

## Behavior of individual electromagnetic cascade shower with the LPM effect in geomagnetic field

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**Abstract.** It is well known now that individual LPM shower in a dense media like lead show various diversities over their shower development. Such distinguished characters never be expected in individual LPM shower in the atmosphere due to lower density of the medium, but we could expect large deviation from their average values even in individual LPM shower in the atmosphere. In this sense, we should understand characters of individual LPM shower in the atmosphere. On the other hand, the existence of the magnetic bremsstrahlung and pair production processes due to the Earth magnetic field causes 'pre-shower' by incident photon before entering into the atmosphere. These effect make the LPM effect weaken in the LPM shower in the atmosphere. In this paper, we discuss individual LPM shower in the atmosphere in the presence of the Earth magnetic field.

### 1 Introduction

If extremely high energy photon, say,  $10^{23}$  eV or much more exists outside the atmosphere, it is surely affected by the magnetic bremsstrahlung and magnetic pair production due to the Earth magnetic field and it produce "pre-shower", main component of which are occupied by relatively lower energy photons, not electron before entering into the atmosphere (Stanev and Vankov (1997)). Consequently, these processes make the LPM effect decrease so that extremely high energy photon is suppressed not to produce "effective" LPM shower. It is well known that the LPM showers show wider diversity on their shower developments. Therefore, we are very interested in the individual behavior of the LPM shower under the presence of geomagnetic field.

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### 2 Magnetic bremsstrahlung and pair production cross-sections

It is well known (Erber (1966), Kasahara (1996), Anguelov and Vankov (1999) and Bertou et al (2000)) that probabilities of magnetic bremsstrahlung and pair production are governed by a parameter  $\chi$  (some other people uses  $\Upsilon$ ) defined by

$$\chi = \frac{E}{mc^2} \frac{H}{H_{cr}} \quad (1)$$

where  $E$  is an energy of the particle,  $mc^2$  is the electron mass,  $H$  is the strength of magnetic field and  $H_{cr} = 4.414 \times 10^{13}$  G. The total cross-sections depend only on  $\chi$  for a given value of the magnetic field strength, as shown in Figures 1 and 2. Following Anguelov and Vankov(1999), we rewrite the differential cross-sections of bremsstrahlung and pair production into the functions of  $v = \langle \text{secondary energy} \rangle / \langle \text{primary energy} \rangle$  as:

$$\phi_{br}(E, v)dv = \frac{C_a}{E} dv \left[ \left(1-v + \frac{1}{1-v}\right) K_{\frac{2}{3}}(\xi) - \int_{\xi}^{\infty} K_{\frac{1}{3}}(y) dy \right] \quad (2)$$

where

$$\xi = \frac{2}{3\chi} \frac{v}{1-v}, \quad (3)$$

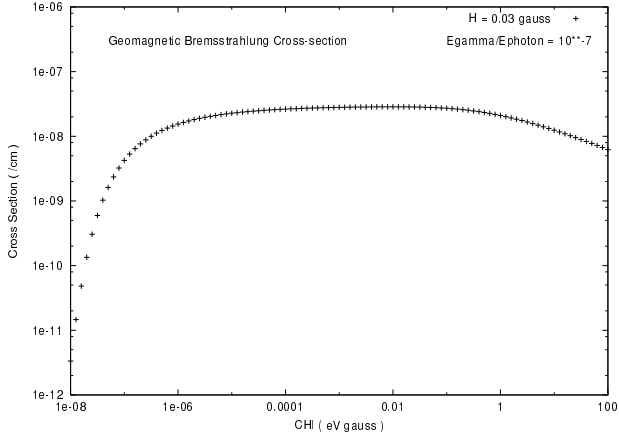
$$C_a = \frac{\alpha m^2}{\pi \sqrt{3}} \quad (4)$$

$$\phi_{pa}(E, v)dv = \frac{C_a}{E} dv \left[ \left(\frac{1-v}{v} + \frac{v}{1-v}\right) K_{\frac{2}{3}}(\zeta) + \int_{\zeta}^{\infty} K_{\frac{1}{3}}(y) dy \right] \quad (5)$$

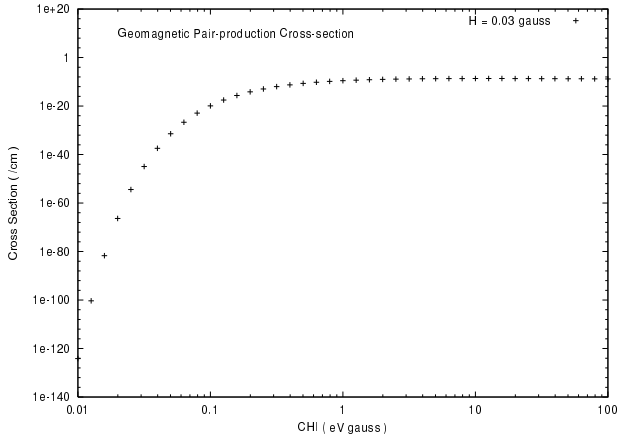
where

$$\zeta = \frac{2}{3\chi} \frac{1}{v(1-v)} \quad (6)$$

where  $E$  is energy of primary electron for bremsstrahlung or that of primary photon for pair production, and  $K_{\nu}$  ( $\nu =$

