LPM Showers in the Atmosphere Taking into Account the Geomagnetic Field

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Abstract

It has become a common knowledge that a correct calculation of the development of air showers initiated by UHE ($> 5 \times 10^{19}$ eV) primary photons should take into account the interactions in the geomagnetic field before entering the atmosphere and the Landau-Pomeranchuk-Migdal effect (LPM) in the atmosphere. We show that the geomagnetic field has also a noticeable effect on the UHE electromagnetic shower development in the atmosphere and has to be accounted for in precise calculations of the shower characteristic.

1. Introduction

At ultrahigh energies (UHE) the geomagnetic field becomes an effective target in which gamma rays create electromagnetic cascades before entering the atmosphere. A study of the consequences of such interactions with the geomagnetic field with future giant air shower arrays could identify the nature of the highest energy cosmic rays as either gamma rays or nuclei [5].

Usually geomagnetic cascading is accounted for only outside the atmosphere. Then the particles of the generated "preshower" are used as an input for the air shower simulation packages and the geomagnetic field within the atmosphere is neglected. The assumption is that the processes in the geomagnetic field cannot compete with the corresponding processes in matter(air). Good illustration for this is Fig.6 in [3] where energy dependent break-even altitudes are presented. The break-even points are defined at altitudes where matter and magnetic field effects are the same [1].

The break-even altitudes are indeed high but this does not mean that the impact of the magnetic effects on the shower development inside the atmosphere is negligible. According to the estimations in [2], the interactions of shower particles with the geomagnetic fields in the atmosphere ($H_\perp = 0.35\ G$) decreases the

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number of shower particles at sea level by ~ 13% for primary photons of 10^{20} eV, injected vertically into the atmosphere, and ~ 2 times for 10^{21} eV primary photon.

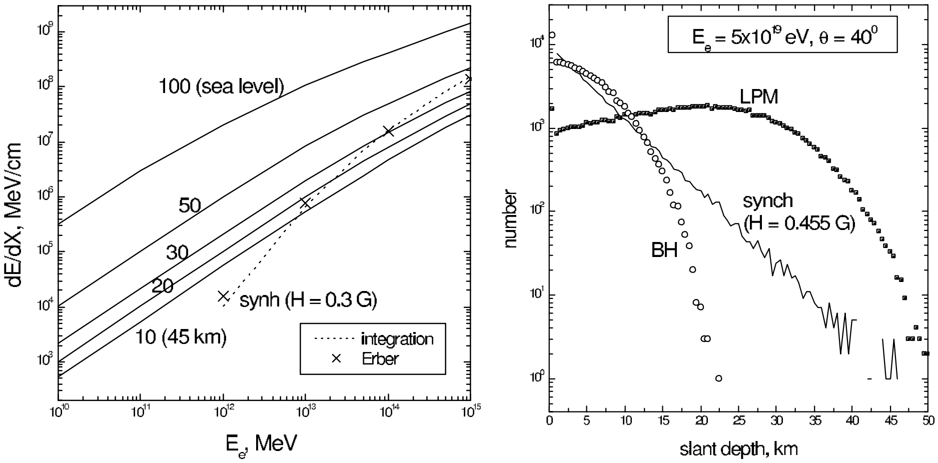

Fig. 1. Lefthand panel: Electron energy loss rate due to bremsstrahlung as a function of energy at different altitudes in the atmosphere (solid lines) compared with synchrotron energy loss rate (dotted line and crosses). Righthand panel: Distribution of the first interaction point of an electron of energy 5×10^{19} eV injected at the top of atmosphere.

A photon of energy 10^{20} eV injected vertically at the top of the atmosphere has ~ 14% chance to produce pair on the magnetic field ($H_\perp = 0.35$ G) instead on the air nucleus. For 10^{21} eV photon this chance is ~ 58%. The probability for magnetic pair production sharply decreases with decreasing photon energy, which quickly eliminates the influence of this process on the shower development.

The situation with magnetic bremsstrahlung (synchrotron radiation) is different because of the different energy dependence of the cross section. Fig. 1a shows the electron energy loss rate $\frac{dE}{dx}$(MeV/cm) due to bremsstrahlung as function of the energy at different altitudes compared to synchrotron energy loss rate for $H_\perp = 0.35$ G. The synchrotron energy loss rate is calculated by a numerical integration of the expression (3) in [6] for the differential probability per unit length. For comparison, results from Erber's review [1] (formula 2.18) are also presented.

One can see that the synchrotron energy loss rate starts to compete with bremsstrahlung energy loss at energies $> 10^{18} eV$ in the upper layers of the atmosphere. For example, the break-even altitude for bremsstrahlung and synchrotron radiation of a 10^{20} eV electron is ~ 35 km a.s.l.

