Cascades initiated by EHE photons in the magnetic field of the Earth and the Sun

W. Bednarek
Department of Experimental Physics, University of Łódź,
90-236 Łódź, ul Pomorska 149/153, Poland
bednar@krysia.uni.lodz.pl

Abstract

The content of extremely high energy (EHE) photons in the highest energy cosmic rays can be investigated by analyzing showers arriving from directions where the perpendicular component of the Earth’s magnetic field is high or showers arriving from the region surrounding the Sun. We perform Monte Carlo simulations of cascades initiated by photons with parameters of the highest energy showers observed by the past and present detectors (AGASA, Fly’s Eye, Yakutsk, Haverah Park). The purpose is to find out which events should cascade with high probability if initiated by photons. It is shown that EHE photons arriving from directions towards the magnetic poles cascade with higher probability. Alternatively, the lowest probabilities of cascading are expected for photons arriving from directions of the equator at the zenith angles equal to the angle between location of the specific observatory and the magnetic pole. We show that very unusual showers should arrive from direction of the Sun due to cascading of photons in the Sun’s magnetosphere if EHE photons are numerous at the highest energies. The rate of such showers is estimated on about one per ten years. However extraordinary lateral distribution of secondary particles of such showers in the Earth’s atmosphere may help to distinguish them from the ordinary showers arriving isotropically from the sky.

PACS: 95.85.Pw; 96.40.Pq; 96.40.-z; 98.70.Rz; 98.70.Sa

Key words: Cosmic rays; γ-rays; Extensive air showers
1 Introduction.

The spectrum of cosmic rays shows very interesting and unexpected features at the highest energies. Different experiments report a change in the spectral slope at $\sim 10^{19}$ eV which is usually interpreted as a transit from Galactic to extragalactic origin. This hypothesis is supported by the recent observations of significant enhancements of cosmic rays from the direction of the galactic plane at energies $(0.8 - 2.0) \times 10^{18}$ eV [1, 2] and the lack of anisotropy above $10^{19}$eV [3]. Such an explanation for the change in the spectrum at $\sim 10^{19}$ eV is also consistent with reports of the Fly’e Eye group on the change of composition of cosmic rays from heavy to light at energies above $10^{18}$ eV [4] (see also the conclusions based on the AGASA data [5] and their re-analysis [6]). If the highest energy cosmic rays are extragalactic, then they cannot travel from cosmological distances because of their interaction with the microwave background radiation (MBR). The propagation distances of heavy nuclei on fragmentation in the MBR have been recently re-calculated by Stecker & Salamon [7] and Epele & Roulet [8] (see the references therein for earlier calculations). Protons with energies above $5 \times 10^{19}$ eV produce charged and neutral pions in collisions with the MBR photons. The neutral pions decay in turn into photons. Since the propagation distances of hadrons are relatively short (a few tens of Mpc), it is expected that the spectrum of cosmic rays above $5 \times 10^{19}$ eV should decline (so called the Greisen-Zatsepin-Kuz’min cut-off [9, 10]). Such a cut-off in the spectrum is not found in the recent AGASA data [11]. However an interesting small deficit of particles at around $10^{20}$eV is noted by Takeda et al. [11]. It may suggest the emergence of a new component in the spectrum above $10^{20}$ eV.

EHE photons with energies $\sim 10^{20}$ eV are also absorbed in collisions with MBR on a distance scale of the order of several Mpc. This is comparable to the propagation distances of protons with such energies. However the propagation distances for photons above $10^{20}$ eV decreases but the propagation distances of protons do not change significantly. If the strong radio background exists[12], the propagation distances for photons becomes longer than that ones for protons at energies greater than $\sim 10^{21}$ eV. The number of photons at energies above $10^{19}$ eV may be significant from two reasons. EHE cosmic ray protons, distributed uniformly in the Universe, produce many photons in collisions with the MBR photons [13, 14]. The EHE photons can be also efficiently produced from decay of massive particles (e.g. Higgs and gauge bosons), as predicted by some more exotic theories (see [15] and references therein). Interestingly, this last model predicts that a new component in the cosmic ray spectrum should emerge above $\sim 10^{20}$ eV, composed mainly from photons and neutrinos.

Since the number of photons at the highest energy cosmic rays may be high, it is reasonable to discuss the consequences of assumption that the observed highest energy showers are due to the interaction of photons. However photons with such energies should interact at first with the dipole magnetic field of the Earth. In this paper we compute the cascades initiated by EHE photons using the parameters of the highest energy showers observed by the present and past detectors. Moreover, we investigate the effects of cascading of EHE photons at the locations of the Southern and Northern Auger Observatories. The detailed investigation of the parameters of
the showers observed by these detectors (the arrival directions, energies) should give us information about the possible content of photons in the EHE cosmic rays.

The magnetic field of the Sun is about an order of magnitude stronger than that of the Earth. Therefore detection of secondary photons from cascades initiated in the magnetic field of the Sun can allow an investigation of the photon content in the EHE cosmic ray spectrum at energies about an order of magnitude lower, provided that a large enough detector of cosmic ray showers is available. We calculate the cascades initiated by photons in the magnetic field of the Sun and discuss the possibility of detection of extraordinary showers in the Earth’s atmosphere produced by the secondary photons from these cascades by the Auger Observatories.