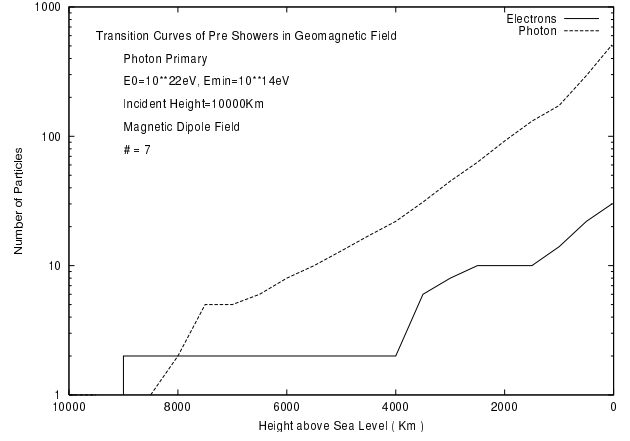


**Fig. 1.** Total cross section of bremsstrahlung in geomagnetic field.

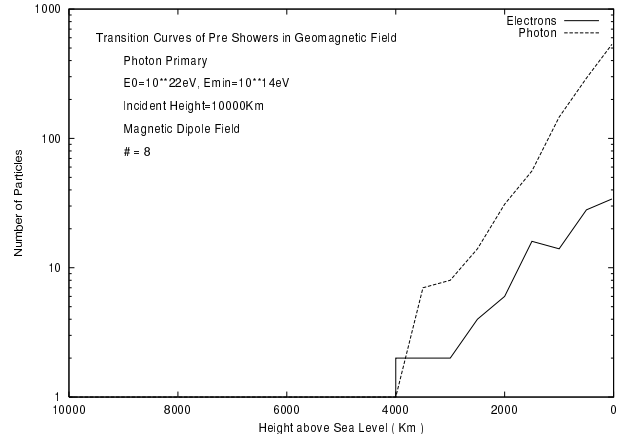


**Fig. 2.** Total cross section of pair production in geomagnetic field.

$2/3$  or  $1/3$ ) is a modified Bessel function of fractional order. We can easily see from these equations that the 'shape' of the cross-sections do not depend on the energy of parent particle but only on  $v$  and  $\chi$ . After calculating the cross-sections for given values of magnetic field strength  $H_1$  and primary energy  $E$  once, it is easy to recalculate them for another value of magnetic field strength  $H_2$ . For example, let  $\sigma_{br}(E, H)$  be bremsstrahlung total cross-section for energy  $E$  and for the field strength  $H$ . We fix the value of magnetic field strength as  $H_1$  at first, and calculate total cross-sections for various values of energy. And suppose we get the value of bremsstrahlung cross-section as  $\sigma_1 = \sigma_{br}(E_1, H_1)$  with  $\chi = \chi_1$  (see equation (1)). Then we can get the total cross-section  $\sigma_2$  for another magnetic field strength  $H_2$ , where  $H_2/H_1 = a$ , as  $\sigma_2 = \sigma_{br}(E_1/a, H_2) = a\sigma_1$  as long as  $E_2 (= E_1/a)$  and  $H_2$  give the same value of  $\chi = \chi_1$ . It is convenient to make the tables with respect to  $\chi$  in order to reproduce bremsstrahlung and pair production in computers.



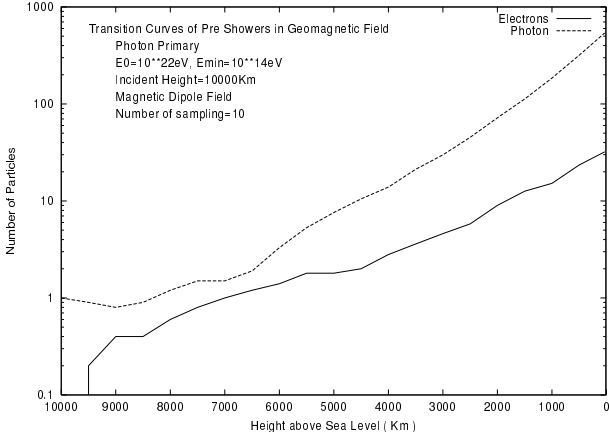
**Fig. 3.** One example of individual pre-shower in geomagnetic field with primary energy  $E_0 = 10^{22}$  eV