The break-even altitude decreases with increasing electron energy. The magnetic effects become however even more efficient when the LPM effect suppresses the Bethe-Heitler cross sections. At altitude of 35 km the energy loss of a 10^{20} eV electron on bremsstrahlung is decreased by $\sim 30\%$. Fig. 1b shows the distribution of the interaction points of an electron of 5×10^{19} eV, injected at the top of atmosphere with zenith angle 40°, arriving at AGASA from the North. The value of $H_{\perp} = 0.455$ G corresponds to the component of the geomagnetic field normal to the electron trajectory. The corresponding mean values are $\lambda_{LPM} \approx 18.8$ km and $\lambda_{BH} \approx 4.94$ km, while $\lambda_{synch} \approx 4.95$ km.

2. Simulation

We follow the shower development by direct simulation that includes the LPM effect, magnetic pair production and synchrotron radiation down to a threshold energy E_{thr}, bellow which the LPM effect is not effective. The subthreshold particles are then replaced by analytical approximations. We assume that $H_{\perp}$ is constant in the atmosphere, which has a height of 50 km a.s.l. The range of the field at sea level is about 0.25 - 0.65 G depending on the geographical coordinates and direction.

3. Results

In Fig.3 we show the atmospheric shower profile of 5×10^{19} eV electron injected vertically (lefthand panel) and under zenith angle 40° (righthand panel) into the atmosphere, with and without account for the magnetic effects. Magnetic effects accelerate shower development. They increase the number of particles at maximum and decrease the depth of the maximum. The effect is stronger for primary electrons than for photons of the same energy.

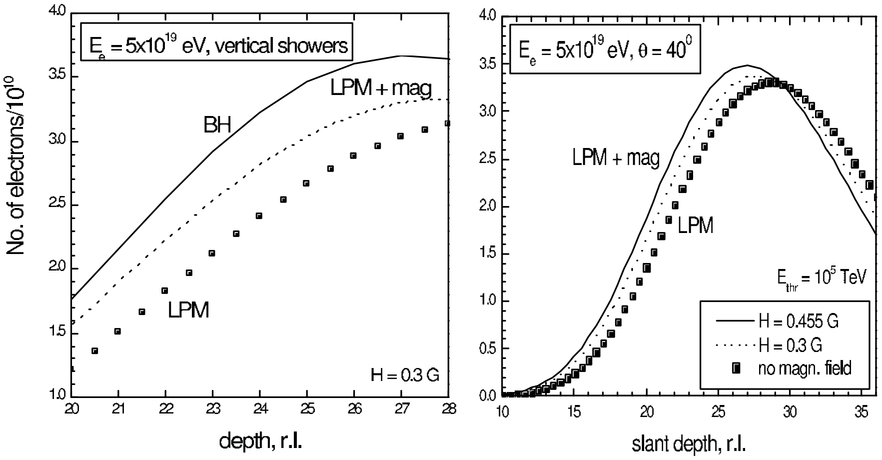

Fig. 2. Atmospheric shower profile of 5×10^{19} eV electron

4. Discussion and conclusions

The geomagnetic field influences the atmospheric shower development mostly through synchrotron radiation. For example, in a 5×10^{19} eV electron shower (0.3

G and $\theta = 40°$) there are no magnetic produced pairs at all, while $\sim 5\%$ of all electron interactions in the shower are synchrotron radiation with about 35% of the primary energy lost in this process (these estimates are for energies above E_{thr}). If the primary particle is a photon $\sim 12\%$ of the energy is synchrotron radiated and $\sim 1.6\%$ of all pairs are created on the magnetic field. The magnetic effects are significant at the initial stage of the shower development when particle energies are high and and the atmospheric density is low. At higher primary energies ($> 7 \times 10^{19}$ eV in 0.3 G field) the cross section for magnetic pair production increases and magnetic effects become stronger. We should note, however, that if photons of such UHE are of cosmic origin, they will convert with high probability into pairs in the geomagnetic field far from the Earth and arrive in the atmosphere as a bunch of particles of lower energy.

The magnetic effects decrease the number of shower particles at sea level by up to a factor of 2 in comparison to LPM only showers at energy $\sim 10^{21}$ eV. The shower maximum decreases by $1.5 - 2$ r.l. The number of charged particles at ground level is an important observational parameter for the air shower arrays. This number at shower maximum and the depth of the maximum are important observables for optical detectors. Thus, magnetic effects in the atmosphere can affect the determination of the primary energy. It is not *a priory* obvious how the different energy spectrum of the γ–rays from synchrotron radiation will influence the number of GeV muons generated in these showers.

The impact of the geomagnetic field on the electromagnetic shower development in the atmosphere is not negligible and must be taken into account in simulations that aim at accuracy of 10% or better. We did not, however, discuss all processes. Magnetic fields can also suppress the probability for bremsstrahlung and pair production in matter ("magnetic suppression"). This is only one of the possible suppression mechanisms [4] that, in addition to the LPM effect, could affect the shower development at UHE. Precise shower calculations require additional studies of these effects and this work is now in progress.

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