Simulation of Electromagnetic Cascades in Intergalactic Radiation Fields in connection with the Highest Energy Cosmic Ray Event

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Abstract

The existence of cosmic rays with energies exceeding the Greisen–Zatsepin–Kuzmin cutoff is yet an unresolved puzzle. Even though the quality and quantity of experimental data on the Ultra High Energy Cosmic Rays (UHECR) has improved considerably , it has not been possible to explain the origin of UHECR. In this context it is of interest to simulate the development of electromagnetic cascades, initiated during the propagation of UHECR in the Cosmic Microwave Background (CMB). A new simulation code has been developed to study properties of electromagnetic cascades, generated in interactions with the background radiation fields. The detailed simulation of the relevant processes (pair production and Compton scattering) allows for a determination the energy spectra and arrival directions of secondary particles for different settings of background radiation, distances to the source and injection spectra. In this paper, first results obtained by simulating different injection spectra of photons are presented. The effect of cascading on the shape of the injected spectra is shown.

1 Introduction

The discovery of the Cosmic Microwave Background (CMB) was initially seen as *"the end of the cosmic ray spectrum"* (Greisen 1966). As a consequence of the existence of a universal radiation field, it was quickly realised, that it is unlikely for cosmic rays with $E > 5 \cdot 10^{19}$ eV to survive propagation in the CMB over distances exceeding a few Mpc without energy loss. Inelastic interactions with the low energy photons of the CMB would cause the UHECR to lose a substantial part of its initial energy. Nevertheless, the energy is not lost but mostly channelled into electromagnetic cascades, eventually producing photons with energies $\lesssim$100 TeV. The question, to which extent UHECR are possibly accompanied by numerous TeV photons is of interest for air shower detectors sensitive in this energy range. The report by the HEGRA group (OG.3.2.24) of a possible correlation between a spatially extended excess seen in the distribution of arrival directions close to the direction of the most energetic cosmic ray event detected by the Fly's Eye group may be explained by cascade photons produced during the propagation of UHECR coming from a close ($\lesssim$30 Mpc) single steady-state source.

In order to estimate the flux of secondary photons with $E_\gamma \lesssim$100 TeV, a simulation of the complete propagation process is necessary, which includes the photohadronic interaction of the UHECR, the decay of the resonances and mesons and the processes which lead to the formation of electromagnetic cascades.

In this paper, a newly developed simulation code is described, which employs Monte Carlo techniques to calculate the energy and arrival directions of all particles produced during the *electromagnetic cascading* process. In order to test the performance, first results concerning the energy spectra of the cascade photons are calculated and compared with other calculations to ensure the correct treatment of interactions and to test the framework of the simulation code.

The first part of the paper describes the development of electromagnetic cascades and the simulation techniques applied. First results are presented in the second part of the paper.

2 Development of Electromagnetic Cascades

The development of electromagnetic cascades depends upon the spectral energy distribution of the target photons. The well-known thermal spectrum of the CMB is the dominant component of the diffuse extragalactic background radiation (DEBRA). Nevertheless, due to the fact that the pair-production process has a steeply rising cross section above the threshold and after reaching its maximum it falls off with $1/s$ (s denoting the square of the centre of momentum energy) the interaction of high energetic photons of energy $E_{TeV} = E/10^{12}$eV occurs predominantly with low energetic photons in a narrow energy band centred upon the energy $\epsilon_{eV} \approx E_{TeV}^{-1}$. It is obvious, that if one considers photons with energies exceeding $\approx 10^{19}$ eV, the diffuse radio background is the dominant target. On the other hand, photons with energies below 100 TeV are most likely interacting with the background radiation in the infrared and even optical part of the diffuse background. Unfortunately, the experimental data on the shape of the spectral distribution of the DEBRA in the radio and optical/infrared is scarce. As a consequence, the design of the cascade simulation program allows for the input of an arbitrary spectral energy distribution.

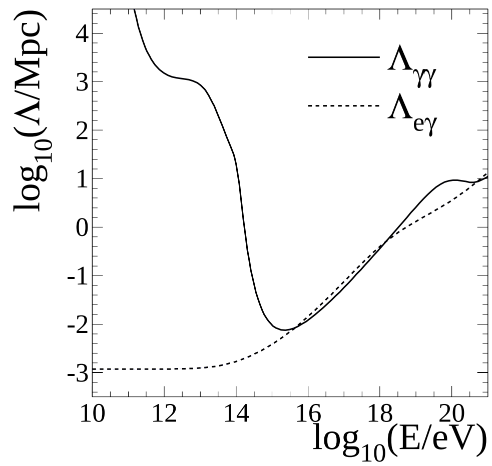


Figure 1: The mean free path length for electrons and photons in diffuse background radiation

