Features of Inclined Air Showers Induced by EHE Gamma Rays

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Abstract

Using the numerical solution of adjoint cascade equations we analyze characteristics of air showers produced by extremely high energy (EHE) photons taking into account the Landau-Pomeranchuk-Migdal (LPM) effect and the interaction of EHE photons and electrons with the geomagnetic field (GMF). The calculational results on the radial distributions, mean squared radii, angular distributions and mean squared angles of cascade electrons are presented for EHE ($10^{18} \div 10^{21}$ eV) inclined air showers. The calculations correspond to conditions of the southern location of the Auger Observatory.

We claim an existence of invariant functions of radial and angular distributions independent on the primary photon energy, the shower age and assumptions on the LPM and GMF effects (regarding or disregarding). This feature takes place for both the vertical and inclined air showers. A slight dependence of the invariant function shape on the shower arrival angle is observed at large angles (near 60^o) for the radial distribution.

1. Introduction

The origin and nature of extremely high energy cosmic rays (EHECRs) is one of important problems of astrophysics. Origin and evolution scenarios of EHECRs allow to expect among them some proportion of γ-rays [1-3]. Measurement of the γ/p ratio would give an information about sources of EHECRs and their acceleration mechanisms [4]. Therefore it's important to analize properties of air showers created by EHE γ-rays.

For EHE γ-rays two effects have to be accounted in the study of the air shower development. They are the the Landau-Pomeranchuk-Migdal (LPM) effect [5,6] and the interaction of EHE photons and electrons with the geomagnetic field (GMF) [7]. The main purpose of this report is an investigation of the influence of the LPM and GMF effects on radial and angular distributions of electrons in the EHE air showers.

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2. Method

The numerical solution of adjoint cascade equations is used to calculate characteristics of electromagnetic cascades in the atmosphere and magnetosphere of the Earth [4,8,9].

We consider all essential processes of cascade particle interaction with matter at energy region $E \geq 10^4$ eV. Calculations are performed for the US standard atmosphere. The GMF intensity profile corresponds to the southern location of the Auger Observatory (Mendoza, Argentina) [10] and the shower arrival direction from the south magnetic pole. A wide range of shower arrival angles is considered ($\Theta = 0^o \div 60^o$). The observation level is 890 g/cm^2. The threshold energies of cascade particles are $E_{th} = 0,1$ MeV for lateral characteristics and $E_{th} = 1$ MeV for angular ones.

3. Results

We present here lateral distribution functions (LDFs) of electrons and their mean squared radii as well as angular distributions of electrons and their mean squared angles for the energy region $E = 10^{18} \div 10^{21}$ eV and inclined air showers.

3.1. Radial distributions and mean squared radii

Our analysis has shown that the LPM and GMF effects, taken into account separately, change considerably the lateral development of the air shower. On the contrary, being accounted simultaneously, the LPM and GMF effects compensate sufficiently each other. We illustrate these statements by fig. 1. where we present the mean squared radii r_{msq} of electrons for inclined air showers. It is seen from the figure that, for example, at energy $E_\gamma = 10^{20}$ eV the LPM effect reduces r_{msq} by as much as 18 %, where as the GMF increases this quantity by $\simeq 12$ %. However the simultaneous influence of both effects is only ~ 4 % at this energy. For the longitudinal development of EHE air showers this "compensation" effect was discussed firstly in [11].

As it follows from our calculations, with an increase of the shower arrival angle Θ the LPM effect influences r_{msq} more seriously, where as the GMF influence remains almost the same. At the same time an effect of the LPM and GMF "compensation" becomes stronger with Θ growth. For example, at energy $E_\gamma = 3 \cdot 10^{20}$ eV the difference between mean squared radii calculated with the help of the Bethe-Heitler approach and with regarding the LPM and GMF effects decreases from 12 % (vertical air shower) to 4 % ($\Theta = 60^o$).

According our analysis after a "scaling" transformation of LDFs:

$$xf(x, E, s, \Theta) = r_{msq} rf(r, E, s, \Theta), \quad x = r/r_{msq} \tag{1}$$

the shape of function f does not depend on the LPM and GMF effects (see

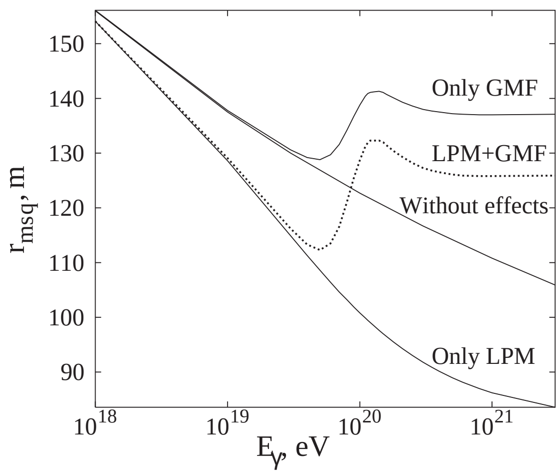

Fig. 1. The mean squared radii of electrons for inclined air showers ($\Theta = 45^o$) via the primary energy E_γ for different assumptions on the LPM and GMF effects