2 Magnetic $e^\pm$ pair cascades.

An EHE photon with energy $E_\gamma$ can convert into an $e^\pm$ pair in the magnetic field $B$ if the value of the parameter $\chi_\gamma = (E_\gamma/2mc^2)(B/B_{cr})$ (where $B_{cr} \approx 4.414 \times 10^{13}$G and $mc^2$ is the electron rest mass) is high enough [16]. The secondary $e^\pm$ pairs produce in turn synchrotron photons in the magnetic field. For the electrons with the highest energies expected, the synchrotron photons are produced in the quantum domain and the efficiency of the process is determined by energy of the electron and the parameter $\chi_e = (E_e/mc^2)(B/B_{cr})$. The energies of synchrotron photons can be high enough to produce the next generation of $e^\pm$ pairs. We simulate the development of such a cascade by using the Monte Carlo method and applying the exact quantum mechanical rates for $e^\pm$ pair production by $\gamma$-ray photon and synchrotron emission by secondary $e^\pm$ pairs as given by Baring [17]. In Fig. 1, we compare the Baring’s rates with the approximate Erber’s rates [16] for conversion of a photon into an $e^\pm$ pair and for emission of synchrotron photons by an electron (positron) by calculating the probabilities of production of $e^\pm$ pair with energy below $E_e$ and the probabilities of emission of synchrotron photons with energies below $E_{syn}$. The top figures show the results for conversion of a photon into an $e^\pm$ pair and the bottom figures for emission of synchrotron photons by an electron. Significant differences between the Baring’s and the Erber’s rates are evident for large values of $\chi_\gamma$ and $\chi_e$. The Erber’s rates give on average lower energy $e^\pm$ pairs from conversion of photons and lower energy synchrotron photons from electrons. Therefore, the cascades calculated with the Baring’s rates are more penetrating. Note that for the surface magnetic fields typical for the Earth and the Sun and for energies of events which may be detected by the Auger Observatory, the parameters $\chi$ can reach values above ten.

In Fig. 2 we show the mean free path for conversion of photons with energy $E_\gamma$ into $e^\pm$ pairs in a perpendicular magnetic field with strength 0.3 G (full curve) and for production of synchrotron photons by electrons (positrons) with energy $E_e$ in this same magnetic field (dashed curve). The mean free paths for other magnetic fields can be obtained from Fig. 2 by simple linear scaling of the present computations (shift to the left and down for stronger magnetic field). For example, the mean free paths in the magnetic field of 3 G (a value typical near the surface of the Sun) for photons with energies $10^{20}$ eV are $\sim 7$ km and for the production of synchrotron photons by electrons with energy $10^{18}$ eV are $\sim 0.38$ km. Photons must have energies
above $\sim 3 \times 10^{19}$ eV in order to cascade efficiently in the Earth’s magnetic field with $B = 0.3$ G (the limit obtained from comparisons of the photon mean free path with the radius of the Earth). For the Sun this minimum photon energy is $\sim 2 \times 10^{18}$ eV for $B = 3$ G.

3 Photons cascading in the magnetic field of the Earth.

The magnetic field of the Earth is strong enough so that photons with energies corresponding to energies estimated for the highest energy atmospheric showers have chance to be converted in the magnetic field into $e^\pm$ pair. These effects of cascading of EHE photons have been already generally discussed some time ago [18, 19]. More recently general analysis of the interaction of EHE cosmic ray photons with energies $> 10^{20}$ eV with the Earth’s magnetosphere has been performed by Karaku /suppress la et al. [20, 21, 22] and by others [23, 24]. These authors use some simplifications (e.g. for the cross sections of pair production and synchrotron emission, or neglect the inclination of the magnetic axis in respect to the Earth rotational axis). Specific showers are not analyzed in these papers under the hypothesis of their photonic origin. These authors do not discuss also what effects of cascading should we expect for the sites of both planned Auger Observatories. In this section we analyze the cascades in the Earth’s magnetosphere initiated by photons with energies and arrival directions of the showers observed by the Haverah Park, Yakutsk, AGASA arrays and Fly’s Eye detector. The results of this work will create an input for further analysis of cascades in the Earth’s atmosphere under the hypothesis that these events are caused by photons. We expect that inclusion of effects of cascading in the Earth’s magnetosphere may have impact on the estimation of the primary energy of photons responsible for these events. We predict the efficiency of cascading of photons arriving to the locations of both Auger Observatories and localize the regions on the sky with the lowest and highest probability of cascading.

For the magnetic moment of the Earth we use the value $8 \times 10^{25}$ G cm$^3$. The co-ordinates of the North Magnetic Pole are the following: longitude $108^\circ$ and latitude $77.5^\circ$ (for the year 1980).

3.1 Photons with energies of the observed EHE cosmic rays.

We simulate the cascades initiated by photons with energies and arrival directions of the highest energy events observed by the air shower detectors at different geographic locations, i.e. the Haverah Park event with an energy of $1.59 \times 10^{20}$ eV [25], the Yakutsk event with an energy of $2.3 \times 10^{20}$ eV [26, 27], the AGASA event with an energy of $2.1 \times 10^{20}$ eV [28, 11], and the Fly’s Eye event with an energy of $3.2 \times 10^{20}$ eV [29]. The number of secondary $\gamma$-rays produced per $\Delta(logE_\gamma) = 0.1$ in these cascades are shown in Fig. [3]. The spectra marked by the thick full histogram are averaged over 100 primary photons and the spectra with the smallest and highest numbers of secondary photons, selected from these 100 simulations, are marked by
the dotted and thin full histograms, respectively. It is evident that fluctuations of the total number of secondary photons produced in these cascades are large, of the order of $3 \pm 4$ around the average value. Photons with energies of these highest energy events cascade with high probability, although photons with the parameters of the AGASA event may not cascade at all with the probability $\sim 3\%$. In all cases a significant part of energy of primary photon is still carried by the secondary photons with energies above $10^{19}$ eV. On average, 6 photons produced in the case of primary photon with the parameters of the Fly’s Eye event carry $\sim 31\%$ of total energy of the event. In the case of other events these numbers are: the Haverah Park event - 3.3 photons and $\sim 34\%$, the Yakutsk event - 3.9 photons and $\sim 25\%$, and the AGASA event - 4.6 photons and $\sim 41\%$.

