10^{18.5}$ is better pronounced and the recovery at higher energy is faster. The GZK effect seems to take place at slightly lower energy and the flux decrease is not as steep as in HiRes data set. As far as the highest energies are concerned the shower statistics is too small to be analyzed.

The question now is: which of the available models fit the experimental spectrum the best. There are in principle three available models. The one of Berezinsky et al. [18,19] uses steep acceleration spectrum ($E^{-2.7}$) down to about $10^{18}$ eV. This model emphasizes the dip in the spectrum that is due to the $e^+e^-$ pair production loss in propagation and its conversion to purely adiabatic energy loss. This model is unique because it fits the cosmic ray flux above $10^{18}$ eV with extragalactic cosmic ray protons without any galactic component. The model fits the HiRes spectrum better than it fits the Auger one.

The second, also proton model, was suggested by Waxman&Bahcall [20] and supported also by other authors. It uses a flat $E^{-2}$ acceleration spectrum, strong cosmological evolution of the cosmic ray sources and predicts a dip where the flux of extragalactic cosmic rays intersects the galactic cosmic ray component. This model requires that our Galaxy accelerates some cosmic rays to energies above $10^{19}$ eV.

A third model uses cosmic rays at their sources with a composition similar to the GeV galactic cosmic rays [21,22]. Since there is a significant fraction of heavy cosmic ray nuclei the energy loss in propagation is different in this model. Heavy nuclei lose energy in photodisintegration in the photon fields. The energy threshold coincides with the giant dipole resonance, and is thus much lower than photoproduction. The nuclei lose nucleons in the process - the energy per nucleon is stable but the total energy per nucleus decreases. The total energy loss length is not dissimilar to that for proton photoproduction. As well as the other two models it fits the measured spectra quite well with an intermediate acceleration spectrum of $E^{-2-2.3}$.

The three models predict quite different nuclear compositions for the UHECR. In the Berezinsky et al model the transition from galactic to extragalactic cosmic rays, and from very heavy to very light composition, is at the approach of $10^{18}$ eV. In the flat spectrum model this transition is at significantly higher energy and UHECR should contain some iron nuclei even above $10^{19}$ eV. The mixed composition model is somewhat intermediate. In the whole energy range there is a significant fraction of protons released in the photodisintegration process complementing the primary and secondary nuclei. Only in the highest energy range the composition becomes light.

The experimental data shown in Fig. 5 do not seem to support any of the models. The circles and the pentagons show the HiRes data set. As far as the highest energies are concerned the shower statistics is too small to be analyzed.

Figure 4. Spectrum of the highest energy cosmic rays detected by different experiments.
Figure 5. Cosmic ray nuclear composition at the highest energies. The measured quantity is the depth of maximum which is converted by me to \(\langle \ln A \rangle\).

4. Cosmogenic neutrinos

Cosmogenic neutrinos are the neutrinos generated in photoproduction interactions of the propagating cosmic rays in the photon fields of the Universe. In the MBR the current threshold energy for proton photoproduction is about \(3 \times 10^{19}\) eV. Protons lose less than 20% of their energy in the threshold energy range. We can roughly estimate the average cosmogenic neutrino energy as \(\langle E_\nu \rangle = E_p \times K_{\text{inel}}/4\) where \(K_{\text{inel}}\) is the average energy loss of the protons per interaction and each neutrino takes 1/4 of the pion energy, i.e. \(\langle E_p \rangle = 10^{18}\) eV. Cosmogenic neutrinos were first proposed by Berezinsky & Zatsepin [26] and have been calculated many times, most recently in Ref. [27]. Neutrinos generated at higher redshift have adiabatic losses. In addition the cosmological evolution of MBR makes possible the interactions of lower energy protons so the average energy of the cosmogenic neutrinos after integration in redshift is of the same order.

