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Neutrino and Gamma Ray Flux Expectations from HiRes Monocular Fits

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Abstract: A simple model of a homogeneous population of cosmic accelerators injecting protons following a unique power law has long been shown to fit the HiRes monocular data very well. The model evolves the sources with redshift and adjusts both the redshift evolution and the exponent in the injecting power law to fit the data. At lower energies galactic iron is added in as suggested by composition measurements of Ref. [1]. The model includes interactions between cosmic ray protons of extragalactic origin and photons of the cosmic microwave background radiation; in particular photopion production, which causes the GZK cutoff. We present neutrino and gamma ray fluxes derived from proton propagation given the fitted injection spectrum and redshift evolution of their extragalactic sources.

Introduction

Energies of the ultra high energy cosmic rays (UHECRs) extend up to more than 10^{20}eV. At these highest energies cosmic rays are believed to be of extragalactic origin. Extragalactic origin of the UHECRs favors bottom-up scenarios of cosmic ray production. The composition studies [1] show that the highest energy cosmic rays should be primary protons and light nuclei with the heavier nuclei starting to play role at lower energies and having a galactic origin.

The assumption that the UHECRs are protons accelerated in extragalactic sources gives us an opportunity to connect them with the ultra high energy (UHE) neutrinos and gamma rays. The highest energy cosmic rays have enough energy to interact with the photons of the cosmic microwave background (CMB) to produce pions. These collisions result in the suppression of cosmic ray flux at the energies above 10^{20}eV. The effect is known as the GZK cutoff. The decay of secondary pions in the photopion production reaction creates UHE neutrinos and gamma rays.

Propagation of UHE Protons

This work extends the results of Ref. [2] to find the neutrino and gamma ray fluxes at the Earth by fitting the HiRes monocular spectra to the expectations derived from a model assuming a uniform density of sources modified only by a redshift evolution (USM for Uniform Source Model). This model fits the spectrum well, reproducing the well known features of the ankle and the GZK cutoff. At lower energies galactic iron is added proportionally as suggested by the composition measurements of Ref. [1].

Proton propagation is handled as described in Ref. [2]. Protons are propagated from their creation at a particular redshift to the Earth. During propagation in the extragalactic medium protons interact with the CMB background photons. The most important proton energy loss process is the photopion reaction. We only use the single-pion resonance channel in calculating the cross-section for the reaction. This is a good approximation for the energy range under consideration.

The protons are followed through the CMB evaluating their interaction probability for suitable steps in redshift. The photon energies are drawn randomly from the appropriately Lorentz-boosted

CMB blackbody radiation spectrum, and the energies of the daughter particles are determined from the decay kinematics. The evolution of the CMB temperature and energy losses due to the expansion of the universe are also included. Electron positron pair-production is taken into account using the continuous energy-loss formalism of Berezinsky *et al* [3, 4].

The Monte Carlo creates a spectrum of proton energies for protons arriving at earth for each proton input energy and distance of origin. These calculations are done for every 0.01 step in z from $z = 0$ to $z = 4$. For a given distribution of sources, we add up the contributions from all the different z shells according to their respective weight in the z evolution under consideration. Sources are assumed to be uniformly distributed at any given redshift, but their density evolves with redshift as $(1 + z)^m$. At the end we can predict the observed spectrum at the current $z = 0$. In Fig. 1 the series of spectra colored blue to red lines show the contribution from sources within given shells in redshift, weighted appropriately (taken from Ref. [2]). Each energy is determined by different range in z. Sum of the shells gives the spectrum for fitting (red line on the top of the colored ones).

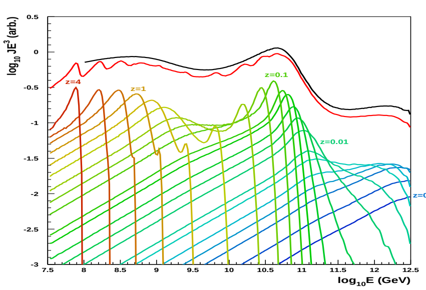

Figure 1: Contributions from sources within different shells in redshift to the proton spectra

Each individual source contributes with an injection spectrum at the source of the form $E^{-\gamma}$. Both, m and γ, are varied to build up a spectrum at the Earth that optimally fits the observed monocular HiRes spectra. As discussed above the galactic component is added in according to the heavy component identified in the composition measurements (Ref. [1]). The only other free parameter is an overall flux normalization.