In Fig. 4 we show the probability ($\Delta N/\Delta \log(R/R_Z)$) of the first interaction of photons with parameters of these highest energy events as a function of distance from the Earth’s surface $R$ in units of the radius of the Earth $R_Z$. Additionally, we show such probability for the supposed event with direction of the highest energy Fly’s Eye event but with energy $10^{21}$ eV. Photons with parameters of all observed events have the highest probability of first interaction at the distance closer than one radius of the Earth. The event with energy $10^{21}$ eV will have the highest probability of interaction at the distance of $1 - 1.1$ radii of the Earth. Therefore, we conclude that our assumption on the dipole magnetic field structure of the Earth’s magnetosphere is correct since the effects of interaction of the Solar wind with the Earth’s magnetic field are important at distances $\sim 8 - 10R_Z$.

In order to have an idea about the importance of cascading effects which might be observed by different experiments under the assumption that the highest energy cosmic rays are photons, we estimate the probability of interaction of photons taking into account the parameters of the larger number of the highest energy events. These probabilities are given in Table 1 for photons with the parameters of ten highest energy events observed by the AGASA array [11]. The specific event in this table is characterized by the date of detection, its energy, the zenith angle $Z$, the azimuth angle $A$, and the angle to the magnetic axis $\phi$. The azimuth angles are measured clockwise from the North Magnetic Pole and are recalculated based on the information from Table 2 in Takeda et al. [11]. As we can see in Table 1, the probability of interaction depends not only on the event energy but also on the arrival direction. Therefore, the events with energies even below $10^{20}$ eV (e.g. the events with energy $9.8 \times 10^{19}$ eV and $9.1 \times 10^{19}$ eV), which arrive from the Northern direction, have a higher probability of cascading than the highest energy events detected by the AGASA array. Moreover, the probability of interaction of photons arriving from the Southern direction may change significantly if the arrival directions of photons differ by several degrees. Therefore, the photon with the parameters of the second highest energy event has low chance of cascading in the Earth’s magnetosphere (the estimated probability of cascading is only 0.04). The cascades in the atmosphere initiated by these two highest energy AGASA events, if photonic in nature, should have significantly different depths of the maximum in the Earth’s atmosphere because of the influence of the Landau-Pomeranchuk-Migdal effect [30, 31, 32]. Similar computations of the probability of interaction of photons with the parameters of ten highest energy events detected by the Haverah Park array
are shown in Table 2. Again, the photons arriving from the Southern direction may have significantly different probability of interaction even if their arrival direction differ by $\sim 20^\circ - 30^\circ$ degrees (see events with energies $1.26 \times 10^{20}$ eV, $1.16 \times 10^{20}$ eV, and $9.9 \times 10^{19}$ eV). These conclusions will be discussed further in the case of locations of the Auger Observatories (see section 3.2).

### 3.2 Cascades initiated by photons at locations of the Auger experiment

The geographic latitudes of the planned Southern and Northern Auger Observatories are similar but their locations with respect to the magnetic axis (angles equal to $\alpha_{\text{SAO}} \approx 66^\circ$ for the Southern Observatory and to $\alpha_{\text{NAO}} \approx 38^\circ$ for Northern Observatory) differ by about $28^\circ$. Therefore, it is expected that EHE photons arriving from specific directions to the locations of the Southern and Northern Auger Observatories should initiate cascades in the magnetosphere with different characteristics. In order to have an idea about the efficiency of cascading, we compute the values of the perpendicular component of the magnetic field along different directions of motions of primary photons, defined by the azimuth and zenith angles (see Fig. 5).

In general, the dependence of the magnetic field on direction is quite complicated. The characteristic cusps at certain directions correspond to distances from the observatories at which the magnetic field is oriented along the direction of primary photon. The perpendicular component of the magnetic field reaches the lowest values for direction towards the Equator (the azimuth angle $\phi = 180^\circ$) and the zenith angles corresponding to the values of the angles between the location of the specific observatory and the magnetic pole ($Z = \alpha_{\text{SAO}}$ or $Z = \alpha_{\text{NAO}}$). The strongest perpendicular component of the magnetic field is met in directions towards the magnetic poles. Our results are not consistent with the conclusions presented in [23]. It is shown in that paper in Fig. 3 that the array on the Northern hemisphere sees the strongest magnetic field from the Southern direction. We localize the region of the lowest magnetic field with the Southern direction and at the limited values of the zenith angles (between $0^\circ$ and $\alpha_{\text{mag}}$). This result has not been found in previous calculations. According to our calculations the highest energy events observed by the AGASA array [3] come from directions where the perpendicular component of the Earth’s magnetic field is relatively low and the cascading effects of photons should be less efficient in comparison to other directions.

