Simulations of EAS with the AIRshower Extended Simulation Program

A. Geranios[1], S. Maltezos[2], M. Vassiliou[1], I. Papadakis [1], P. Moyssides [2]

[1]Physics Department, Nuclear and Particle Physics Section, University of Athens, Panepistimioupoli, Athens Greece ZIP 15771
[2]Physics Department, Faculty of Applied Sciences, NTUA., 9 Heroon Polytechniou, Zografos, Athens, Greece ZIP 15780

Abstract

We examine the possibility to estimate the cosmic ray composition of energies above the GZK cut-off ($5x10^{19}$ eV) from the number of gammas, betas, muons and all particles created in Extensive Air Showers (EAS), from the first interaction depth and the depth of shower maximum of EAS. This examination is based on the simulation of EAS at primary energies of 10^{20} eV (100 EeV) beyond the GZK cut-off, using the AIRES (**AIR**shower **E**xtended **S**imulations) program.
AIRES uses a set of programs and subroutines to simulate particle showers produced after the incidence of high energy cosmic rays on the earth's atmosphere and to manage all the data associated with these simulations (Sciutto, 1999, 2001).
The following simulations assume a primary high energy proton, gamma or iron entrance in the earth's atmosphere and present the longitudinal and lateral behaviour of the created EAS. Two conclusions can be drawn: 1. Gamma primary produces fewer particles, gamma rays and muons on ground than proton or iron nuclei and 2. Due to its low cross section, the first interaction depth and shower maximum are much higher than that of proton and iron.

The GZK cut-off

There is a predicted cut-off energy of cosmic rays, which was calculated by Kenneth Greisen in the United States and G.T. Zatsepin and V.A. Kuzmin in the Soviet Union in 1965, the so called GZK cut-off. Space is filled with microwave radiation, the cosmic microwave background, which is considered as leftover radiation from the Big Bang. While a microwave photon doesn't have much energy, a sufficiently energetic cosmic ray would see the photon's wavelength to be reduced due to the Doppler effect. From the cosmic ray's perspective, the microwave photon would appear to be a gamma ray. Interactions between cosmic ray protons and gamma rays most often result in the production of pions, which cause the proton to lose energy. With each interaction, the proton would lose roughly 20% of its energy. This only happens for cosmic rays that have at least 5×10^{19} eV of energy, and this is the predicted GZK cut-off. So, if cosmic rays were given an initial energy greater than that, they would lose energy in repeated collisions with the cosmic microwave background until their energy fell below this cut-off. However, if the source of the cosmic ray is close enough, then it will not have made very many collisions with microwave photons, and its energy could be greater than the GZK cut-off. This distance is about 150 million light years. An other alternative to avoid the GZK cut-off is the assumption that either the primary particle is a neutrino or an exotic particle, both not interacting with microwave background radiation and therefore not loosing any part of their initial energy.

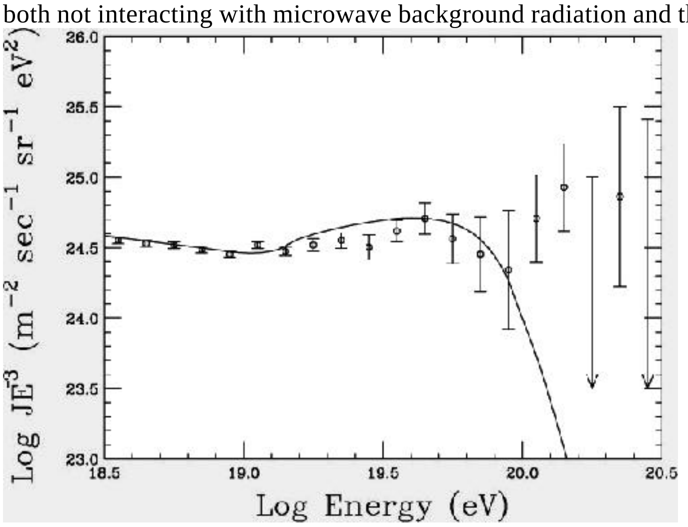


Fig. 1. The cosmic ray energy spectrum for very high energies close to the GZK cut-off. The nearly horizontal shape of the spectrum is an artefact due to the log JE^{-3} scale of the vertical axis (Hayashida et al., 1994).

Figure 1, focuses on the extreme upper part of the cosmic ray energy spectrum, which is characterised by the GZK cut-off. According to this, no protons with greater energy are expected. However, certain experimental evidence shows protons with higher energies!

