Simulation of horizontal electromagnetic showers in the atmosphere at ultrahigh-energies

Hristofor Vankov, Slav Petrov
Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences
vankov@inrne.bas.bg
(Research report. Accepted on 15.01.2008)

Abstract. We simulate horizontal electromagnetic showers in the atmosphere at ultrahigh-energies (UHE) ($\geq 10^{20} eV$) that start at different slant depths and different heights above sea level. Such showers could be created by UHE neutrinos of astrophysical origin. We show that the geomagnetic field has a noticeable effect on the electromagnetic showers at higher altitudes and has to be accounted for in precise calculations of the shower characteristics.
Key words: electromagnetic showers simulation, neutrino

Симулации на хоризонтални електромагнитни порои в атмосферата при ултрависоки енергии

Христофор Ванков, Слав Петров

Симулирани са хоризонтални електромагнитни порои в атмосферата при ултрависоки енергии ($\geq 10^{20} eV$), започващи на различни дълбочини и височини в атмосферата. Такива порои биха могли да бъдат породени от неутрино от астрофизичен произход. Показано е, че геомагнитното поле забележимо влияе на развитието на пороя на по-големите височини в атмосферата и трябва да бъде взето предвид при прецизното пресмятане на поройните характеристики.

Introduction

After the detection in 1962 of a cosmic ray of energy 10^{20} eV (Linsley [1962]) and the discovery of the microwave background radiation (MBR) four years later it was realized simultaneously by Greisen [1966] and Zatsepin and Kuzmin [1966] that the cosmic ray energy spectrum should end around 5×10^{20} eV due to interactions with photons of MBR (GZK cutoff). The cosmic rays around this energy and higher, ultrahigh energy cosmic rays (UHECR), are very rare - only about 1 event per square kilometer per century per steradian. Now, more than 40 years later the world experimental statistics is still small and mysteries still surround the nature and origin of UHECR.

Because of their very low flux, UHECR are detected by the extensive air showers (EAS) of particles they generate in the atmosphere. The atmosphere acts as a deep calorimeter in which a cascade of huge number of secondary particles, mainly electrons, positrons and photons, develops reaching their maximum and then starts being absorbed. These particles are spread over a large area when they reach the ground. During their propagation in the atmosphere charged shower particles ionize and excite nitrogen atoms and molecules, which emit fluorescence light. The light is emitted isotropically. Charged particles also emit Cherenkov light in a narrow cone along their direction.

UHECR air showers are detected by two methods: ground arrays of particle detectors (scintillators or water Cherenkov tanks) that cover a large area and fluorescence telescopes. Several large arrays explored UHECR during the last 40 years. The largest among them was the Akeno Air Shower Array (AGASA) in Japan (1990 - 2004)(Ohoka et al. [1997]). The High-Resolution Fly's Eye (HiRes) experiment further developed the pioneer Fly's Eye optical detector, which in 1991 observed the event with record energy of 3×10^{20} eV (Bird et al. [1995]). The fluorescent technique is very suitable for detection of UHECR because the shower can be seen from long distances independently from the shower direction. A big advantage of this method is the possibility to observe the shower maximum directly, which gives information about the particle energy and its mass.