In order to confirm our expectations, which base on the analysis of the magnetic field profiles, we present in Fig. 6 and 7 the results of simulations of cascades initiated by primary photons with energies $10^{20}$eV (figures (a) and (b)) and $3 \times 10^{20}$eV (figures (c) and (d)) arriving to the location of the Southern Auger Observatory from zenith angles $Z = 75^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ$ and $0^\circ$ and azimuth angle $\phi = 0^\circ$, measured clockwise from the North Magnetic Pole (full histograms from the thickest to the thinnest in figures (a) and (c)), and from zenith angles $Z = 75^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ$ and azimuth angle $\phi = 180^\circ$ (histograms in figures (b) and (d)). Figures show the numbers of secondary photons per $\log E_{\gamma} = 0.1$ averaged over 100 simulated primary photons. In fact, the strongest cascading effects (the higher numbers of secondary photons) occur at the highest zenith angles in direction towards the
magnetic poles (see Figs. 6a,c, and 7a,c). Alternatively, photons with energies \(10^{20}\) eV arriving from the South at zenith angles 15° and 30° do not cascade at all (see Figs. 6b and 7b). Note also that photons with energies of \(3 \times 10^{20}\) eV arriving to the Northern Auger Observatory at zenith angles \(Z = 15°\) cascade more efficiently than these ones arriving at angles \(Z = 30°\) (Fig. 7d). These features are consistent with the conclusions obtained from the analysis of the magnetic field profiles. It is evident that the weakest cascading effects are for photons arriving from directions at zenith angles somewhat smaller than the zenith angles \(Z = \alpha_{SAO}^{\text{mag}}\) and \(\alpha_{NAO}^{\text{mag}}\). This is due to the fact that the perpendicular component of the magnetic field at large distances along these directions from the observatories is higher than for direction defined by \(Z = 0°\) (compare the dot-dashed and dot-dot-dot-dashed curves with full curves in Fig. 5). In Fig. 8 we compare also the average numbers of secondary photons (results averaged over 100 simulated primary photons) from cascades initiated by primary photons arriving randomly from the sky to both Auger Observatories. Although as we show above, there are significant differences between photons arriving from specific directions, on average the differences between averaged cascade spectra produced by photons arriving randomly from the sky to these two Observatories should be rather small.

The secondary photons, produced in cascades in the Earth’s magnetosphere, enter the atmosphere within a very small cone. Based on deflection of the secondary \(e^\pm\) pairs in the Earth’s magnetic field during development of the cascade, we estimate the radius of this cone on a few centimeters. Therefore cascades initiated by separate secondary photons produced by this same primary photon are indistinguishable. However, cascades initiated by secondary photons in the atmosphere should differ significantly from cascades initiated by primary photons arriving from directions with small values of perpendicular magnetic field because of the negligible influence of the Landau-Pomeranchuk-Migdal (LPM) effect on the development of the photon induced showers with energies below \(\sim 10^{19}\) eV (see e.g. [24]). Therefore the showers initiated by photons arriving to the Auger Observatories from directions of the Equator and at the zenith angles between \(\alpha_{mag}^{\text{SAO}}\) (and \(\alpha_{mag}^{\text{NAO}}\)) and the zenith should have a significantly larger depth of the maximum. We plan to study these effects in details in the future paper.

4 Photons cascading in the magnetic field of the Sun.

The Sun has a large scale dipole magnetic field with the value on the surface about an order of magnitude higher than the Earth. Therefore it is expected that photons with energies about an order of magnitude lower should already interact with the Solar magnetic field. The dipole magnetic moment of the Sun is \(M_s \approx 6.87 \times 10^{32}\) G cm\(^3\). We neglect the influence of the active regions on the Sun’s surface (hot spots) with 2-3 orders of magnitude stronger magnetic field, since they dominate only in the Solar chromosphere.

We consider the problem of whether or not secondary photons from cascades initiated by EHE primary photons in the magnetic field of the Sun can be observed by...
detection of showers in the Earth’s atmosphere. The motion of primary photon in the Sun’s magnetosphere is defined by the impact parameter $s$ and the angle $\phi$ between the photon path and the magnetic axis. We investigate the cascades initiated by primary photons which enter randomly within a circle of radius $s$ around the Sun. The number of secondary photons, per $\Delta \log E_{\gamma} = 0.1$, from cascades initiated by primary monoenergetic photons with energies $10^{19}$ and $10^{20}$ eV, injected randomly within the circles $s = 1.5, 2$ and $3r_s$ around the Sun (where $r_s$ is the radius of the Sun) are shown in Figs. 9a,b by the thick, middle, and thin histograms, respectively. These results are averaged over 100 simulated primary photons in the case of primary photons with energy $10^{19}$eV, and over 10 simulations in the case of photons with energy $10^{20}$ eV. All primary photons with energies $10^{19}$ eV injected within the circle $s = 1.5r_s$ from the Sun cascade but only a fraction of such photons interact if injected within larger circles (61% for $s = 2r_s$, and 33% for $s = 3r_s$). All primary photons with energies $10^{20}$ eV cascade if injected within the considered range of the parameter $s$.