For the calculations presented in this paper, an averaged model for the infrared and optical part of the DEBRA was used derived from Macminn and Primack 1996. The radio background was taken from Clark, Brown and Alexander 1970. The simulation aims to model the propagation over cosmologically small distances ($\lesssim$100 Mpc), where evolutionary effects are of no importance for the background radiation. The mean free path length for Compton scattering as given e.g. in Blumenthal and Gould 1970 and for pair production as given in Gould and Schréder can be evaluated numerically. The result is presented in Figure 1, displaying the mean free path length $\Lambda_{\gamma\gamma}$ in Mpc as a function of energy for pair production and Compton scattering ($\Lambda_{e\gamma}$). It is obvious, that once the mean energy of the particles drops below $\approx 10^{14}$ eV, the electrons lose their energy quickly ($\Lambda_{e\gamma} \ll 1$ Mpc), whereas the photons cool off over distances of the order of Mpc.

Besides the mean free path length, the fractional energy loss of the electrons is of importance for the cascade process. In the case of $E_e\epsilon \gg m_e^2c^4$ (Klein–Nishima limit), the emerging photon will gain almost all of the electron's energy, whereas in the case of $E_e\epsilon \ll m_e^2c^4$ (Thomson limit) the electron will gradually lose its energy. In the Thomson limit, the mean energy of the emerging photons is $\epsilon' \approx 4/3\gamma^2\langle\epsilon\rangle \ll E_e$ ($\gamma = E_e/m_ec^2$, $\langle\epsilon\rangle$ denoting the mean energy of the background photons).

The outline of the simulation procedure is straight–forward. An interaction length is sampled according to the mean free path length for a given particle and for a given energy. The target photon's direction and energy are sampled using the technique described in Protheroe and Stanev 1987. The interaction is treated in the appropriate inertial frame (centre of momentum for the photon–photon interaction, electron rest frame for the Compton scattering) using the exact differential cross sections. The final state is boosted back in the original inertial frame and the lower energetic particle is followed until the energy drops below a predefined threshold or until it would interact behind the observer. In the latter case, the arrival time, energy, direction and coordinates in the plane perpendicular to the direction of the primary particle are recorded.

In contrast to the matrix method applied in Protheroe and Stanev 1987, the full information of each particle (including its direction and arrival time) is retained. This is of importance for experiments trying to observe cascade radiation, since the apparent angular size due to the cascading is a distinct feature. To avoid excessive processing time, the code has been optimised for speed by using look–up tables and fast algorithms for all numerical calculations. Nevertheless, it is necessary to restrict the simulation process to energies above ≈ 100 GeV. The most time-consuming task in the simulation is to follow electrons deep in the Thomson regime, where the scattering takes place on comparably short distance scales.

3 Results

To ensure the correct treatment of the interactions and to test the framework of the simulation code, a single photon with an energy of 10^{15} eV is injected at a distance of 10 Mpc to the observer. By tracking all particles until they reach the observer, it is possible to check that the energy and momentum conservation are fulfilled by simply adding up the energy and momentum of the particles produced. Additionally, by comparing the resulting energy spectrum with previously published results (Coppi and Aharonian 1997), it is demonstrated that the propagation code reproduces the well-known feature, that the energy spectrum of the cascade radiation roughly follows a power law $\mathrm{d}N_\gamma/\mathrm{d}E \propto E^{-1.5}$ (see Figure 2). This feature of the cascade is independent of the exact shape of the DEBRA. It is interesting to note, that the shape is also independent of the energy of the injected photon as long as the mean free path length of the photon at the given energy is small compared to the distance of the source to the observer.

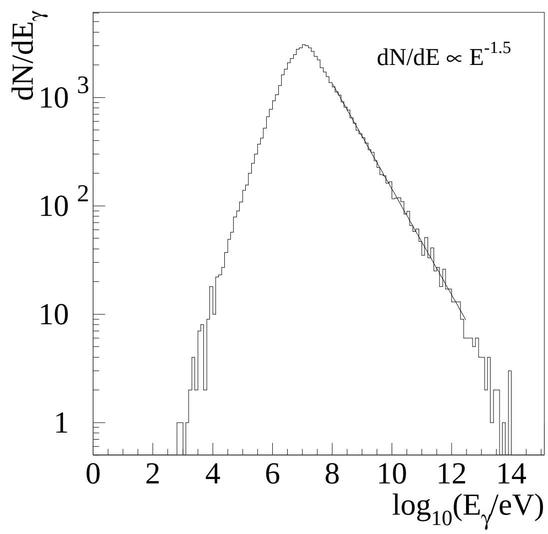
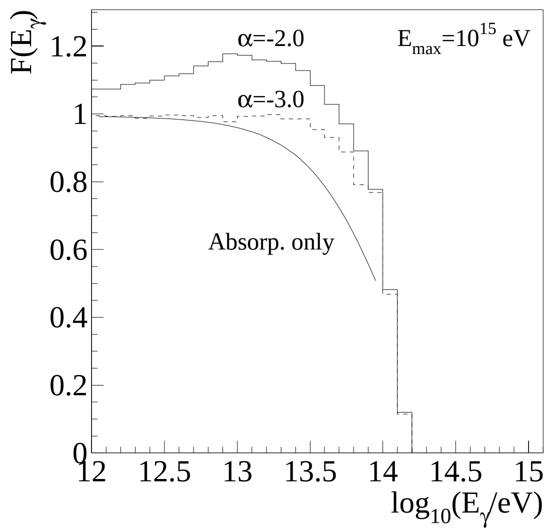


