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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. 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] of cosmic rays shows 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 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) producing 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 earth by fitting the HiRes monocular spectra to expectations derived from a model assuming a density of uniform 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.

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. 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 Lawrence-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 MC 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 for $z = 0$ to $z = 4$. At the end for a given input spectrum at a given z, we can calculate the observed spectrum at the current $z = 0$.

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 is assumed to evolve with redshift as $(1+z)^m$. Each individual source contributes with an injection spectrum at the source of the form E^γ. Both, m and γ, are varied to build up a spectrum at earth that optimally fits the observed monocular HiRes spectra. As discussed above the galactic spectrum is added in according to the heavy components identified in the composition measurements. The only other free parameter is an overall flux normalization.

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 delta resonance has a 1/3 probability of producing a positively charged π meson.

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

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:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \qquad (2)$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu_\mu} \qquad (3)$$

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:

$$n \longrightarrow p + e^- + \bar{\nu_e} \qquad (4)$$

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 with other particles.

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:

$$p + \gamma_{cmb} \longrightarrow \Delta^+ \longrightarrow p + \pi^0 \qquad (5)$$

Each pion decays into two gamma rays:

$$\pi^0 \longrightarrow \gamma + \gamma \qquad (6)$$

Following production, the gamma rays will usually convert into electron-positron pairs through interaction with CMB photons. Once a gamma ray interacted with the CMB it is considered to be lost:

$$\gamma + \gamma_{cmb} \longrightarrow e^+ + e^- \qquad (7)$$

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 [5].

Neutrinos and Gamma Ray Fluxes

We will present the calculations of cosmogenic neutrino and gamma ray spectra at earth according to uniformly distributed extragalactic sources. We use the fluxes corresponding to the best fit parameters from fitting the propagated proton spectra to the HiRes monocular spectrum. 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.

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