Let us again consider possibility that EHE cosmic ray spectrum $> 10^{18}$ eV contains significant proportion of photons. We compute the spectra of secondary photons from cascades initiated by primary photons, with the cosmic ray spectrum observed at the highest energies ($\propto E^{-2.7}$, see e.g. [33]), in the magnetosphere of the Sun. These photons are injected randomly within a certain circle $s$ around the Sun. In Fig. 10a, we show the spectra of secondary photons (multiplied by the photon energy squared) from cascades initiated by primary EHE photons injected within $s = 1.5, 2, 3r_s$ (from the thickest to thinnest histograms respectively). It is assumed that the primary photon spectrum extends up to $E_{\text{max}} = 3 \times 10^{20}$ eV. It is normalized to the observed cosmic ray spectrum at $10^{19}$ eV. The observed cosmic ray spectrum at energies above $10^{14}$eV and the spectrum of injected primary photons are marked in this figure by the dashed and dotted curves, respectively. As expected, the spectrum of primary photons cut-offs at lower energies for smaller impact parameters (defined by $s$), as a result of cascading in the Sun’s magnetic field. For the circle around the Sun defined by $s = 1.5r_s$, photons with energies above $\sim 10^{19}$eV should not be observed, but for $s = 3r_s$ only photons with energies above $\sim 10^{20}$eV are absorbed. In Fig. 10b we show that the spectrum of secondary photons is almost independent on the cut-offs in the primary spectrum. However such dependence may be present if the spectrum of primary photons above a few $10^{20}$eV flattens considerably as predicted by some exotic theories of cosmic ray origin [15].

The solid angle corresponding to a circle with the radius $2r_s$ around the Sun is equal to $\Delta \Omega = 3r_s^2/4r_{s-z} \approx 1.6 \times 10^{-5}$ sr (Sun disk discounted), where $r_{s-z}$ is the distance of the Earth from the Sun. Therefore the chance of detection of a particle with energy $> 10^{19}$eV from the direction of the Sun by the present (and past) detectors is very low. The number of events which will be detected by both Auger Observatories can not be precisely predicted, since the spectrum of cosmic rays at the highest energies is not well known. We assume, following Boratav [34], that both Auger Observatories will observe several thousands events $> 10^{19}$ eV during one year of operation. The number of such events from the circle of $2r_s$ around the Sun observed by both Auger Observatories can be estimated from

$$N = k \Delta \Omega N_{AO} \approx 1.2 \text{ events per 10 years}$$

(1)
where $k \approx 0.5$ is the part of the sky observed by the Auger Observatories, and $N_{AO} \approx 15000$ is the number of events which are likely to be observed by the Auger Observatories above $10^{19}$ eV. Therefore, we should expect some events from the direction of the Sun during years of operation of the Auger Observatories. If photons dominate the cosmic ray spectrum above $\sim 10^{19}$ eV, the secondary photons from their cascades in the Sun’s magnetosphere arrive to the Earth’s atmosphere with the significant perpendicular extent which is the result of deflection of paths of the secondary electrons by the Sun’s magnetic field. Using our cascade code we have estimated this perpendicular extent by counting deflection of secondary cascade electrons from the direction of the primary photon. The angles of deflection of escaping secondary photons are estimated from

$$\theta \approx \sum_i \Delta x_i / r_L,$$

where the sum is over all secondary parent electrons (and positrons) which are responsible for production of specific escaping secondary photon, $\Delta x_i$ is the propagation distance of i-th secondary electron (or positron) responsible for production of secondary photon of i-th generation, and $r_L$ is the Larmor radius of secondary electron (or positron) in the local magnetic field of the Sun’s magnetosphere. The fact that secondary electrons and positrons of the cascade are deflected in opposite directions is included in the calculations by taking the deflection of positrons with opposite sign than in the case of electrons. In Fig. 11 we show the number of secondary photons with energies above $E_{\gamma,s}$, which fall on the Earth’s atmosphere within a ring with the width $\Delta D = 0.2$ km and at the distance $D$ from direction of the primary photon. Figure (a) shows the results for the primary photon with energy $E_\gamma = 10^{20}$ eV, entering the Sun’s magnetosphere at the distance $s = 2r_s$ and at the angle $\phi_s = 0^\circ$ and for $E_{\gamma,s} = 10^{18}$ eV, $10^{17}$ eV, and $10^{16}$ eV (from the thickest to the thinnest histogram). Figure (b) shows the results for $E_\gamma = 10^{20}$ eV and $\phi_s = 0^\circ$, and $E_{\gamma,s} = 10^{17}$ eV, but for $s = 4, 3, 1.1R_s$ (from the thickest to the thinnest histogram). Figure (c) shows the results for $E_\gamma = 10^{19}$ eV, $E_{\gamma,s} = 10^{17}$ eV and: $s = 1.5r_s$ and $\phi_s = 0^\circ$ (thick histogram), $s = 1.1R_s$ and $\phi_s = 90^\circ$ (middle), $s = 1.5R_s$ and $\phi_s = 90^\circ$ (thin). As expected, the perpendicular extent of secondary photons depends strongly on their energies. Secondary photons with energies above $10^{17}$ eV create ‘a core’ (the number of secondary photons per ring greater than 3 for primary photons with energy $E_\gamma = 10^{20}$ eV and greater than 2 for $E_\gamma = 10^{19}$ eV) with a typical extent of a few kilometers, and an extended ‘tail’ with secondary photons sporadically reaching distances even a few tens kilometers from direction of the primary photon. Note that the perpendicular extent of secondary photons will mainly concern one direction which is perpendicular to the direction of the magnetic field in the place of the cascade in the Sun’s magnetosphere. This is due to the ordered magnetic field of the Sun. Therefore it is expected that the secondary photons fall on the Earth’s atmosphere within a highly prolate ellipse. This feature may help to distinguish such events from the events which produce ordinary circular showers.