The best fit spectrum to the most recent HiRes monocular data is shown in Fig. 2 (m=2.46, γ=2.42). As can be seen the model provides a reasonable fit to the data, reproducing the well known features of the ankle and the GZK cutoff. The fall at lower energies into the ankle region is most sensitive to m, whereas the rise above the ankle is most sensitive to γ. Fig. 3 shows the χ^2 contour around the best fit in the $m - \gamma$ plane.

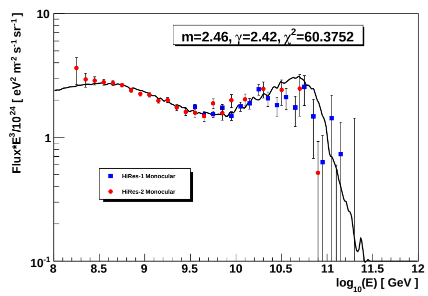

Figure 2: Best USM-plus-galactic fit to the HiRes monocular spectra

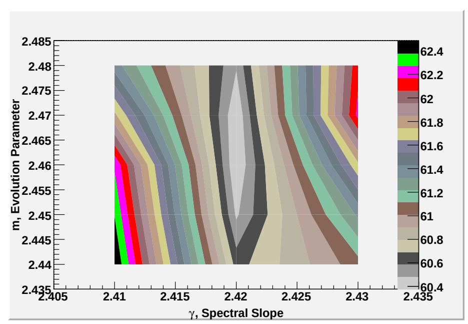

Figure 3: χ^2 contour map around the best fit in the $m - \gamma$ plane

Neutrino and Gamma Rays from Propagation of UHE Protons

We consider two processes that contribute to the production of UHE neutrinos associated with photo-pion interaction. Photopion production through the Δ^+ resonance has a 1/3 probability of producing a positively charged π meson (Ref. [5]).

$$p + \gamma_{cmb} \longrightarrow \Delta^+ \longrightarrow n + \pi^+ \qquad (1)$$

The subsequent decay of a pion into a muon and a neutrino and the decay of a muon into two neutrinos and a positron results in a total count of two muon neutrinos and one electron neutrino per pion decay:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \tag{2}$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu_\mu} \tag{3}$$

The other process that contributes to the neutrino production is the decay of a secondary neutron into a proton, an electron and an electron antineutrino:

$$n \longrightarrow p + e^- + \bar{\nu_e} \tag{4}$$

Through the creation of one charged pion in the photopion interaction of UHE protons on the CMB, we end up with four neutrinos, not distinguishing between neutrinos and antinuetrinos. Generated neutrinos lose their energies only adiabatically due to the expansion of the universe. Neutrinos generated with energy E at a given z are redshifted to energy $(1+z)^{-1}E$ at the earth. In our calculations we neglect any possible neutrino interactions along their way to the Earth.

The production and propagation of the UHE gamma rays requires more consideration. Gamma rays are created through the decay of neutral pions. There is 2/3 probability of a neutral pion creation in proton interaction on the CMB and the subsequent decay of the Δ^+ resonance (Ref. [5]):

$$p + \gamma_{cmb} \longrightarrow \Delta^+ \longrightarrow p + \pi^0 \tag{5}$$

Each pion decays into two gamma rays:

$$\pi^0 \longrightarrow \gamma + \gamma \tag{6}$$

Following their production, the gamma rays will with the high probability convert into electron-positron pairs through interaction on the CMB. Once a gamma ray interacted with the CMB it is considered to be lost from the propagation process:

$$\gamma + \gamma_{cmb} \longrightarrow e^+ + e^- \tag{7}$$

We calculate the survival probability of each gamma ray, given its energy and the distance from the earth, according to the Ref. [6].

