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Networks in extensive air showers

Ashok Razdan *

Astrophysical Sciences Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, India

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ABSTRACT

Extensive air showers are produced when high energy cosmic rays or γ-rays enter from the top of the atmosphere. Extensive air showers are multi-fractal in nature and in this paper we explore the topological properties of these showers. We show that the topology of extensive air showers has an exponential distribution which may arise due to the inherent tree structure character of its passage in the atmosphere.

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1. Introduction

The characterisation of the topology of complex networks has attracted a lot of attention in recent times. Earlier the topology of networks was confined to the random graph theory of Erdos and Renyi [1], but with the discovery of scale free networks [2], and small world networks [3] a rich and diverse class of networks has been characterised, e.g. networks in superconductors [4], networks in earthquakes [5], etc. In this paper we explore the topology of extensive air showers (EAS) initiated by an ultra high energy (UHE) γ-ray entering from the top of the atmosphere and attempt to characterise it. Topology is the layout pattern of various elements of a network. Topology can be physical or logical. The logical topology is about the pattern in which information flows through the network without any regard for the physical connections. EAS falls in the category of logical networks in which energy passes from the top of the atmosphere to the ground level.

An UHE γ-ray [6] of energy, say, E_0 (as shown in Fig. 1) entering from the top of the atmosphere may interact with air molecules after travelling a distance R and may produce an electron/positron ($e^{\pm}$) pair due to pair production (pp) each having energy $\frac{E_0}{2}$. In the next radiation length, the electron/positron loses half of its energy and each radiates one photon of energy $\frac{E_0}{4}$ due to the bremsstrahlung process (bp). Both pp and bp take place in the presence of a nucleus, hence in the presence of air molecules. In the UHE limit, the radiation lengths of pp and bp are the same. Thus after two radiation lengths there are two photons and two charged particles of energy $\frac{E_0}{4}$ each. At the n-th level the total number of particles (photons+charged particles) is 2^n each having energy $\frac{E_0}{2^n}$. On the average a EAS shower consists of $\frac{2}{3}$ (charged particles) and $\frac{1}{3}$ of photons. The cascade finally stops when average energy per particle [6] drops to the critical energy E_c below which the dominant loss of energy is due to ionisation. The maximum number of interactions take place at the shower maximum. The depth of the shower maxima has logarithmic dependence on the incident energy. The shower development is characterised by a parameter age S [7,8]. For $S < 1$, the shower is young as it will develop further. $S = 1$ signifies the shower maximum and $S > 1$ corresponds to an old shower. This is also clear from Fig. 2 which shows the average number of nuclei (nodes in our case) involved in interactions of a shower of energy 100 GeV and its dependence on atmospheric depth. The total distance travelled by a charged particle in cosmic ray physics is called the track length. The track length distribution for

* Tel.: +91 022 25591798; fax: +91 022 25505151.
E-mail address: akrazdan@barc.gov.in.

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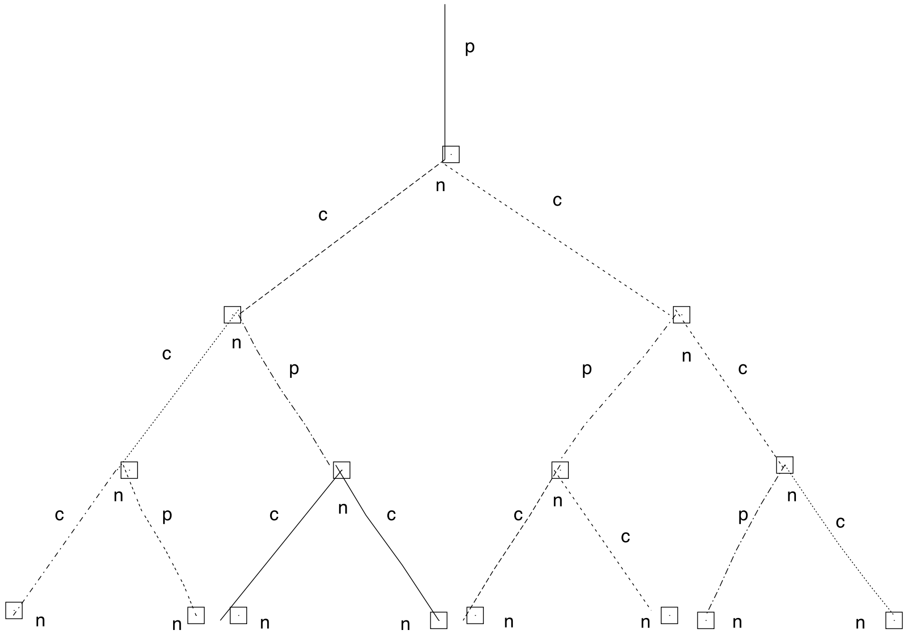

Fig. 1. Schematic view of electromagnetic shower. In this figure '*p*' represents photon, *c* corresponds to the charged particles (electron or positron) and '*n*' represents the nuclei in the air molecule.

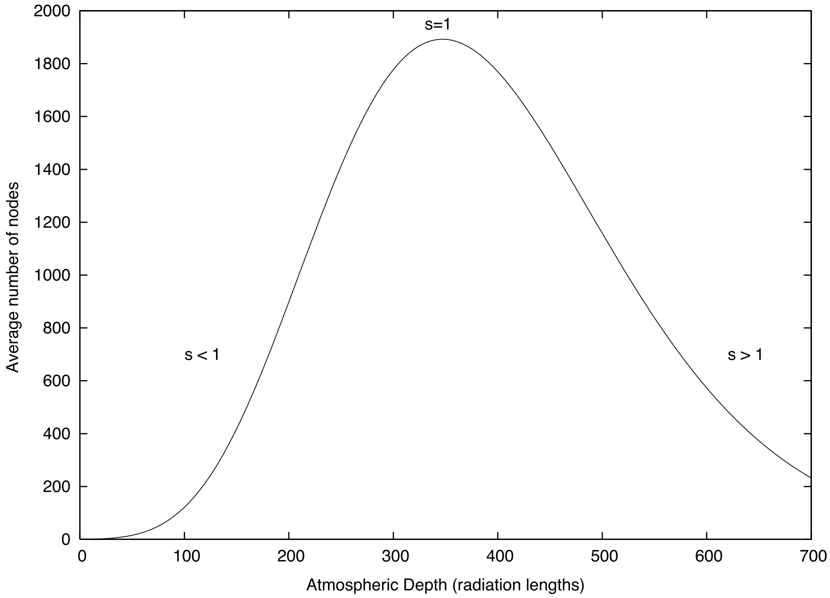

Fig. 2. Displays average number of nuclei (nodes in our case) for 800 GeV photon for different ages '*s*'.

charged particles is given as $f(E) \propto \frac{1}{E^2}$ and for Ref. [9] photons $g(E) \propto \frac{9}{7E^2}$ where E is the energy. For a γ-ray initiated shower of energy E_0, the average total number of charged particles [8] is given as

$$N_e = \frac{0.31}{\sqrt{(y)}} \exp[T(1 - 1.5\ln(S))] \tag{1}$$

where T is the depth measured in radiation lengths and $y = \ln\left(\frac{E_0}{E_c}\right)$ and shower age S is given as

$$S = \frac{3}{1 + 2\left(\frac{T_{\max}}{T}\right)}. \tag{2}$$

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