Cosmology, Galaxy Formation and Astroparticle Physics
on the pathway to the SKA
Klöckner, H.-R., Jarvis, M. & Rawlings, S. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

The Cosmogenic Neutrino Flux and Its Dependence on the Cosmic Ray Primary Composition

A.M. Taylor[1]

Astrophysics, University of Oxford, Oxford, OX1 3RH, UK

Abstract. In this paper the composition the high energy cosmic rays is brought into question, with both protons and nuclei considered as feasible candidates. Through an application of their propagation from source to Earth, the subsequent neutrino flux generated is determined and compared. Finally such fluxes are used to predict the flux of neutrinos expected to be observed by the forthcoming km sized neutrino telescope ICECUBE.

Based on work in carried out in [1].

Introduction

High energy cosmic rays (E>$10^{18.5}$eV) of unknown origin are detected at Earth by ground array and fluorescence detectors. If such particles are hadronic, their interactions with background radiation fields will limit their propagation through space to less than 1000 Mpc (ie. they're constrained to come from our neighbouring superclusters). At higher energies (E>10^{19}eV) cosmic rays are constrained to originate from within 100 Mpc.

The presence or absence of the GZK cutoff, a feature expected in the cosmic ray spectrum at $\sim 10^{19.6}$eV, due to the "turning on" of the pion creation energy loss process, would be a definite signature of distant cosmic ray sources (greater than 100 Mpc). Conversely a failure to observe such a feature in the spectrum would be indicative of local (less than 100 Mpc) sources.

Cosmic Ray Spectrum Measurements

Two previous experiments that have measured the cosmic ray spectrum at energies $\sim 10^{19.6}$eV (the energy region in which the GZK cutoff signature is expected) were AGASA [2], a ground array detector, and FLY'S EYE [3], a fluorescence detector. The flux measured by AGASA is inconsistent with the GZK cutoff [4] and [5] being present, whereas the FLY'S EYE spectrum appears to exhibit the GZK feature. The AUGER experiment, who's exposure is already comparable to both these experiments, will measure the spectrum around the GZK energy with far more statistics, removing the present ambiguity.

Cosmic Ray Proton Energy Loss During Propagation

In the energy range $10^{18.5} < E(\mathrm{eV}) < 10^{19.6}$, the predominant energy loss process for protons is pair creation,

$$p + \gamma \rightarrow p + e^+ + e^- \tag{1}$$

Above $10^{19.6}$ eV the dominant energy loss process is pion production,

$$\begin{aligned} p + \gamma &\rightarrow n + \pi^+ && (2)\\ &\rightarrow p + \pi^0 && (3) \end{aligned}$$

which leads to a dramatic decrease in the cosmic ray's energy, limiting propagation distances for cosmic rays above these energies to <100 Mpc. In this process neutrinos are generated through the subsequent decay of the pion,

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \tag{4}$$

and the free neutron,

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{5}$$

The energy of the neutrinos produced through pion decay being $\sim$10% of the proton's energy, similarly, the energy of the neutrino produced through neutron decay $\sim$0.1% of the neutron's energy. This results in each GZK interaction leading to 3 neutrinos with energies $\sim 10^{18}$ eV being produced through pion decay and a single $\sim 10^{16}$ eV neutrino from neutron decay.

Such high energy cosmic ray protons, if they exist and their sources are sufficiently far away, will lead to a cosmogenic neutrino flux being produced.

Cosmogenic Neutrino Flux From Cosmic Ray Protons

From an application of the pion production cross section along with the spectral shape of the dominant radiation field for the process (see fig. 3), energy loss lengths for pion production may be calculated and consequently the cosmogenic neutrino flux, for a given cosmic ray proton flux, determined.

In order to do this a distribution for the cosmic ray sources must be assumed. Here a distribution of the form,

$$\frac{dN}{dV} \propto \begin{cases} (1+z)^3 & : z < 1.9 \\ (1+1.9)^3 & : 1.9 < z < 2.7 \\ (1+1.9)^3 e^{(2.7-z)/2.7} & : 2.7 < z < 8 \end{cases} \tag{6}$$

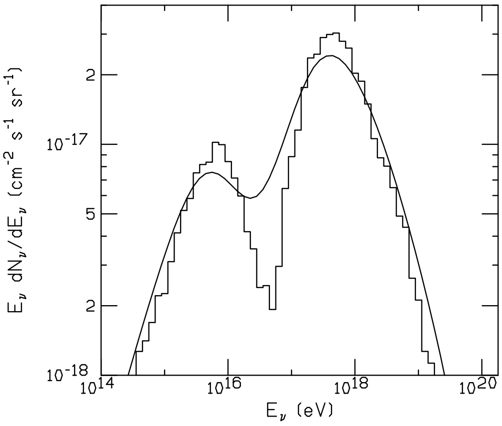

Fig. 1. The cosmogenic neutrino flux produced by the propagation of cosmic ray protons (histogram). The solid line shows a previous result [6] for comparison