Figure 2: The differential energy spectrum of photons resulting from the cascade initiated by a single photon of energy 10^{15} eV injected at a distance of 10 Mpc

As a next step, a continuous energy distribution of photons following a power law with a slope α is injected at a given distance D. The injected spectrum has a maximum energy at E_{max}. The photons initiate electromagnetic cascades and the resulting particles are recorded when they pass the plane of the observer. To emphasise the change of the injected and propagated energy spectrum, the ratio of recorded and injected photons (the modification factor) for a given energy bin i is calculated $F_i = N_{recorded,i}/N_{injected,i}$. The resulting factor F_i for $D = 10$ Mpc, $E_{max} = 10^{15}$eV, $\alpha = -2.0$ and $\alpha = -3.0$ are displayed in Figure 3a. For means of comparison, the spectrum obtained by assuming that the photons do not initiate cascades (i.e. pairs produced in interactions are ignored) is displayed in the same Figure. One can clearly see that the cascading substantially alters the spectrum for the case of a harder injection spectrum. For a steeper ($\alpha = -3.0$) injection spectrum, the cascade photons compensate for the absorbed photons, but no pile-up is evident.

To study the influence of E_{max} on the observable spectrum, two injection spectra with $\alpha = -2$ were simulated with $E_{max} = 10^{14} eV$ and $E_{max} = 10^{18}$ eV. Figure 3b displays the result. Clearly, the shape of the observable spectrum is strongly dependant upon the maximum energy. The pile-up of radiation below 10^{14} eV is strongly enhanced for the case of a higher maximum energy in the injected spectrum. One can see by comparing Fig. 3a and 3b that once E_{max} approaches 10^{15} eV, the spectral shape does not change significantly for higher energies.



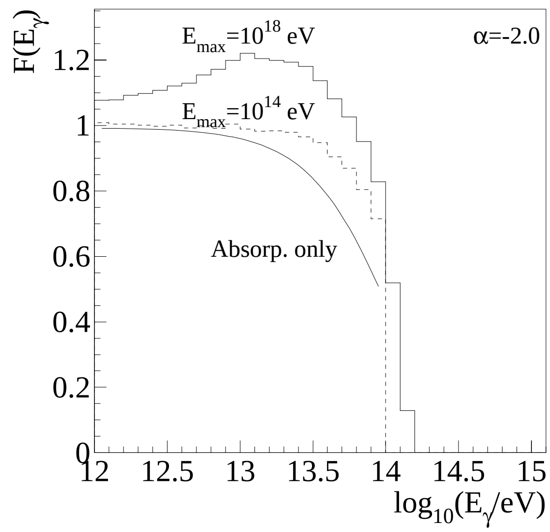


Figure 3a: The modification factor for $E_{max} = 10^{15}$ eV and injection spectral indices $\alpha = -2.0$ and $\alpha = -3.0$. Also shown is the modification factor taking only the pair production into account (labelled absorption only).

Figure 3b: The modification factor for $\alpha = -2.0$ and $E_{max} = 10^{14}$ eV and $E_{max} = 10^{18}$ eV .

4 Summary and outlook

It has been shown that a detailed simulation of electromagnetic cascades on the extragalactic diffuse background radiation can be used to determine the energy spectra and distributions of arrival directions. The final states of the treated interactions (Compton scattering and pair production) are determined using the exact cross sections and kinematics. As a first application different injection spectra are simulated. The resulting energy spectra show strong dependence upon the shape of the injected spectrum. The flatter the injection spectra the more important becomes the effect of cascading. A steep spectrum (with a power of $\alpha < -3.0$) will show basically only absorption features whereas a flat injection spectrum ($\alpha > -2.0$) will be substantially altered by the effect of cascading. The maximum energy of the injection spectrum strongly influences the shape of the observable spectrum. After testing the performance of the simulation of electromagnetic cascades, it is foreseen to include the simulation of photohadronic interactions in the near future. This would make a direct estimate of the observable cascade radiation in the TeV energy region due to propagation of UHECR possible.

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