Neutrinos from cosmological cosmic rays

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Abstract

The production of neutrinos from homogeneous distributions of cosmological sources of cosmic rays is investigated. Analytic approximations are developed that allow the study of a large variety of models. Current limits on neutrino and low energy photon fluxes are shown to set already strong constraints on these models and may give information on the production mechanisms of the highest energy cosmic rays.

1. Introduction

Neutrinos from interactions of ultra high energy cosmic rays (UHECR) with the cosmic microwave photons are difficult to avoid. Many detailed simulations have been made for a range of models [1,2,3,4] (and references therein) but the predicted fluxes depend on details of the specific models for cosmic ray production and for source evolution. We have developed analytical solutions of the transport equations, in good agreement with numerical solutions, that allow us to describe a large range of models in simple analytical terms. We obtain the evolved spectrum, calculate the expected neutrino flux in the assumption of primary proton composition and relate the flux prediction to the model assumptions. Our results indicate that the range of neutrino fluxes obtained from cosmic ray interactions with the background photons is quite wide. We finally comment on our results in the light of existing bounds.

2. Proton and Neutrino Fluxes

Our approach consists on solving the transport equations for cosmic ray proton propagation. This approach has also been used by previous authors, see Ref.[2]. The evolution equation for propagation of cosmic rays can be written as

$$\frac{\partial \phi_p(E,x)}{\partial x} = -\frac{1}{\lambda(E)}\phi_p(E,x) + I[\phi_p(E,x)] + \frac{\partial}{\partial E}(b(E)\phi_p(E,x)), \qquad (1)$$

where $\phi_p(E,x)$ is the cosmic ray spectrum, assumed to be composed of nucleons, $\lambda(E)$ is the mean free path of a cosmic ray of energy E. The second term in

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eq.(1) represents the regeneration of cosmic rays by collisions with the photon background. It is given by the convolution of the cosmic ray flux with the cross section for interaction with the photon background, see [5]. Finally the last term in eq.(1) is the continuous energy loss mainly due to e^+e^- pair production and redshift. A similar equation can be written for the pion flux.

In order to obtain diffuse fluxes we assume an isotropic distribution of sources with luminosity function $\rho(z) = \rho_0(1+z)^3$ and an evolution given by $\eta(z, E > E_0) = \eta_0(1+z)^m$. The fluxes and corresponding power are obtained by integrating over z. We have solved the resulting equations analytically after making several approximations. Our analytical results have been checked against direct numerical solutions of the evolution equations which include all relevant mechanisms of energy loss for the protons at these energies, *i.e.* pion photo-production, pair production, and redshift. The results are sufficiently accurate to allow the use of the analytical approximation. Details will be published elsewhere.

3. Results

Once we fix the source distribution and the characteristics of the injected spectrum, namely spectral index, γ, normalization and maximum energy, and its evolution with redshift, the parameter m and the maximum redshift at which UHECR are injected, our calculations give a modified proton spectra, the resulting neutrino flux and the power injected into electromagnetic particles which cascades down to the 100 MeV region. The analytical approach is particularly enlightening because the results can be easily related to the different processes taking place and the assumptions made.

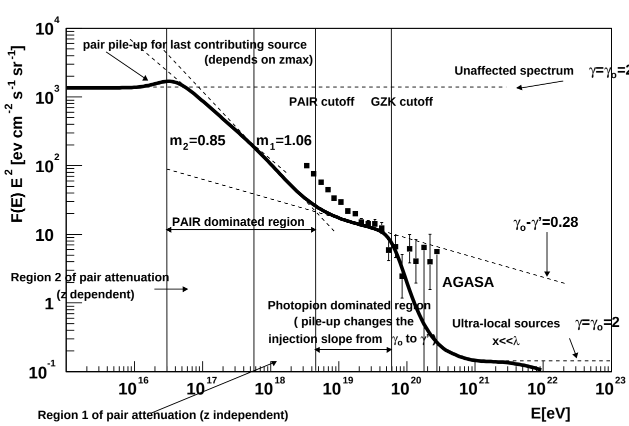

Fig. 1. Cosmic ray flux after cosmological propagation for a model with source evolution and spectral index as marked. Regions where pile up due to photoproduction and pair production are shown. The AGASA data above 5 10^{18} eV is plotted.

The evolved cosmic ray spectrum presents a rich structure and we can differentiate three different energy regions. These are condensed in fig. 1..