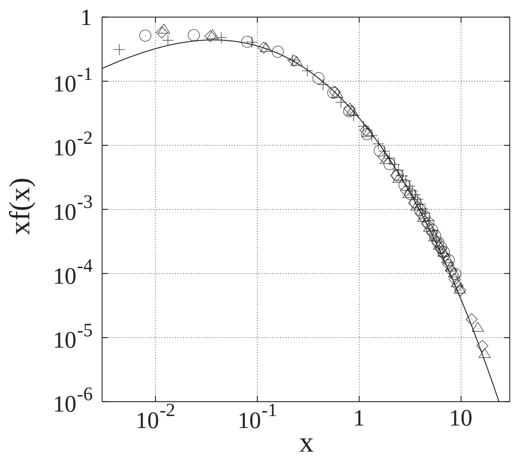

Fig. 2. The invariant LDFs of electrons for vertical and inclined air showers: $\diamond$ — $E_\gamma = 10^{19}$ eV, $\theta = 0^o$, without effects; $\circ$ — $E_\gamma = 10^{21}$ eV, $\theta = 45^o$, LPM + GMF; + — $E_\gamma = 3 \cdot 10^{20}$ eV, $\theta = 60^o$, only GMF; $\triangle$ — $E_\gamma = 10^{20}$ eV, $\theta = 30^o$, only LPM; solid line — invariant LDF for vertical air showers and $E_\gamma \leq 10^{18}$ eV [12]

fig. 2.) in interval $3 \cdot 10^{-2} \lesssim x \lesssim 15$. Besides that, the function f does not depend practically on the primary photon energy E_γ, shower age s and arrival direction (while $\Theta < 60^o$):

$$xf(x, E, s, \Theta) \approx xf(x). \qquad (2)$$

However, a slight dependence of the invariant function shape on the arrival angle is observed at large angles (near 60^o); $f(x)$ becomes broader.

Previously the property (1),(2) was discovered in [12] for vertical air showers with energy below EHE region. In our case the shape of invariant LDF of electrons is close to that found in [12]:

$$xf(x) = exp(-3.63 - 1.89 \cdot \ln x - 0.37 \cdot \ln^2 x - 0.0168 \cdot \ln^3 x).$$

3.2. Angular distributions and mean squared angles

Mean squared angles θ_{msq} have a behaviour similar to mean squared radii. However, dependence of θ_{msq} on the primary photon energy is weaker (see fig. 3.). For example, at energy $E_\gamma = 10^{20}$ eV difference between mean squared angles calculated without effects and with the LPM effect only is 3 %, between ones without effects and with the GMF only — $\simeq 2$ %.

Invariant functions of normalized angular distributions are not exposed to considered here effects in interval $3 \cdot 10^{-2} < y < 2$ and depend only on $y = \theta/\theta_{msq}$:

$$\theta_{msq}\theta f(\theta, E, s, \Theta) = y f(y, E, s, \Theta) \approx y f(y).$$

We offer the following fit for the invariant part of angular distributions:

$$yf(y) = exp(-3.517 - 1.619 \cdot \ln y - 0.3 \cdot \ln^2 y - 0.0179 \cdot \ln^3 y). \qquad (3)$$

Earlier the property $\theta_{msq}\theta f(\theta, E, s) \simeq yf(y, s)$ was described in [13].

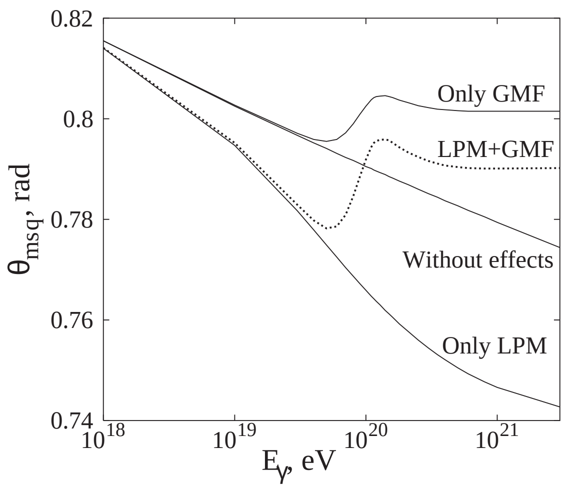

Fig. 3. The mean squared angles of electrons for inclined air showers ($\Theta = 45^o$) via the primary energy E_γ. Different assumptions on the LPM and the GMF effects are considered

4. References

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