The cascade code allows us also to estimate the time delay between the arrival of specific secondary photons to the Earth’s atmosphere. It results from the fact that the velocities of secondary electrons responsible for emission of specific secondary photons

$$\theta \approx \sum_i \Delta x_i / r_L,$$
photons are different and because of different path lengths of secondary photons from the Sun to the Earth’s atmosphere. The time delay due to the development of the cascade can be estimated from

\[ \Delta t_k = \sum_i \Delta x_i (1 - \beta) / c \beta \approx \sum_i \Delta x_i / 2c \beta \gamma^2, \]

(3)

where \( \beta \) and \( \gamma \) are the velocity and the Lorentz factor of secondary electrons, and \( c \) is the velocity of light. Since the Lorentz factors of electrons which produce secondary photons with investigated energies are very high (above \( \sim 10^{10} \)), this time delay is negligible. The time delay due to the propagation of secondary photons from the Sun to the Earth can be estimated from

\[ \Delta t_p = r_{s-z} (1/ \cos \theta - 1) / c \approx r_{s-z} \theta^2 / 2 \approx D^2 / 2cr_{s-z} \approx 1.1 \times 10^{-14} D^2 \text{ s}, \]

(4)

where \( D \) is in kilometers. Therefore for photons falling at large distances this time delay might be measurable.

The Auger Observatories will be arrays of 10 m\(^2\) Water Cherenkov detector units in a 1.5km spaced triangular grid. The synchronous, multiple secondary photons with energies above \( 10^{17} \text{ eV} \), produced by primary photons with energies above \( 10^{19} \text{ eV} \) in the Sun’s magnetosphere, initiate separate showers in the atmosphere within the radius of \( \sim 2 \text{ km} \). In the case of primary photons with energies of \( 10^{20} \text{ eV} \) the core radius have the perpendicular extent of a few kilometers (see Fig. [1]). Each shower should trigger at least one detector with the signal of \( \sim 3 \) vertical equivalent muons (VEM) (see Fig. 4.8 in [35]), and some nearby detectors with the signal below 1 VEM. As we noted, the triggered detectors should be distributed within prolate ellipse which should help to distinguish such showers from the ordinary circular showers. We suggest that it is worth to investigate the future Auger Observatories data for such extraordinary showers from the direction of the Sun because they may give interesting information about the photon content in the highest energy cosmic rays.

5 Summary and Conclusion.

We have investigated the interaction of EHE photons with the magnetic field of the Earth and the Sun in the context of detection capabilities of products of such magnetic e\(^\pm\) pair cascades by the past, present, and future detectors of the EHE cosmic ray showers. It is assumed that photons may be copious at the highest energies as suggested by some models of EHE cosmic ray origin.

Assuming that the highest energy showers observed by different cosmic ray detectors (AGASA, Fly’s Eye, Yakutsk, and Haverah Park) are caused by photons, we estimate their probability of cascading in the Earth’s magnetic field and compute the spectra of secondary photons which fall on the Earth’s atmosphere. We find that the probability of cascading strongly depends not only on the photon energy but also on the arrival direction of the photon (see Tables [1][2]). Therefore the highest energy events detected by the AGASA and Haverah Park arrays do not have the highest probability of cascading when compared with other events detected by these arrays.
Our computations show that the fluctuations in the number of secondary cascade photons are high. In the case of photons with the parameters of the highest energy events detected by the AGASA array, there is a small probability that cascades may not even develop (see Figs. 3a,d, and Tables. 1 and 2). However photons with parameters of the highest energy events observed by the Haverah Park, Yakutsk, and Fly’s Eye detectors should cascade with the probability higher than 99%. These effects are caused by the fact that the perpendicular component of the magnetic field along the path of the primary photon strongly depends on the direction and location of the detector (Fig. 5). We have found that for detector located on the Northern hemisphere the highest probability of cascading is for photons arriving from the Northern direction and the lowest for the Southern direction at the zenith angles between the zenith and $\alpha_{\text{mag}}$, where $\alpha_{\text{mag}}$ is the angle between the location of the detector and the magnetic axis. This region of the weakest magnetic field and so the lowest probability of cascading has not been localized in the previous works on this topic. The probability of initiating a cascade close to the border of this region can change drastically even if the direction of motion of the primary photon changes by several degrees. Therefore two photons with comparable energies but arriving within the angular distance of several degrees from the direction of the equator to the detector may behave differently (e.g. AGASA events with energies $2.1 \times 10^{20}$ and $1.5 \times 10^{20}$ eV or Haverah Park events with energies $9.9 \times 10^{19}$ eV and $1.16 \times 10^{20}$ eV).

The above conclusions are verified by simulation of cascades initiated by photons arriving to the locations of the planned Southern and Northern Auger Observatories (see Figs. 6,7). As predicted the least efficient cascading of photons occurs for directions from the Equator and at specific range of zenith angles. Since the angles between the location of these Observatories to the magnetic axis will differ by about 28° degrees, the regions of the lowest probability of cascading are different. However the spectra of secondary photons averaged over random directions of primary photons with energies $10^{20}$ and $3 \times 10^{20}$ eV do not show large differences between the Southern and Northern Auger Observatories (Fig. 5). Therefore, the possibility of cascading by photons with parameters of specific EHE events has to be considered individually.