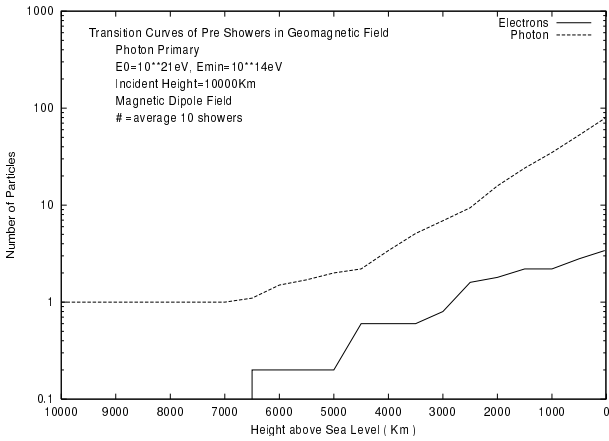
**Fig. 4.** Another example of individual pre-shower in geomagnetic field with primary energy  $E_0 = 10^{22}$  eV

### 3 Simulation of pre-shower

We simulate interactions of gamma-rays and electrons with geomagnetic field from 10000km to 30 km in altitude one dimensionally. We simulate pre-showers as follows. We divide the total range of simulation into layers with interval thickness of 20km. We calculate the strength of geomagnetic field using the dipole model, at first, when a particle (gamma-ray or electron) comes into one of those layers. We calculate the parameter  $\chi$ , next, get the mean free path of the particle with the spline interpolation of the table that is calculated preliminarily for the fixed values of  $\chi$ 's. The ranges of  $\chi$  are  $10^{-2}$  to  $10^2$  for gamma-rays and  $10^{-8}$  to  $10^2$  for electrons respectively in pre-calculated tables, and divided one decade into ten equal regions logarithmically. Then we sample free path  $\Delta t$  of the particle with a uniform random number. When free path is larger than the thickness of the layer, 20km, particle goes through the layer without interaction and goes to next layer. Otherwise, pair production or bremsstrahlung occurs. We calculate the secondary energy of pair production



**Fig. 5.** Averaged transition curves of pre-shower in geomagnetic field with primary energy  $E_0 = 10^{22}$  eV

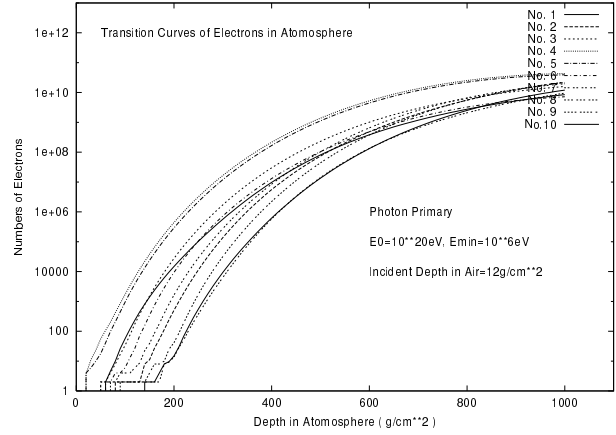


**Fig. 6.** Averaged transition curves of pre-shower in geomagnetic field with primary energy  $E_0 = 10^{21}$  eV

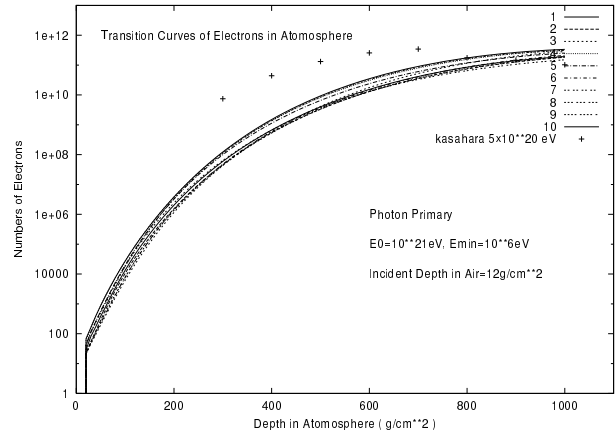
or bremsstrahlung by interpolating two-dimensionally,  $v$  and  $\chi$ , on the pre-calculated table. Produced electrons of pair production or secondary gamma-ray and survived electron of bremsstrahlung are pursued similarly above in the rest interval from the produced position to bottom of the layer.