The spectrum of cosmogenic neutrinos depends on the UHECR acceleration spectrum, the UHECR source distribution and very strongly on the cosmological evolution of the UHECR sources [12]. Flat acceleration (\(\gamma = 1\)) models generate high flux because they contain higher number of interacting protons of energy above \(3 \times 10^{19}\) eV and because they need strong cosmological evolution of the cosmic ray sources in order to fit the observed cosmic ray spectrum. The model of Berezinsky et al., on the other hand, has much smaller number of interacting protons for the same source emissivity and does not need cosmological evolution of the sources. Figure 6 shows the fluxes of cosmogenic neutrinos generated by these models. Note that the \(\bar{\nu}_e\) spectrum peaks at about \(10^{15.3}\) eV while all other flavors peak at \(10^{18}\) eV. The reason is that \(\bar{\nu}_e\) are generated in neutron decay rather than in photoproduction interaction. They take a very small fraction of the neutron energy. Since the acceleration spectrum is protons only, the neutrons are secondaries coming from charge exchange interactions. Only at very high energy some secondary neutrons interact to produce high energy \(\nu_e\) with the same distribution as the other flavors.
Figure 6. Cosmogenic neutrinos generated by protons with a flat acceleration spectrum ($\gamma=1.0$) with cosmological evolution and a steep one ($\gamma=1.7$) without evolution. Electron neutrinos are shown with a solid line, electron antineutrinos with dots, muon neutrinos - with dashes and muon antineutrinos with dash-dotted line. The symbols show the sum of all neutrino flavors.

It is of some importance to note that MBR is not the only target for neutrino production. The second most important one is the isotropic infrared and optical background (IRB). Its number density is, of course, much lower, but lower energy protons can interact in it and even in the case of flat acceleration spectra the number of interacting protons to a large extent compensates for the lower photon target density.

Fig. 7 shows the spectra of cosmogenic neutrinos generated by a flat ($\gamma=1.0$) and steep ($\gamma=1.7$) UHECR acceleration spectra in the MBR and IRB. Since the steep injection spectrum has higher number of lower energy protons it provides more interactions in the IRB and decreases the difference between the two models. The flat acceleration spectrum model contains more high energy cosmogenic neutrinos.

The mixed composition model generates mostly $\bar{\nu}_e$ due to the decaying neutrons released by the photodisintegrating neutrons [28]. Since there are many more such neutrons than photoproduction interactions electron antineutrinos dominate the cosmogenic neutrino flux. Electron neutrinos would have the same spectrum as $\nu_\mu$ and $\bar{\nu}_\mu$, the peak of which is similar to the neutrinos from the flat spectrum model. Note that such much lower energy neutrinos have a significantly lower cross section and do not contribute much to the total event rate. Their peak energy is also below the the Glashow resonance energy of $6 \times 10^6$ GeV. Still, in case we are lucky enough to detect cosmogenic neutrinos with the neutrino telescopes under construction and design they could help a lot in limiting the models for the origin of the ultrahigh energy cosmic rays. We have to remember, however, the expected event rate of cosmogenic neutrinos is small, less than 1 per km$^2$.yr and such detection requires new detector technologies (radio detection?) that can cover hundred km$^2$.

5. Summary

The new UHECR data sets agree that UHECR spectrum experiences a steepening energy spectrum at about $5-6 \times 10^{19}$ eV which looks consistent with the GZK effect which is due to the energy loss of these particles in photoproduction
or photodisintegration interactions. It is not yet obvious what are the parameters of the acceleration process and what is the evolution of the cosmic ray sources. All these questions will probably have to wait until the total world statistics is increased by a large factor.

The composition of all particles above $10^{19}$ eV is not yet established. Different experimental data are not far away from each other, but do not currently contribute to the understanding of the UHECR origin. The advance in that respect is the strict limit of 2% that the Auger collaboration has set on the fraction of $\gamma$-rays in the cosmic ray flux above $10^{19}$ eV.

Different UHECR models predict various fluxes of cosmogenic neutrinos that are generated by the cosmic rays at propagation from their sources to us. Detection of such neutrinos and a comparison of their fluxes to the direct observations of UHECR would contribute significantly to understanding of the UHECR origin. For this to happen, however, we will have to rely on new, bigger neutrino observatories.

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