Longitudinal Evolution of EAS

With the simulation program AIRES we have treated characteristic cases of EAS evolution due to primary protons. For all examples, we assume: a vertical incidence of the cosmic ray particle with zero azimuth angle, the Linsley standard atmospheric model, an injection altitude 100 km (1.28×10^{-3} g/cm^2) and a ground altitude of 297.96 m (1000 g/cm^2).

The different population of the three main components (hadrons, photons and muons) from a 100 EeV proton initiated EAS, is shown in figure 2. Note the dominating electromagnetic component due to the bremsstrahlung and the pair production effects taking place within the shower, and the maximum of the shower at near ground atmospheric depths, due to the very high energy of proton.

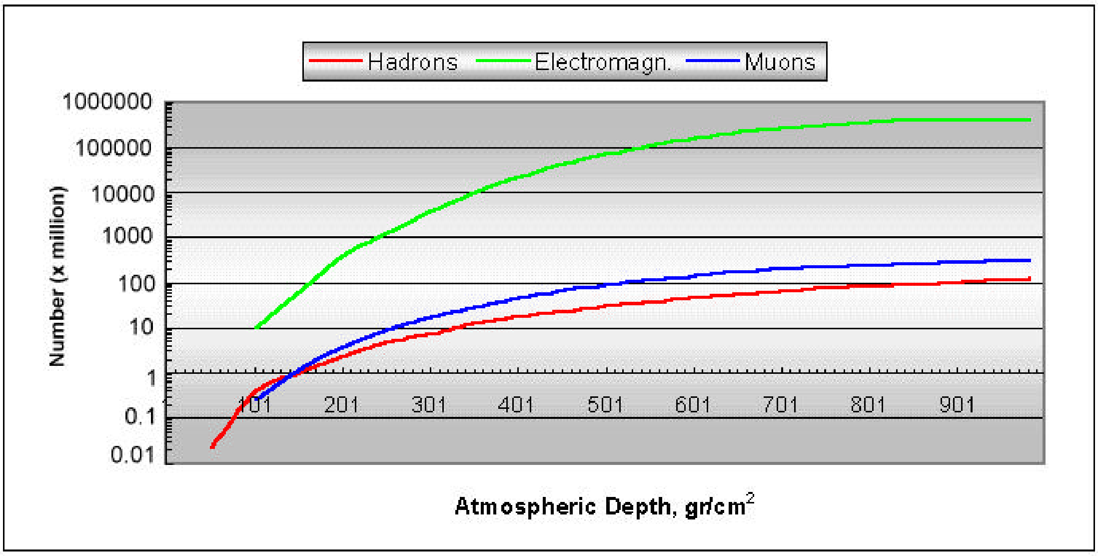


Fig. 2. The longitudinal distribution of an EAS initiated by a 100 EeV cosmic ray proton.

In Table I, a set of 100 cosmic ray showers is created and the results are presented for primary gamma, proton and iron cosmic rays.
Although, AIRES simulation program includes fluctuations on the number of particles, there are not visible, since the number of showers is quite large (100).

Table I.
Characteristic results for three sets of showers created by 100 EeV gamma, proton and iron cosmic rays

EAS, 100 EeV	**Primary**	**Primary**	**Primary**
Particles at ground level, (x 10^9)	**Gamma**	**Proton**	**Iron**
Gamma	201	299	234
Beta	39,3	52,4	39,2
Muons	0,065	0,33	0,43
Pions	0,0067	0,016	0,017
Kaons	0,0001	0,003	0,002
Neutrons	0,0436	0,11	0,121
All particles	240	352	273
First interaction depth, gr/cm^2	67,8	37,3	13,12
Shower maximum, gr/cm^2	1104	883	781
Charged particles at maximum	47,8	66	67,6

Some remarks are: 1. The muon component at ground level in showers initiated by gamma rays is much poorer than the muons initiated by proton and iron cosmic rays. 2. The first interaction depth for gamma rays is much higher than for protons or iron particles. 3. The shower maximum for gamma rays occurs at high atmospheric depths due to the low interaction cross section of gammas with the atmosphere and to the LPM effect (Landau and Pomeranchuk, 1953, Migdal, 1956). All the above three observations can be used for distinguishing if a shower is produced by a gamma ray or not.