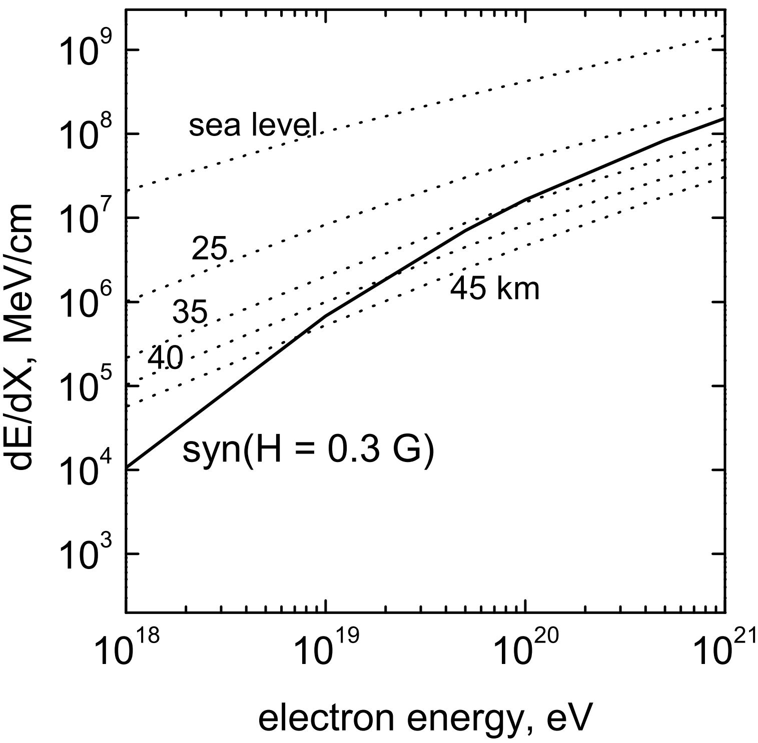

Fig. 1. Electron energy loss rate due to bremsstrahlung as a function of energy at different altitudes in the atmosphere (dotted lines) compared with synchrotron energy loss rate (solid line)

The conflicting results from AGASA and HiRes determined the need of construction of detectors with effective areas in thousands of km^2. The Pierre Auger Observatory (3000 km^2) (Abraham et al. [2004])uses both detection techniques simultaneously (the array is almost fully deployed) and the data set now exceeds that from all other experiments. This first set of results with good statistics supports the conclusion of HiRes about existing of a steepening of the spectrum, which may be consistent with the expected GZK cutoff (Abbasi et al. [2007]). In addition to this, events with energy above 6×10^{19} eV do not arrive to the Earth isotropically showing correlation with the positions of active galactic nuclei (AGN) lying within ≈ 75 Mpc (The Pierre Auger Collaboration [2007]). The last result supports the idea that the UHECR astronomy is possible.

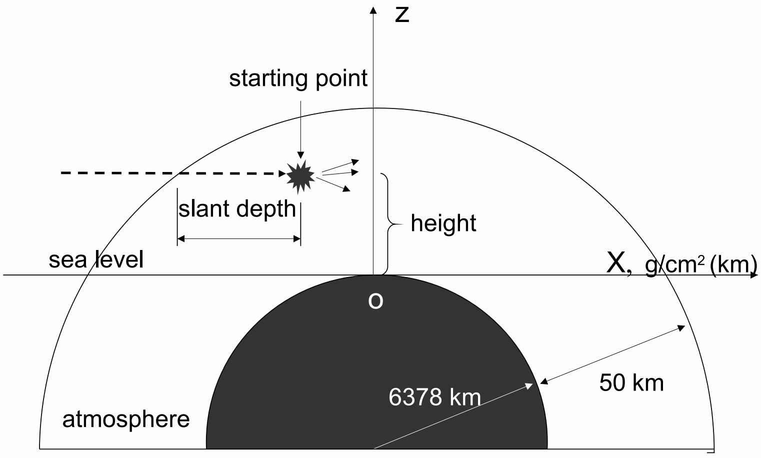

Fig. 2. Schematic view of horizontal atmospheric showers

UHE neutrino detection is one of the most exciting challenges in particle astrophysics. Many models of UHECR origin, in particular the "top-down" models, predict significant flux of astrophysical neutrinos with ultrahigh energies. The study of UHE neutrino flux could help to discriminate these models. The propagating UHECR generate the so-called cosmogenic neutrinos in photoproduction interactions in the photon fields of the Universe. Detection of such neutrinos and a comparison of their fluxes to the direct observations of UHECR would contribute significantly to understand the UHECR origin (Stanev [2007]). Neutrinos do not suffer the GZK effect and do not deflect in magnetic fields pointing back to their sources. Neutrino energy spectrum could extend to significantly higher energies than UHECR. Unlike other primaries neutrinos may carry information about the central part of the cosmic accelerators. This means that neutrino astronomy gives us the possibility to explore the extreme boundaries of the Universe. UHE neutrinos are also a unique opportunity to test fundamental particle physics at energies well beyond current or planned accelerators.

UHE neutrinos can also be detected by produced EAS. Neutrinos interact with nucleons of the atmosphere through deep inelastic scattering creating an electromagnetic plus a hadronic shower. The produced electrons receive $\approx 80\%$ of the neutrino energy in average creating an electromagnetic shower, the reminder is transferred to the target nucleus producing a hadronic shower. Neutrinos have very low interaction probability and create showers deep in the atmosphere, mostly in near horizontal directions, which can be used to distinguish neutrino showers from primary protons and nuclei.