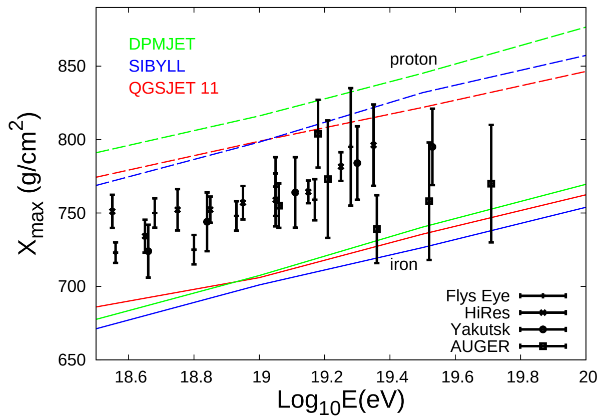

Fig. 2. Measured values of X_{max} at different energies

has been employed, as used in previous studies [6]. Such a source distribution is motivated by the luminosity density distribution of quasi-stellar-objects [7] and represents a uniform distribution of sources up to a redshift of 1.9, with sources beyond this distance becoming sparser.

Similarly, a cosmic ray energy spectrum of the form,

$$\frac{dN_{CR}}{dE_{CR}} \propto E_{CR}^2 \exp\left[\frac{-E_{CR}}{10^{21.5}\text{ eV}}\right] \tag{7}$$

where E_{CR} is the cosmic ray energy, was assumed. Such an energy spectrum is motivated by the theory of Fermi shock acceleration [8] and assumes an upper limit to the cosmic ray spectrum of just above $10^{21.5}$ eV.

With these assumptions in mind, the cosmogenic neutrino flux, produced by the propagation of cosmic ray protons, is shown in fig. 1

The cosmogenic neutrino flux, produced by cosmic ray proton propagation, was normalised by ensuring the cosmic ray flux at 10^{19} eV concurred with an average of measurements made by the AGASA [9] and HiRes [10] cosmic ray detection experiments at $10^{19.5}$ eV. A preliminary measurement of the cosmic ray flux has also been made by the AUGER experiment [11], this flux sitting in closer agreement with that measured by the HiRes experiment than the AGASA experiment.

Uncertainty in Cosmic Ray Primary Composition

Information about the cosmic ray composition must be inferred indirectly from features of the electromagnetic shower, created when a cosmic ray interacts with a nucleus in the atmosphere. One of the key aspects of these showers with regards cosmic ray primary, is the position, from the start of the shower, of the maximum number of particles in the shower, referred to as $X_{\max}$. This signature of cosmic ray, for a given energy cosmic ray, is expected to be greater for proton cosmic rays than heavy nuclei cosmic rays.

Fig. 2 comes from the analysis of measurements of X_{max} by fluorescence detectors, highlighting the uncertainty in the composition of the high energy cosmic rays.

Cosmic Ray Nuclei Energy Loss During Propagation

Cosmic ray nuclei may be excited by highly Lorentz boosted CMB and IRB photons through the giant dipole resonance at ∼30 MeV, leading to loss of nucleons from the nucleus, and a corresponding decrease in the nucleon's energy. This is the predominant energy loss process for high energy nuclei (ie. for all cosmic ray energies under consideration here).

Such disintegration also contributes to the cosmogenic neutrino flux since free neutrons are produced through some of the photodisintegration channels. These neutrinos, being produced by nuclei with $\gamma \sim 10^9$, where γ corresponds to the Lorentzian factor, are expected to have energies $\sim 10^{15}$ eV, as a similar Lorentz factor for the neutrino can be expected.

The degree of photodisintegration, undergone by cosmic ray nuclei during propagation, is dependent upon the IRB, as well as CMB, background whose spectrum has a relatively large degree of uncertainty, as is seen in fig. 3. In this letter, the "Malkan and Stecker" [12] model shall be employed. No evolution of the IRB with redshift is considered.

The rate of photodisintegration also requires a knowledge of the photodisintegration cross sections. These cross sections may be parameterised using Gaussian [13] or Lorentzian [14] fits. Since no appreciable difference is found between these two parameterizations [15] Gaussian cross sections have been used in the calculation.