The secondary photons produced in cascades arrive at the Earth’s atmosphere within a very small cone with the radius of the order of centimeters. Therefore cascades initiated in the atmosphere by specific secondary photons are indistinguishable. However, the energies of secondary photons are significantly lower than those of primary photons. This has consequences for the development of cascades in the atmosphere because of the lower influence of the Landau-Pomeranchuk-Migdal effect. Therefore the showers with this same energy but arriving from regions on the sky which we call the 'high' and 'low' probability regions, should have on average different depths of the maximum. If photons are common at the highest energies, then such differences of the depth of the maximum of the highest energy cosmic ray showers should be observed by the Auger Observatories.

In the future paper we plan to investigate the cascades initiated in the Earth’s atmosphere by photons with the parameters of the highest energy events detected by the operating detectors using as an input the results presented in this work. It is
likely that energies of these events, estimated based on the development of hadronic cascades in the atmosphere, may not give good estimate for the energy of primary particle under the hypothesis that photon is responsible for the specific event. We intend to obtain the reported detector response to the observed highest energy showers by searching for the best energy of the primary photon. Such simulations in the Earth’s atmosphere will be done also for photons arriving from different directions to both Auger Observatories.

We have investigated the consequences of cascades initiated by EHE photons with energies above $\sim 10^{19}$ eV in the magnetosphere of the Sun. The secondary photons, products of such cascades, arrive to the Earth’s atmosphere within a highly prolate ellipse with the 'core' dimension of the main axis of the order of a few kilometers (see Fig. 11). The 'core' dimension strongly depends on the energy of secondary photons, i.e. the higher energy photons arrive closer to the direction of the primary photon. Some secondary photons from such cascades can even trigger detectors of the array at the distance of a few tens kilometers. These secondary photons arrive to the Earth almost simultaneously (see Eqs. (3) and (4)). We predict that if photons are common at the highest energies, then both Auger Observatories may observe some very atypical showers from the direction of the Sun during years of operation. The future Auger Observatory data should be investigated for very extraordinary showers coming from the direction of the Sun. The predicted rate of such showers will be low (about 1 per 10 years). However it will be possible to distinguish them from the ordinary circular showers due to the different shape and lateral profile. In the future work we plan to perform simulations of the cascades initiated in the Earth’s atmosphere by secondary photons produced in the cascade initiated by primary photon in the Sun’s magnetic field.

Acknowledgments.

I would like to thank the anonymous referees for useful comments and suggestions, and Prof. M. Giller and dr J. H. Beall for discussion and reading the manuscript. This work is supported by the Komitet Badań Naukowych grant No. 2P03D 001 14.

References

[1] N. Hayashida et al., *Astropart.Phys.* 10 (1998) 303.

[2] D.J. Bird et al. *ApJ* 511 (1999) 739.

[3] M. Takeda et al., *ApJ* 522 (1999) 225.

[4] T.K. Gaisser et al., *Phys.Rev. D* 47 (1993) 1919.

[5] N. Hayashida et al., *J.Phys.G* 21 (1995) 1101.

[6] B.R. Dawson, R. Meyhandan, K.M. Simpson, *Astropart.Phys.* 9 (1998) 331.
[7] F.W. Stecker, M.H. Salamon, *ApJ* **512** (1998) 521.
[8] L.N. Epele, E. Roulet, *Phys.Rev.Lett.* **81** (1998) 3295.
[9] K. Greisen, *Phys.Rev.Lett.* **16** (1966) 748.
[10] G.T. Zatsepin, V.A. Kuz’min, *Zh.Exp.Teor.Fiz.* **4** (1966) 114 [JETP Letters **4** (1966) 78].
[11] M. Takeda et al., *Phys.Rev.Lett.* **81** (1998) 1163.
[12] R.J. Protheroe, P.L. Biermann, *Astropart.Phys.* **6** (1996) 45.
[13] J. Wdowczyk, A.W. Wolfendale, *ApJ* **349** (1990) 35.
[14] F. Halzen et al., *Phys.Rev. D* **41** (1990) 342.
[15] P. Bhattacharjee, G. Sigl, *Phys.Rep.* (1999) in press, astro-ph/9811011.
[16] T. Erber, *Rev.Mod.Phys.* **38** (1966) 626.
[17] M.G. Baring, *A&A* **225** (1989) 260.
[18] B. McBreen, C.J. Lambert, *Phys.Rev. D* **24** (1981) 2536.
[19] F.A. Aharonian, B.L. Kanevsky, V.A. Sahakian, *J.Phys.G* **17** (1991) 1909.
[20] S. Karakula, T. Mlyntycky, W. Tubek, *Proc. Frascati Workshop 1995*, ed. F. Giovannelli & L. Sabau-Graziati (Italian Physical Society, Bologna, Italy) **47** (1996) 547.
[21] S. Karakula, W. Tubek, *Proc. Vulcano Workshop 1994*, ed. F. Giovannelli & G. Mannocchi (Mem.It.A.S.) **67** (1995) 65.
[22] S. Karakula, *Proc. Vulcano Workshop 1996*, ed. F. Giovannelli & G. Mannocchi (Italian Physical Society, Bologna, Italy) 57 (1997) 355.
[23] Stanov, T. & Vankov, H.P. 1997, *Phys.Rev. D* **55**, 1365.
[24] K. Kasahara, *Proc. Int. Symposium on Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories*, ed. M. Nagano (Univ. of Tokyo) (1997) 221.
[25] Catalogue of Highest Energy Cosmic Rays, No. 1, Haverah Park, Institute of Physical and Chemical Research, Itabashi, Tokyo, Japan, (1980) p.61.
[26] N.N. Efimov et al., *Proc. Int. Workshop of the Astrophysical Aspects on the Most Energetic Cosmic Rays*, ed. M. Nagano & F. Takahara (World Scientific) (1991) 20.
[27] B.N. Afanasiev et al., *Proc. Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays*, (University of Tokyo) (1993) 35.
[28] N. Hayashida et al., *Phys Rev Lett.* **73** (1994) 3491.
[29] D.J. Bird et al., ApJ 424 (1994) 491.