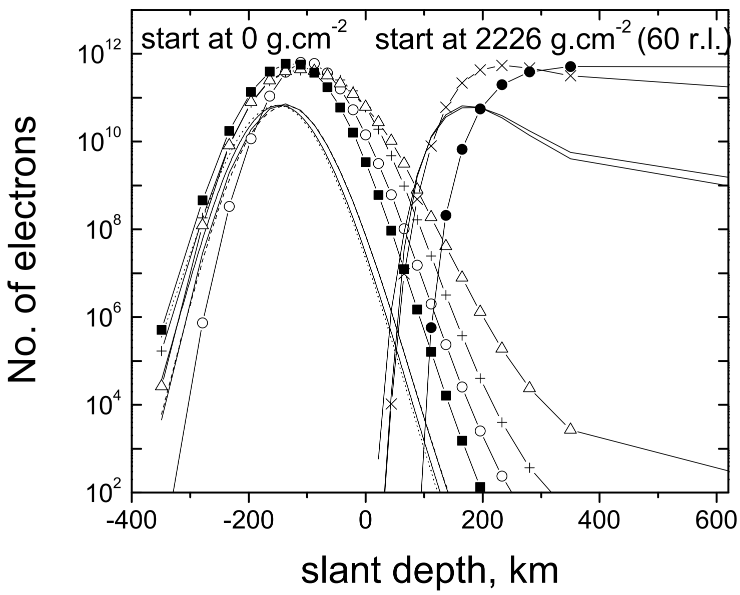

Fig. 3. Longitudinal development of individual horizontal showers from primary electrons of energies 10^{20} eV (solid lines) and 10^{21} eV (lines with symbols) in the atmosphere. Slant depths are 0 and 2226 g/cm^2 (60 r.l.) at 20 km a.s.l.

UHECR are so rare, that even Pierre Auger Observatory with its expected statistic of about 30 events per year is unable to study in detail the GZK energy region and higher energies. New bigger experiments are planned like JEM-EUSO [2007] and TUS (Tkatchev et al. [2007]) - spaced-based observatories which use the whole earth as a detector. They will monitor gigantic volume of the atmosphere from space orbit at altitude of ≈ 400 - 600 km and detect fluorescent and Cherenkov light from EAS with different directions in the atmosphere. The instantaneous aperture of JEM-EUSO is larger than that of Pierre Auger Observatory by a factor of 56 - 280.

1 Results and discussion

The aim of this work is to study the longitudinal development of electromagnetic showers at UHE that penetrate the atmosphere in horizontal direction at different altitudes starting at different slant depths. Simulations of EAS at ultra-high energies are difficult task due to the huge number of followed particles. Widely used simulation codes are designed for cosmic ray experiments and it is not a routine task to adapt them for modeling of horizontal or up going showers. Our simulation code for one-dimensional Monte Carlo modeling of EM shower is simple and flexible allowing easy modifying of the geometry. Important feature of electromagnetic showers at UHE is the influence of the Landau-Pomeranchuk-Migdal (LPM) effect (Landau and Pomeranchuk [1953]), (Migdal [1956]), which depends on the air density.

In (Vankov et al. [2003]) we showed that the geomagnetic field has also a noticeable effect on the UHE electromagnetic shower development in the atmosphere. The effect is stronger at high altitudes and increases with shower energy. If we define the break-even points as altitudes where matter and magnetic field effects are the same (Erber [1966]), one can see from Fig.1 that the synchrotron energy loss rate starts to compete with bremsstrahlung energy loss at energies $\geq 10^{18} eV$ 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 above sea level (a.s.l.) for a magnetic field of 0.35 G. The photons have also a chance to create a pair through magnetic pair production process but the probability for this sharply decreases when the photon energy decreases. As a result the magnetic field affects the shower development mostly through synchrotron radiation and accelerates shower development. This must be taken into account in simulations that aim at accuracy of 10% and better.