#### 4 The method for the linkage of the pre-shower with the showers in the atmosphere

After interaction with the geomagnetic field, produced secondary particles fall into the atmosphere as pre-shower which are mainly photons with relatively low energies. We link such secondary showers with the atmospheric LPM shower program which starts now at  $12g/cm^2$  (30km above sea level). In our program for the atmospheric LPM showers, we pursue the shower particle with energy above  $10^{16}$  eV by full Monte Carlo method. When the energy of the shower particle falls below  $10^{16}$  eV, we link with numerical calculation of Approximation B, because the LPM effect is completely



**Fig. 7.** Developments of individual 10 air showers with geomagnetic field and the LPM effect.  $E_0 = 10^{20}$  eV



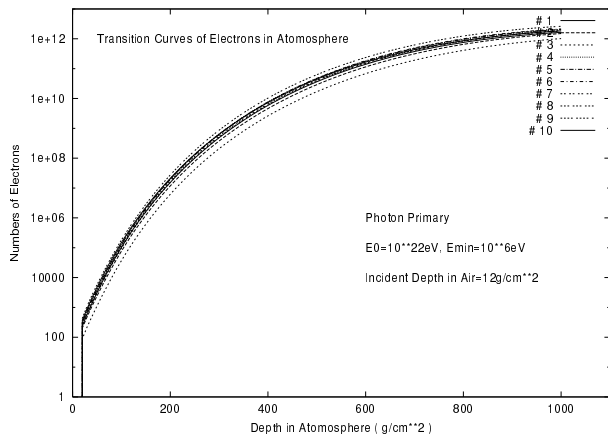
**Fig. 8.** Developments of individual 10 air showers with geomagnetic field and the LPM effect.  $E_0 = 10^{21}$  eV. + denote Kasahara's results with energy  $5 \times 10^{20}$  eV (Kasahara (1996))

negligible in cascade showers initiated by a particles with energy less than  $10^{16}$  eV, and cascade showers are expected to develop as the BH shower.

### 5 Results

#### 5.1 Development of pre-shower

We simulate showers with full Monte Carlo method from geomagnetic to atmospheric interactions. We present here results of 10 showers with primary energies  $E_0 = 10^{20}, 10^{21}$  and  $10^{22}$  eV respectively. First of all, we give the aspect of geomagnetic pre-shower in Figures(from 3 to 6). We give the two samples of individual pre-shower developments with  $E_0 = 10^{22}$  eV in Figures(3 and 4), and the average development of 10 showers in Figure 5. We can find from these figures that number of electrons and photons increase exponentially as the altitude decreases, and at the top of the at-



**Fig. 9.** Developments of individual 10 air showers with geomagnetic field and the LPM effect.  $E_0 = 10^{22}$  eV

mosphere (altitude=30 km) they reach to the numbers similar to average numbers,  $n_\gamma = 540$  and  $n_e = 32$  respectively, though the starting points and exponents of increment are different from each other. Figure 6 shows the average development of 10 showers with primary energy  $E_0 = 10^{21}$  eV. And for the case of  $E_0 = 10^{21}$  eV, it is possible to say that the numbers of electrons and photons have the same tendency of development as the case for  $E_0 = 10^{22}$  eV above, but definite discussion needs more samples of pre-showers than 10. We cannot find apparent development of pre-shower for the case of primary energy  $E_0 = 10^{20}$  eV. It is very interesting that development of geomagnetic pre-shower would be expressed by the exponential law in this energy region.

## 5.2 Development of air shower with Geomagnetic field

As mentioned in previous sub-section, photons with  $10^{20}$  eV almost never be influenced by the geomagnetic field effect so that almost photons reach the top of the atmosphere without multiplication. Namely, they are expected to be surely influenced by the LPM effect. In figure 7, we give individual developments of ten showers in atmosphere in the presence of geomagnetic field for primary energy of  $10^{20}$  eV. As easily understood from the figure, these shower are fluctuated shower to shower, which indicate influence of the LPM effect over showers. In figure 8 and figure 9, we give the results in the cases of  $10^{21}$  eV and  $10^{22}$  eV, respectively. Compared with Figure 7, these figures show too smaller fluctuation. The geomagnetic field effect is so large in these energy regions that much secondary particles with lower energies, mainly photons, are generated which fall onto the atmosphere. The energies of such secondary particles are rather low where the LPM effect could almost be neglected. Therefore, such showers are the aggregates of the BH showers with smaller energies. This is the reason why showers with  $10^{21}$  eV or more have smaller fluctuation with shower with  $10^{20}$  eV. In energy region where the geomagnetic effect is dominant, the essential structure of air shower are governed by the

energy spectrum produced by pre-shower at the top of the atmosphere. For fixed primary photon energies, the energy spectrum on the top of the atmosphere, are not so fluctuated, even if pre-shower development intermediate state are fluctuated. This is the another reason why air showers are not so fluctuated. We compare our results with results obtained by Kasahara(Kasahara (1996)). In Kasahara's paper, the LPM effect works only less than  $2 \times 10^{19}$  eV, while the LPM effect works even at  $10^{20}$  eV.

*Acknowledgements.* The authors would like to acknowledge to Computer Center of Hirosaki University providing us their computation facility.

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