1. The high energy region, above the GZK cutoff $E_{\mathrm{th},\pi} \simeq 6\ 10^{19}$ eV. Here the photoproduction suppression dominates and the cosmic ray flux from cosmological sources is negligible. To account for the UHECR observed spectrum it is necessary to assume a local source overdensity located at a distance, D_{local} comparable to $\lambda_{\mathrm{att},\pi}$.

2. The low energy region, below $E_{\mathrm{th,ee}} \simeq 5\ 10^{18}$ eV. In this range the main energy losses are due to pair production, which cuts off the spectrum for distances $x \simeq \lambda_{\mathrm{att},ee}$. This energy is quite close to the reported ankle energy $E_{\mathrm{ankle}} = 3\ 10^{18}$ eV.

3. The intermediate region $E_{\mathrm{th,ee}} = 5\,10^{18}\ \mathrm{eV} < E < E_{\mathrm{th},\pi} = 6\,10^{19}$ eV. Sources located at distance $x < \lambda_{\mathrm{att,ee}}$ contribute most to this energy region; higher distances are exponentially suppressed by pair production.

As an interesting application we can compare the predictions to current experimental results for cosmic rays and bounds for gamma rays and neutrinos.

The most constraining limit for diffuse neutrino fluxes is the AMANDA bound [6] for the energy range $10^{15} < E_\nu < 10^{19}$ eV:

$$E^2\phi_\nu(E) < 10^3\ \mathrm{eV}[\mathrm{cm}^2\ \mathrm{s\ sr}]^{-1}. \tag{2}$$

It is an order of magnitude below the Fly's Eye limit and about an order of magnitude above the Waxman and Bahcall limit (WB) [7] and the Mannheim, Protheroe, and Rachen limit (MPR) [4]. Both WB and MPR limits are theoretical limits connected to pion production in sources, related to a particular evolution or source model which can be violated for instance if sources are opaque [3,4]. Our results give neutrino flux predictions that vary by well over an order of magnitude as shown in fig. 2.. This figure represents the predicted power that is injected into neutrinos for a range of spectral indices and evolution parameters, when the evolved UHECR flux is normalized to observations. There are scenarios in which the neutrino flux predictions violate WB and the MPR limit. These imply strong evolution and integration to high redshifts.

Any injected power in neutrinos produces also low energy photons due to the electromagnetic cascade that occurs shortly after decay of π^0. A strong limit results from the observation of low energy (in the range of MeV-GeV energies) diffuse fluxes by EGRET. The measured EGRET flux is

$$\Phi_\gamma(E > 100\,\mathrm{MeV}) = 1.45\ 10^{-5}\ \ [\mathrm{cm}^2\ \mathrm{s\ sr}]^{-1} \tag{3}$$

The EGRET measurement is used as an upper limit on the power injected for any mechanism considered but our results indicate that the injected power is dependent on the details of the model. The fraction of energy which goes into the electromagnetic cascade in UHECR propagation is quite dependent on

γ. For low γ the fraction is the same as that which goes into neutrinos, apart from a constant factor of order 1, related to the fraction of neutral and charged pions. However for large values of γ ($\gamma > 2$) the e^+e^- pair production process contributes significantly to the electromagnetic cascade. For these scenarios the EGRET bound thus implies stronger restrictions than naively expected.

Since our model relates the neutrino and electromagnetic fractions we can convert the EGRET limit to an equivalent bound in the neutrino injection power by calculating these two fractions in a range of models characterized in parameter space m and *gamma*. The pair production effect is apparent in the resulting bound that has been included in fig. 2.. From the figure we can see that large spectral index $\gamma \geq 2.2$ are disfavoured for strong source evolution models $m \geq 4$,

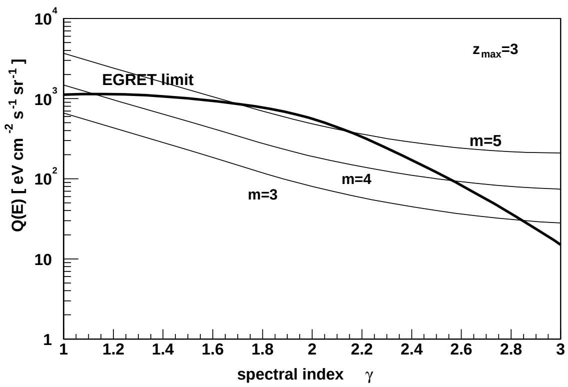

Fig. 2. Injected energy in neutrinos as a function of the spectral index γ for several source evolution models as marked. Also shown are the AMANDA and EGRET limit.

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