2 Simulation

We follow the longitudinal shower development by direct simulation that includes the LPM effect down to threshold energy E_{thr}, bellow which the LPM effect is not effective. In our simulations $E_{thr} = 10^{16}$ eV. Because the LPM effect depends on the air density we divid the 50 km thick atmosphere to 100 layers with equal thickness of 500 m each assuming constant density within the layer. The differential cross sections for bremsstrahlung and pair production are tabulated for each layer. The subtreshold particles are replaced by

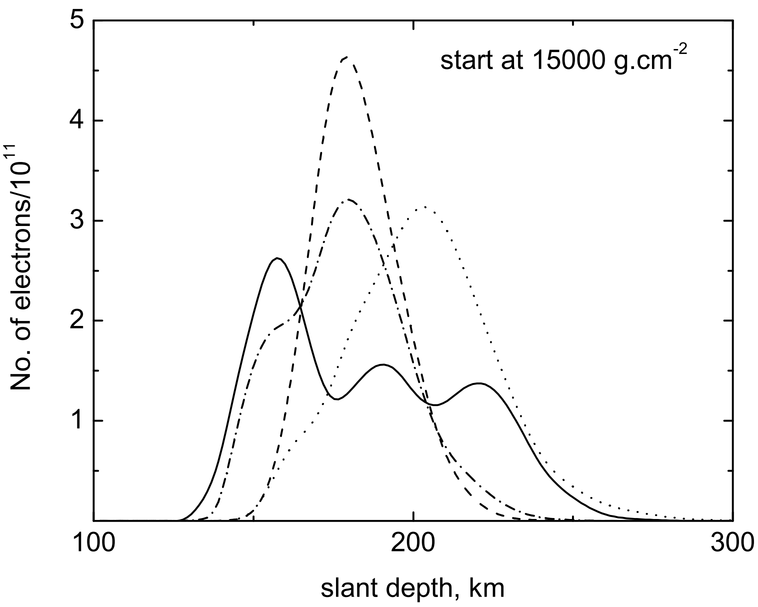

Fig. 4. Sample of shower profiles from primary electrons of energies 10^{21} eV in the atmosphere. Slant depth is 15000 g/cm^2 at 10 km a.s.l.

analytical approximation of shower profile.The particle creating a shower is an electron injected at different slant depths and different altitudes in the atmosphere.

To investigate the geomagnetic field effects on the shower development the code includes magnetic pair production and synchrotron radiation processes. We assume that the geomagnetic field strength (normal component) H is constant along the shower axis. Showers start at different slant depths and heights in the atmosphere and traverse it as shown schematically in Fig.2. Axis Z points to the position of the possible space detector.

Several individual shower profiles (the electron number in the shower as a function of the depth) created by 10^{20} eV and 10^{21} eV electrons are shown in Fig.3. Electrons are injected at two slant depths and traverse the atmosphere at 20 km altitude. The geomagnetic field is not taken into account.

At this height, when the primary particle is injected at the atmospheric boundary (0 g/cm^2 slant depth), the LPM effect do not affect much the shower development even for primary energy of 10^{21} eV. These showers start in the highest and very rarefied atmospheric layers, where the E_{LPM} is close

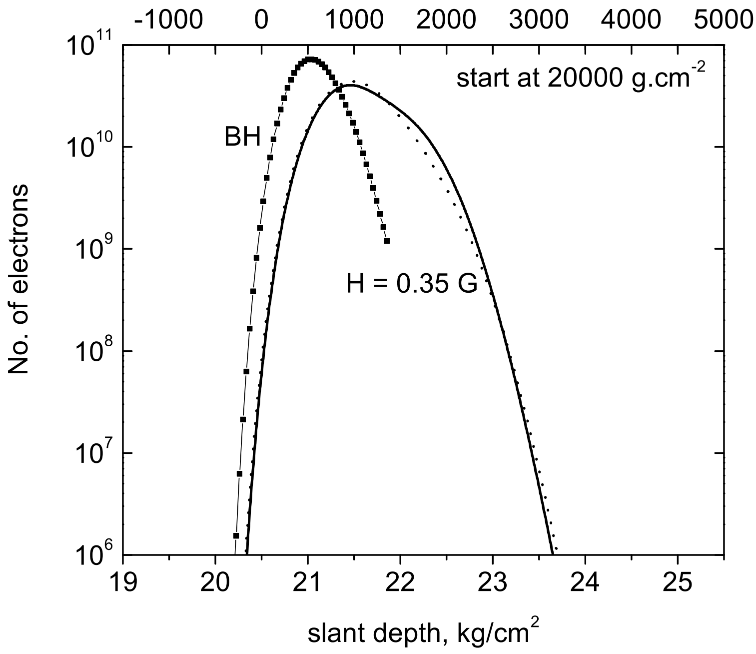

Fig. 5. Mean shower profiles for primary electrons with energies 10^{20} eV with (dotted line) and without geomagnetic field (solid line) in the atmosphere. Slant depth is 20000 g/cm^2 at 5 km a.s.l. Line with symbols is for BH showers (see the text). Top x-axis corresponds to the coordinate system as in Fig.2 and is in units of g/cm^2, the bottom x-axis is measured in kg/cm^2 starting from the atmospheric boundary.