The pion decay is calculated using the appropriate two body decay kinematics, while for the muon and neutron decay the energies are calculated using the three body decay algorithm. See Ref. [7].

Neutrinos and Gamma Ray Fluxes

We present the calculations of cosmogenic neutrino and gamma ray spectra at the Earth according to the USM-plus-galactic model discussed above. The fluxes shown correspond to the best fit parameters from fitting the propagated proton spectra to the HiRes monocular data.

Since the neutrino and gamma ray production is calculated within the same Monte Carlo code, the normalization of the simulated cosmic ray spectra to the HiRes monocular results also provides the normalization for the expected neutrino and gamma ray spectra.

Fig. 4 shows the electron (in green) and muon (in blue) neutrino fluxes based on the best fit to the HiRes monocular data, assuming the models discussed above. The fluxes multiplied by the second power of energy are plotted verses the logarithm of energy in GeV and compared with the cosmic ray flux (in red). The neutrino fluxes presented here are at least one order of magnitude smaller than many theoretical upper limits on the neutrino fluxes discussed in the literature, for example in Ref. [8]

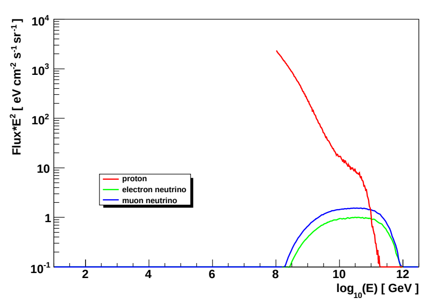

Figure 4: Electron and muon neutrino fluxes based on the USM-plus galactic best fit to the Hires monocular data. $Flux \times E^2$ vs. $log_{10}(E)$

Fig. 5 presents the same spectrum as in Fig. 4, but without E^2 flux multiplication. One can see that electron neutrino (in green) spectrum exhibits a double peak structure. The higher energy peak

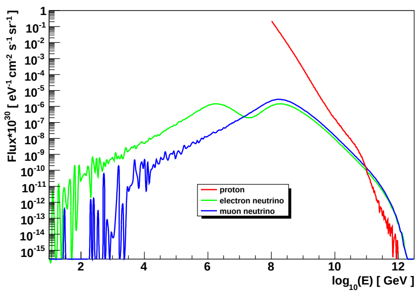

Figure 5: Electron and muon neutrino fluxes based on the USM-plus galactic best fit to the Hires monocular data. $Flux$ vs. $log_{10}(E)$

represents the electron neutrinos from the muon decay, while the lower energy one consists of electron antineutrinos coming from the neutron decay. Half of the muon neutrinos will oscillate into tau neutrinos before arriving at the earth.

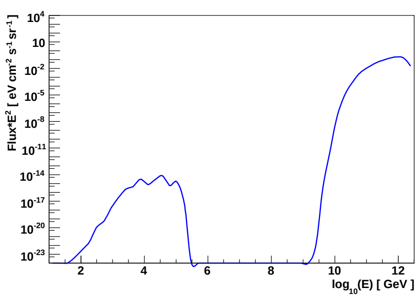

Figure 6: Gamma ray flux based on the USM-plus galactic best fit to the Hires monocular data. $Flux \times E^2$ vs. $log_{10}(E)$

In Fig. 6 we show the corresponding gamma ray fluxes expected at the Earth. The lower peak includes only few gamma rays, but they have high survival probabilities. On the other hand, the higher peak contains a lot of gamma rays, each with low survival probability. As discussed above the only process considered in the study is the gamma ray interaction on the CMB photons. The processes such as electron-positron pair recombination, synchrotron radiation and some others are still have to be included in future analysis.

Conclusions

The best fit to the HiRes monocular spectrum was done based on the USM for extragalactic sources with the addition of the composition motivated galactic component. The fit reproduces all the features of the measured spectrum, and allows us to predict the gamma ray and neutrino fluxes at the Earth for the given redshift evolution and universal injection spectrum at the source. Future investigation will concentrate on the redshift evolution, hoping to base this aspect of the calculation on the measured redshift evolutions for promising source populations.

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