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Propagation of Ultra High Energy Cosmic Rays and the Production of Cosmogenic Neutrinos

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Abstract

We present an updated version of the *SimProp* Monte Carlo code to study the propagation of ultra high energy cosmic rays in astrophysical backgrounds computing the cosmogenic neutrino fluxes expected on earth. The study of secondary neutrinos provides a powerful tool to constrain the source models of these extremely energetic particles. We will show how the newly detected IceCube neutrino events at PeV energies together with the the latest experimental results of the Pierre Auger Observatory and Telescope Array experiment are almost at the level of excluding several hypothesis on the astrophysical sources of ultra high energy cosmic rays. Results presented here can be also used to evaluate the discovery capabilities of future high energy cosmic rays and neutrino detectors.

Keywords: ultra high energy cosmic rays and neutrinos, astrophysical backgrounds, cosmological evolution

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1. Introduction

The study of Ultra High Energy Cosmic Rays (UHECR) started already in '60 with the first pioneering observations of the Volcano Ranch experiment, that, in 1962, observed the first cosmic ray event with energy larger than 10^{20} eV [1]. Nowadays the most evolute experiments observing UHECR are the Pierre Auger Observatory in Argentina [2], far the largest experimental setup devoted to the study of these particles, and the Telescope Array (TA) experiment [3], placed in the United States, with roughly 1/10 of the Auger statistics at the highest energies.

The experimental study of UHECR clarified few important characteristics of these particles: (i) UHECR are charged particles with a limit on photon and neutrino fluxes around 10^{19} eV at the level of few percent and well below respectively [4, 5, 6], (ii) the spectra observed on earth show a slight flattening at energies around 5×10^{18} eV (called the ankle) with (iii) a steep suppression at the highest energies $\simeq 10^{20}$ eV [2, 7].

The propagation of UHECR from the source to the observer is conditioned by the expansion of the universe and the interaction with astrophysical backgrounds, namely the Cosmic Microwave Background (CMB) and the Extragalactic Background Light (EBL). While the propagation of nucleons[1] is conditioned only by the CMB field the propagation of nuclei is also affected by the EBL. Apart from the expansion of the universe that, adiabatically, reduces the energy of any propagating particle, the processes that involve protons are: (i) pair production and (ii) photo-pion production; those involving nuclei are: (i) pair production and (ii) photo-disintegration [8, 9].

One of the most important observables in the physics of UHECR is certainly the chemical composition of

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[1] Hereafter discussing freely propagating UHE nucleons we will always refer only to protons because the decay time of neutrons is much shorter than all other time scales involved [8, 9].

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these particles. The experimental observations of the composition are not conclusive, with different results claimed by TA and Auger. The analysis performed by TA is compatible with a proton dominated composition at all energies, starting from the lowest around 10^{18} eV up to the highest at 10^{20} eV [3] . On the other hand the observations of Auger show a more rich phenomenology with the lowest energies dominated by protons and, starting from energies around 3×10^{18} eV, a composition more and more dominated by heavier nuclei with a strongly reduced number of protons at energies above 2×10^{19} eV [2].

Restricting the analysis to a pure proton composition, as appropriate to the interpretation of TA data, the UHECR observations can be elegantly explained by the dip model [10, 11]. In the framework of this model the flux behaviour in the region of the ankle is due to the effect of the proton pair-production process on the CMB radiation field [10]. While the strong flux suppression at the highest energies is the effect of the photo-pion production process, the so-called Greisen-Zatsepin-Kuzmin (GZK) cut-off [12, 13]. Taking into account the sole Auger data, to reach a reasonable agreement with observations, one should consider mixed compositions. Assuming that protons give their principal contribution only at the lowest energies $\leq 3\times10^{19}$ eV [14, 15], below the photo-pion production threshold $\sim 6 \times 10^{19}$ eV. In this case the flux suppression observed at the highest energies is due to the photo-disintegration process suffered by heavy nuclei [14, 16].

The production of secondary particles due to the interactions of UHECR with background photons is strongly dependent on the chemical composition. As was first realised in [17], the proton content at the highest energies is a crucial quantity that regulates the fluxes of secondary (cosmogenic) photons and neutrinos. In the present paper, implementing an updated version of the *SimProp*[2] Monte Carlo (MC) code [18], we will discuss the production of secondary neutrinos by the propagation of UHECR. The study presented here, discussed in detail in [19], has a twofold interest: from one side using the latest observations of the IceCube [20] and Auger [6] we can already draw interesting conclusions on the sources of UHECR; on the other side this study should be intended as a benchmark computation to asses the discovery capabilities of the next generation experiments.

2. UHECR models and secondary neutrinos

There are two processes by which neutrinos can be produced in the propagation of UHECRs: (i) the decay of charged pions produced by photo-pion production, $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$, and the subsequent muon decay $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$; (ii) the beta decay of neutrons and nuclei produced by photo-disintegration: $n \rightarrow p + e^- + \bar{\nu}_e$, $(A,Z) \rightarrow (A,Z-1) + e^+ + \nu_e$, or $(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$. These processes produce neutrinos in different energy ranges: in the former the energy of each neutrino is around a few per cent that of the parent nucleon, whereas in the latter it is less than one part per thousand (in the case of neutron decay, larger for certain unstable nuclei). This means that in the interactions with CMB photons, with a Lorentz factor threshold around $\Gamma \gtrsim 10^{10}$, neutrinos are produced with energies of the order of 10^{18} eV and 10^{16} eV respectively. Interactions with EBL photons contribute with a much lower probability respect to CMB photons, affecting a small fraction of the propagating protons and nuclei. Neutrinos produced through interactions with EBL, characterised by lower thresholds, have energies of the order of 10^{14} eV in the case of photo-pion production and 10^{16} eV in the case of neutron decay.

Neutrinos produced by the interaction of UHECR, because of their extremely low interaction rate, arrive on Earth unmodified with the overall universe contributing to their flux. This is an important point that makes neutrinos a viable probe not only of the chemical composition of UHECR but also of the cosmological evolution of sources that, as we will show below, can be also constrained by the neutrino flux observed on Earth.

In the following we will consider the two cases of the dip model and mixed composition, discussing the expected neutrino flux with different assumptions on the cosmological evolution of sources. We will consider the case of sources (see [19] and reference therein) (i) with no cosmological evolution, (ii) with the same cosmological evolution of Active Galactic Nuclei (AGN), supposed to play a role in particles acceleration till the highest energies [10], and (iii) with the cosmological evolution of the Star Formation Rate (SFR). All computations presented here, discussed in detail in [19], are performed under the assumption of a homogenous distribution of sources. This assumption does not affect the expected neutrino spectra because in the case of neutrinos the overall universe, till the maximum red-shift, contributes to the fluxes. Possible flux variations due to a local inhomogeneity in sources distribution gives a negligible contribution to the total flux. We also fix a maximum red-shift of the sources $z_{max} = 10$, which is

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[2] *SimProp* is available upon request writing to the authors or at *SimProp-dev@aquila.infn.it.*