to 10^{21} eV. E_{LPM} is defined (Stanev et al. [1982]) as the energy above which the LPM effect is significant. For example, at 20 km a.s.l. (vertically) $E_{LPM} \approx 2.7 \times 10^{19}$ eV. However, the effect becomes stronger, especially for 10^{21} eV showers, starting deep in the denser atmospheric layers. The individual shower profiles fluctuate much stronger. The shape of these profiles after the maximum is determined by the fact that the slant depth is measured in km, not in mass units (g/cm^2) and the shower attenuates in much more rarefied air. At 20 km altitude the chord length in the atmosphere is 4451 g/cm^2 or 1240 km. Important feature of shower development with strong influence of the LPM effect are significant fluctuations of shower profiles and multi-peak structure. It is clearly seen in Fig.4 where a sample of several shower profiles for 10^{21} eV primaries in denser atmosphere is plotted.

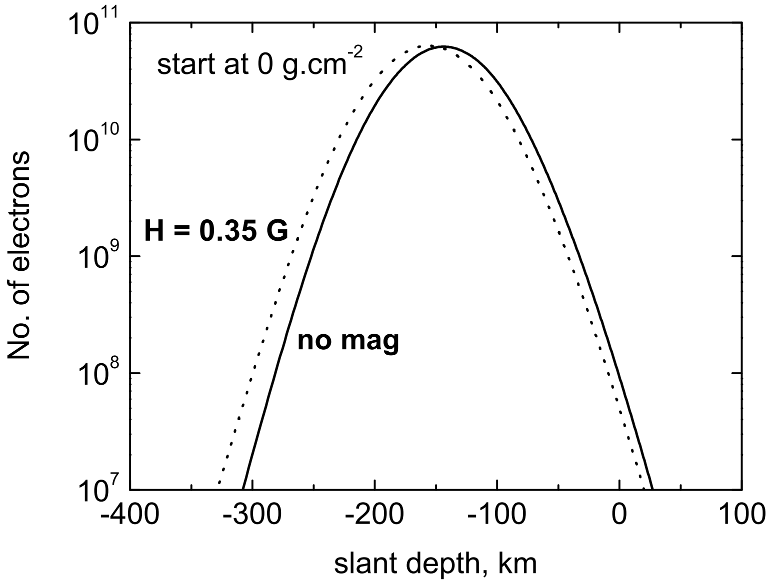

Fig. 6. Mean shower profiles for showers from primary electrons of energies 10^{20} eV with (dotted line)and without geomagnetic field (solid line) in the atmosphere. Slant depth is 0 g/cm^2 at 20 km a.s.l.

Fig.5 shows the mean shower profile at 5 km a.s.l. simulated with the geomagnetic field taken into account. At this altitude the atmosphere thickness is 41000 g/cm^2. The parent electron of 10^{20} eV energy is injected at 20000 g/cm^2 slant depth, which is very near to the Z–axis (see Fig.1). This means that the shower starts and develops in dense atmospheric layers. The impact of the geomagnetic field is negligible, the influence of the LPM effect is strong, which is seen from the comparison with showers simulated with Bethe-Heitler (BH) cross-sections. The shape of the shower profiles have their characteristic form because the slant depth is measured in $g.cm^{-2}$. The length of the shower is about 60 km.