Cosmogenic Neutrino Flux From Cosmic Ray Nuclei

As for the cosmic ray protons case, the application of the photodisintegration cross sections and the dominant radiation fields (see fig. 3) allow the photodisintegration rates

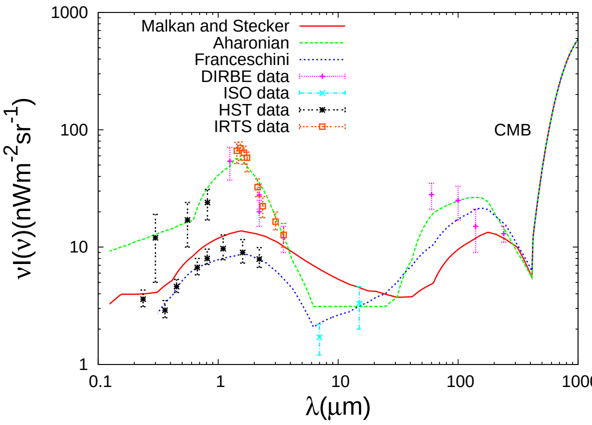

Fig. 3. Three different models of the IRB spectrum compared to related measurements

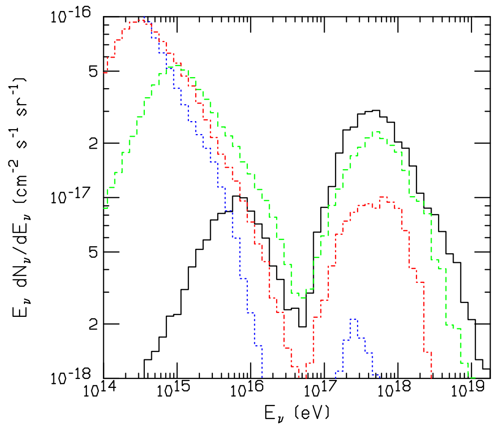

Fig. 4. The cosmogenic neutrino flux produced by the propagation of cosmic ray nuclei. The different colours refer to different species injected: the blue dotted line is for iron; the red dot-dashed line is for oxygen; the green dashed line is for helium and the black solid line is for protons

for all elements (and isotopes) to be determined. Due to the many possible paths through which an element may decay, a monte carlo simulation must be employed. Such simulations allow the eventual population of protons, at the end of a species cascade, to be determined, which may go on to lose energy through pion production, contributing to the neutrino flux. It also enables the number of free neutrons produced through the photodisintegration decay to be calculated, which will beta decay to protons, also contributing to the neutrino flux.

The results of the monte carlo simulations are shown in fig. 4. As for the cosmogenic neutrino flux for proton cosmic rays, the assumed source flux and distribution of cosmic rays was (7) and (6) respectively.

Conclusion

From a comparison of the expected cosmogenic neutrino fluxes for different injected species, the high energy ($\sim 10^{17.5}$ eV) neutrino flux may be as much as a factor of 10 smaller for heavy nuclei than for protons. Since the low energy neutrino flux is swamped out by background neutrino flux of atmospheric origin, the neutrino flux is only anticipated to be observable for neutrino energies above 10^{15} eV [16].

Applying these fluxes to the forthcoming km sized neutrino telescope, ICECUBE, the number of cosmogenic neutrinos anticipated to be detected in a years worth of observation are shown in table 1. The two columns in the table indicating the anticipated rate of showers and high energy muons detectable by ICECUBE. Such showers are produced through both charged and neutral current neutrino interactions. High energy muons, however, are produced solely through charged current muon neutrino interactions.

Table 1. a table showing the number of cosmogenic neutrinos to be detected per year by the full ICECUBE array

Primary	Shower (E^{thr}= 1PeV)	Muon (E_{μ}^{thr} = 1PeV)
Protons (A=1)	0.57	0.72
Helium (A=4)	0.42	0.50
Oxygen (A=16)	0.19	0.23
Iron (A=56)	0.036	0.042

Experimental detection of any of the neutrino fluxes is clearly difficult due to the low fluxes expected. However, future limits on the flux, set by experiments like ICECUBE, will provide a strong constraint on the high energy cosmic ray composition, source energy spectrum and distribution. Compounding this information with measurements of the high energy cosmic ray spectrum and X_{max} by cosmic ray detectors such as AUGER, could allow these unknowns to be separated out. Furthermore, the successful detection of cosmogenic neutrinos would mark an exciting beginning to an understanding of cosmic rays through the employment of these neutral messengers.

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