Lateral Evolution of EAS

Due to the fact that the estimation of the energy of a cosmic ray particle depends on the total number of particles arriving on the Earth, the knowledge of the lateral distribution of the particles with distance from the centre of the EAS is of vital importance (Longair, 1992). The integration of the number of particles over the area in which all particles arrive on ground will give this number, the integration area being a circle or an ellipsis, depending on whether the shower is vertical or inclined.

The AIRES simulation program is used to reproduce the lateral distribution of all particles created by a cosmic ray gamma, proton and iron of energy 100 EeV. Figures 3 and 4 show, for these three cosmic ray primaries, the lateral evolution of all particles and gammas. In these cases, we also have averaged the result of 100 separate showers of the same energy (100 EeV).

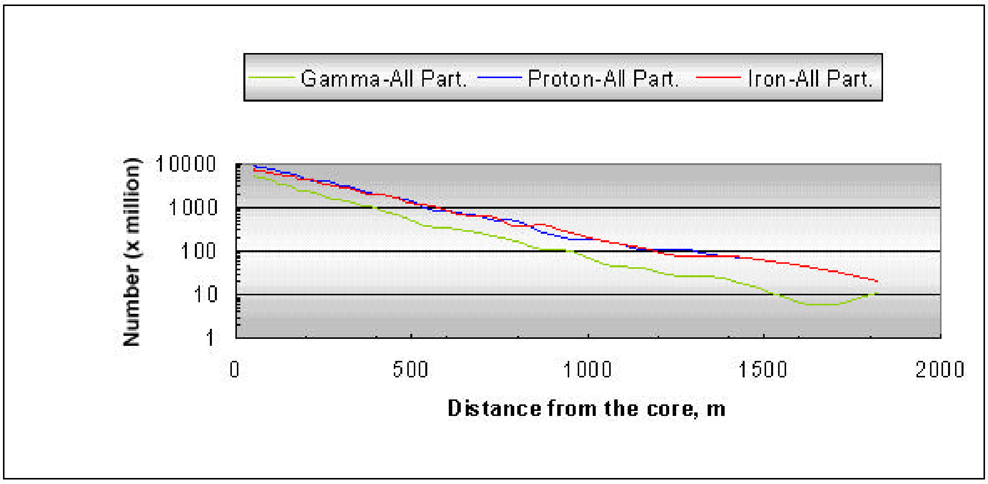


Fig.3. The lateral distribution of all particles on ground created by a primary gamma, proton and iron of energy 100 EeV.

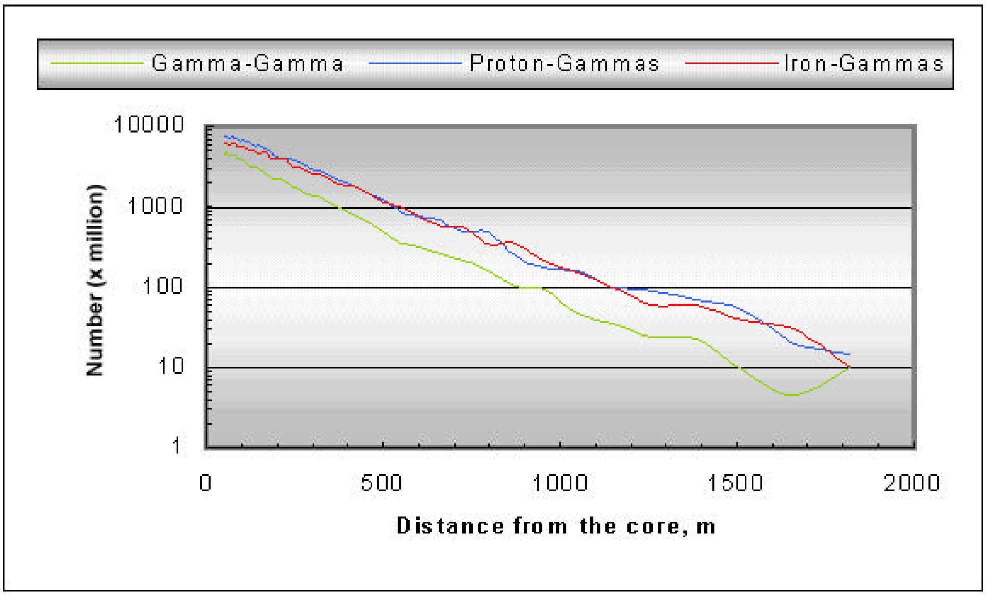


Fig. 4. The lateral distribution of secondary gammas on ground created by a primary gamma, proton and iron of energy 100 EeV.