The mean shower profile for 10^{20} eV electrons injected at the atmospheric boundary and traversing the atmosphere at 20 km a.s.l. with and without geomagnetic field are shown in Fig.6. For simplicity the normal field component H is set constant and equal to 0.35 G. As seen from the figure, the geomagnetic field affects noticeably the shower in this case. Magnetic field accelerates the shower development shifting its maximum position by ≈ 20 km. Effect becomes stronger when the shower develops higher in the atmosphere, as can be seen from the Fig.7. In this case, 30 km a.s.l., however,

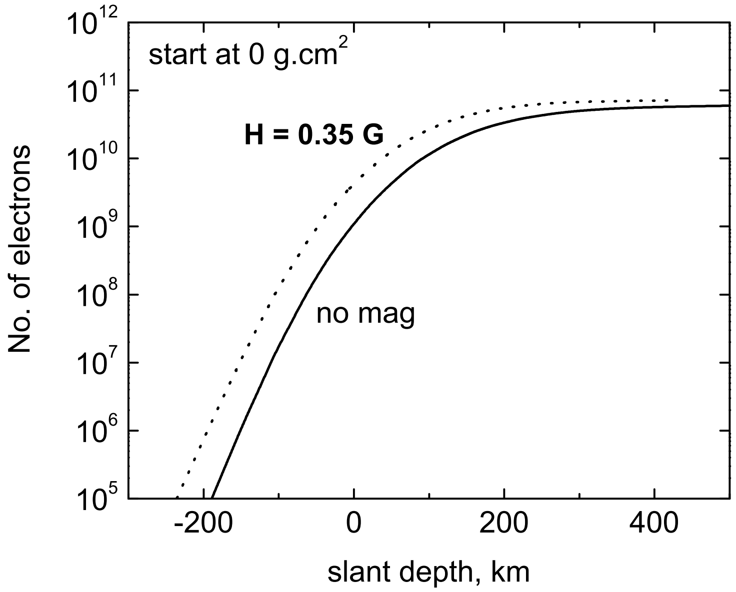

Fig. 7. Mean shower profiles for showers from primary electrons with energies 10^{20} eV with (dotted line)and without geomagnetic field (solid line) in the atmosphere. Slant depth is 0 g/cm^2 at 30 km a.s.l.

the chord length in the atmosphere is only 922 g/cm^2(1240 km) which is not enough for the full shower development at 10^{20} eV. At 30 km a.s.l. (vertically) $E_{LPM} \approx 1.8 \times 10^{20}$ eV and the impact of the LPM effect is negligible.

Our results (without magnetic field effects taken into account) are in good agreement with similar simulations performed by (Wada, et al. [2006]).

Conclusion

We have presented results from one-dimensional simulations of electromagnetic showers at UHE traversing the atmosphere horizontally at different altitudes. Showers at higher altitudes ($>$ 10 km) spread at hundred kilometers. The LPM effect affects the shower development at energies $> 10^{20}$ eV and the influence of the geomagnetic field is noticeable. In lower and denser atmospheric layers the magnetic field effects cannot compete with matter bremsstrahlung and the impact of the geomagnetic field can be neglected. Here the LPM effect is significant leading to strong fluctuations and multipeak structure of the shower profiles.

References

Abbasi, R.U., Abu-Zayyad,T, M. Allen, M. et al., 2007, *arXiv:astro-ph/0703099*
Abraham, J., et al., 2004, *NIM A523, p.50*
Bird, D.J., Corbato, S.C., Dai, H.Y. et al., 1995, *Astroph.J. 441 p.144*
Erber, T., 1966, *Rev.Mod.Phys. 38, p.626*
Greisen, K., 1966, *Phys.Rev.Lett. 16 , p.748*
JEM-EUSO, *http://jemeuso.riken.jp*
Landau, L., Pomeranchuk, I., 1953, *Dok.Akad.Nauk SSSR 92, p.535 and p.735*
Linsley, J., 1962, *Phys.Rev.Lett. 10, p.146*
Migdal, A.B., 1956, *Phys.Rev. 103 , p.1811*
Ohoka, H., Takeda, M., Hayashida, N., et al., 1997, *NIM A385, p.268*
Stanev, T., 2007, *arXiv:0711.1872[astro-ph]*
Stanev, T., Vankov, Ch., Streitmatter, R.E., et al., 1982, *Phys.Rev. D25 , p.1291*
The Pierre Auger Collaboration, 2007, *Science 318 (5852), p.938*
Tkatchev, L., Abrashkin, V., Alexandrov, V., et al., 2007, *In Proc.30th ICRC, Merida, Mexico*
Vankov, H., Stanev, T., Inoue, N. et al., 2003, *In Proc. 28th ICRC, p.523*
Wada, Y., Kato, M., Inoue, N., and Misaki, A., 2006, *J.Phys.Conf.Ser. 39, p.432*
Zatsepin, G., Kuzmin, V.,1966, *JETP Lett. 4, p.78*