The LPM showers traversing the atmosphere

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Abstract. We simulate the LPM showers due to Extremely-High-Energy (EHE) neutrinos traversing atmosphere horizontally without colliding with the Earth. We calculate the LPM showers with energies of $10^{17}$ eV to $10^{22}$ eV, using the hybrid method as exactly as possible. Reflecting the complicated change in the air density along the trajectories of the shower developments, the variety of the LPM showers is shown to depend on their starting points and their heights. The EHE LPM showers in atmosphere are exclusively produced by EHE neutrinos. Therefore, the studies on the LPM showers are very important for EHE neutrino astrophysics. As an example, the air fluorescence photon profiles of the LPM showers are also given for the future satellite-based experiment.

1. Introduction
It is well known that the Landau-Pomeranchuk-Migdal (LPM) effect appears strongly in high density material, such as lead and iron [1,2,3]. However, if the energy of primary electron is quite high, the LPM effect could be effective even in lower density material, such as air. In air, the LPM effect becomes effective at energies $\gtrsim 10^{16}$ eV, deviating the Bethe-Heitler (BH) cross sections for bremsstrahlung and pair production. The electromagnetic cascade showers in which the LPM effect is playing an essential role, say, the LPM showers, behave in different way from the BH showers which are governed by the BH cross sections. Namely, (a) the average behavior of the LPM showers shows significant elongation compared with that of the BH shower [4,5,6,7], (b) individual LPM shower development shows multi-peak structure over wider slant depth, which one could not imagine from average profiles [8].

2. Developments of the horizontal showers due to EHE neutrinos
Let us consider the horizontal LPM showers traversing atmosphere without colliding with the Earth. Such LPM showers are possible to be produced by the charged current deep inelastic scattering by EHE neutrinos. Generally speaking, one could expect the LPM showers initiated by EHE electrons produced by the neutrinos, while one could not almost expect the corresponding LPM showers initiated by EHE gamma-rays due to the existence of the magnetic field of the Earth.

The characteristics of the LPM showers traversing atmosphere horizontally with different altitudes of 0, 1, 10 and 20 km have been studied as schematically shown in Figure 1. Hybrid method simulation of electron induced showers with the LPM effect has been performed. Full
Monte Carlo method is utilized at energies \( \gtrsim 10^{16} \text{eV} \) and the subsequent electron showers are replaced with their average ones from the NKG function [9] at energies \( \lesssim 10^{16} \text{eV} \) because the LPM effect could be negligible.

The longitudinal developments of the LPM showers with a height of 1km and energies from \( 10^{17} \text{eV} \) to \( 10^{22} \text{eV} \) are calculated, and five profiles for each energy are shown in Figure 2. The slant depth in the figure is defined from the origin (0kg/cm\(^2\)), where horizontal shower axis crosses the central axis of satellite telescope view as seen in Figure 1. The development of secondary particles is very complicated because the magnitude of the LPM effect depends strongly on air density along shower axis. The LPM shower profiles at energies \( \lesssim 10^{19} \text{eV} \) show less fluctuations, while larger fluctuations are clearly seen among the LPM showers of 10\(^{17}\) to 10\(^{22}\) eV initiated by primary electrons.

Five examples of shower profiles initiated by electrons with an energy of 10\(^{22}\) eV and a different axis height of 0km, are shown in Figure 3. It is easily found that they are of multi-peak structures with much variety because of their longer path length (72kg/cm\(^2\)) compared to that (64kg/cm\(^2\)) shown in Figure 2. In order to examine the influence of air density to the LPM shower profile, we calculate the LPM showers of 10\(^{22}\) eV with a height of 0km and three different starting points of developments, i.e. -35.8kg/cm\(^2\)(the outer edge of the atmospheric shell), -25.9kg/cm\(^2\) and -5.8kg/cm\(^2\) as shown in Figure 4. The LPM showers starting at -35.8kg/cm\(^2\) develop in smaller air density region of atmosphere and their profiles have less fluctuations. On the other hands, the ones starting at -5.8kg/cm\(^2\), traversing dense air region, show their profiles with larger fluctuations.

### 3. Air fluorescence photons from the horizontal showers

We calculate air fluorescence photons from the LPM showers and estimate for the number of arrival photons to the satellite-based fluorescence telescope (EUSO [10]). The horizontal LPM shower profiles of 10\(^{20}\) eV, traversing atmosphere at different heights of 0, 10 and 20km, are shown in Figure 5. Profiles are drawn as a function of slant depth in km instead of kg/cm\(^2\). Here, to come their profiles into a field of view of the telescope with an opening angle of 60° and an orbital height of 400km, starting points in the atmosphere are selected arbitrarily.
Figure 4. The influence of LPM effect to the fluctuation of shower development of $10^{22}$eV due to different air densities.

Figure 5. Three individual LPM shower profiles; $10^{20}$eV and axis heights of 0, 10 and 20km are assumed.

Figure 6. Expected fluorescence photon profiles by the telescope, calculated from shower profiles in Figure 5.

Shower traversing a smaller air density give their developments over longer distance in a unit of km, while shower profiles expressed in kg/cm$^2$ are almost same independent of their heights. The fluorescence photon yield [11] in a unit of photons/m/electron is applied for photon production at 10g/cm$^2$ intervals along the shower development. Rayleigh scattering of photons in the atmosphere is also taken into account. Figure 6 shows the arrival fluorescence photon profiles could be observed by the telescope with an aperture of 4.9m$^2$. In addition to the fluorescence photons, longer tails can be found in the profiles of 10km and 20km, as a contribution of the scattered Cherenkov photons. It is interesting that the LPM shower developed in higher atmosphere (20km), produces larger number of photons in its development than those from showers developed in lower atmosphere (10km or 0km), because the fluorescence photon yield [11] does not depend so much on the atmospheric altitude between 0km and 20km. Therefore, the detection efficiency of the LPM showers developed in higher atmosphere becomes better than that of showers in lower atmosphere even though they have same energies.

From above argument, we could conclude that the EHE LPM showers(i.e. neutrino induced showers) traversing atmosphere horizontally, suffered strongly from the fluctuation as an increase of their primary energies and the characteristics of LPM showers could not be estimated only by the average profiles. It suggests us that individual analysis of individual LPM shower becomes crucial to understand their properties, especially in the highest energy region.

References
[1] Landau L D and Pomeranchuk I J 1953 Dok.Akad.Nauk.SSSR 92 535
[2] Landau L D and Pomeranchuk I J 1953 Dok.Akad.Nauk.SSSR 93 735
[3] Migdal A 1956 Phys.Rev 103 1811
[4] Konishi E, Misaki A and Fujimaki N 1978 Il Nuovo Cimento 44A 509
[5] Misaki A 1990 Phy.Rev.D 40 3086
[6] Misaki A 1990 Il Nuovo Cimento 13C 733
[7] Misaki A 1990 Fort.Schritt.d.Physik 38 413
[8] Konishi E, Adachi A, Takahashi N and Misaki A 1991 Jour.Phys.G 17 719
[9] Greisen K 1956 Progress in Cosmic Ray Physics North-Holland 1 Vol.3
[10] Scarsi L and EUSO collaboration 2005 Proc. 29th ICRC Pune HE1.5.
[11] Nagano M, Kobayakawa K, Sakaki N and Ando K 2004 Astroparticle Physics 22 235