In both of these figures it is seen that the primary gamma contributes with a much lower number of particles than the other two cosmic rays, which equally share the secondary particles. This lateral characteristic of primary gammas supports the assumption that a primary gamma can be distinguished by its poorer population of all secondary particles. In figure 5, the muon component evolution on the ground for different cosmic ray primaries of equal energy

(100 EeV) is presented. It is worth noting that the maximum population of muons does not coincide with the core of the shower at zero distances, but at distances about 300 meters apart of it. This fact could mean that muons are spread out from the shower core.

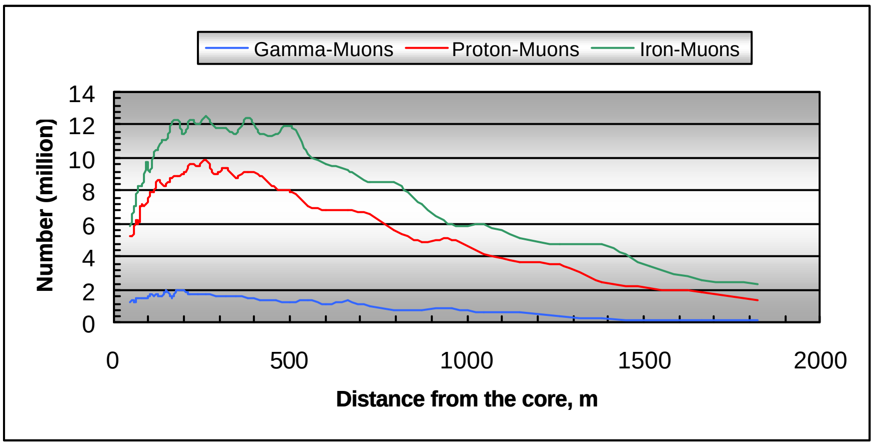
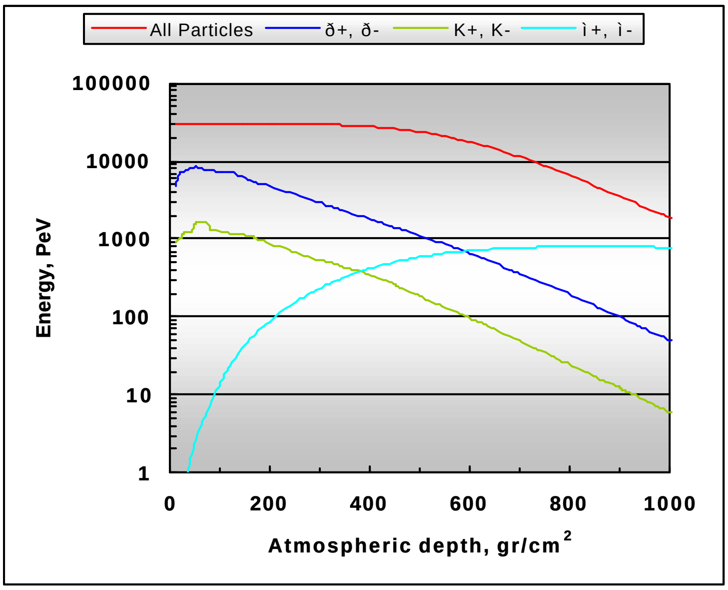


Fig. 5. The lateral evolution of the muon component for three cosmic ray primaries with energy of 100 EeV.

Evolution of the total energy carried out by the secondaries as a function of atmospheric depth

The fluorescence radiation, measured by a fluorescence detector, depends primarily on the energy loss per unit path length (ÄE/Äx) of all electrons and positrons produced. Having these numbers and the air fluorescence yield we could estimate the total number of fluorescence photons emitted (Fokitis et al., 2001).



Applying the AIRES simulation program for a primary proton of 30 EeV, we obtained the total energy evolution of all secondary particles, kaons, pions and muons with the atmospheric depth. In figure 6 we show the computed total energy of particles between an atmospheric depth x and x+Äx. The energy of the sum of all particles (red curve) starts from the initial energy of 30 EeV and for about 400 gr/cm^2 remains unchanged. For larger depths it follows a fall off mainly due to the ionization processes in the lower atmosphere. The muon component is formed later and increases its total energy, which after 600 gr/cm^2 due to its high penetrating power remains practically unchanged.

Fig. 6. The total energy evolution of an EAS in the atmosphere initiated by a primary proton of energy 30 EeV.

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