[30] L.D. Landau, I.J. Pomeranchuk, Dokl. Akad. Nauk SSSR 92 (1935) 535.

[31] A.B. Migdal, Phys.Rev. 103 (1956) 1811.

[32] K. Kasahara, Phys.Rev. D 31 (1985) 2737.

[33] S. Yoshida, H. Dai, J.Phys.G 24 (1998) 905.

[34] M. Boratav (for the Auger Collaboration), Proc. 25th ICRC (Durban) 5 (1997) 205.

[35] The Auger Collaboration, The Pierre Auger Observatory Design Report, Second Edition (1997).
Table 1: Probability of cascading of photons with parameters of the AGASA events.

| shower     | $E_\gamma$ | $Z$  | $A$  | $\phi$ | Prob. |
|------------|------------|------|------|--------|-------|
| 94/07/06   | 1.06       | 40.4°| 37°  | 34.2°  | 1.0   |
| 84/12/17   | 0.98       | 30.4°| 52°  | 45.4°  | 1.0   |
| 91/11/29   | 0.91       | 45.0°| 14°  | 19.5°  | 1.0   |
| 96/10/22   | 1.05       | 37.7°| 101° | 72.5°  | 0.99  |
| 93/12/03   | 2.13       | 22.5°| 205° | 80.1°  | 0.97  |
| 92/09/13   | 0.93       | 25.6°| 70°  | 54.4°  | 0.97  |
| 96/01/11   | 1.44       | 30.2°| 122° | 77.4°  | 0.96  |
| 98/06/12   | 1.20       | 27.5°| 140° | 81.5°  | 0.54  |
| 93/01/12   | 1.01       | 33.4°| 224° | 85.1°  | 0.4   |
| 97/03/30   | 1.50       | 43.6°| 188° | 102.5° | 0.04  |

Table 2: Probability of cascading of photons with parameters of the Haverah Park events.

| shower     | $E_\gamma$ | $Z$  | $A$  | $\phi$ | Prob. |
|------------|------------|------|------|--------|-------|
| 5746080    | 1.58       | 57°  | 5°   | 16.4°  | 1.0   |
| 5140783    | 1.15       | 26°  | 297° | 36.1°  | 1.0   |
| 17684312   | 1.01       | 37°  | 50°  | 31.1°  | 1.0   |
| 9502797    | 0.81       | 41°  | 358° | 1.7°   | 1.0   |
| 10643668   | 0.75       | 49°  | 17°  | 14.4°  | 1.0   |
| 9160073    | 1.59       | 30°  | 109° | 56.3°  | 0.99  |
| 10195820   | 0.99       | 51°  | 140° | 85.2°  | 0.89  |
| 12701723   | 1.26       | 29°  | 226° | 64.0°  | 0.49  |
| 9597348    | 0.72       | 11°  | 82°  | 40.8°  | 0.27  |
| 8185176    | 1.16       | 35°  | 210° | 73.1°  | 0.26  |
| 14617294   | 0.63       | 42°  | 182° | 83.1°  | 0.0   |
| 12953265   | 0.55       | 14°  | 112° | 47.8°  | 0.0   |
Figure 1: Probabilities of production of an $e^\pm$ pair with energy below $E_e$ by the photon with energy $E_\gamma$ (top figures) and the probabilities of emission of synchrotron photons $E_{\text{syn}}$ by the electron with energy below $E_e$ (bottom figures) in the magnetic field corresponding to the selected values of the parameter $\chi_\gamma$ and $\chi_e$. The computations with the Baring’s rates are shown by the full curves and with the Erber’s rates by the dashed curves.
Figure 2: The mean free path for conversion of photon with energy $E_\gamma$ into $e^\pm$ pair (full curve) and for production of synchrotron photon by electron (positron) with energy $E_e$ in the perpendicular magnetic field with strength 0.3 G.
Figure 3: Numbers of secondary photons, per $\Delta(\log E_\gamma) = 0.1$, produced in cascades in the Earth’s magnetic field which are initiated by primary photons with the parameters (energies and arrival directions) estimated for the highest energy events observed by: (a) the Haverah Park array (shower 9160073 with energy of $1.59 \times 10^{20}$ eV); (b) the Yakutsk array (event with energy of $2.3 \times 10^{20}$ eV); (c) the AGASA array (shower 93/12/03 with energy of $2.1 \times 10^{20}$ eV); (d) the Fly’s Eye Observatory (shower with energy of $3.2 \times 10^{20}$ eV). The full histograms show results averaged over 100 simulated primary photons. The cascades with the maximum and minimum number of secondary photons in our 100 simulations are shown by the thin full and dotted histograms, respectively.
Figure 4: Probability ($\Delta N/\Delta \log(R/R_\odot)$) of the first interaction of photons discussed in Fig. 3 as a function of distance from the surface of the Earth measured in units of the Earth’s radius. Specific histograms show the probability for events detected by: Haverah Park (dot-dashed), Yakutsk (dashed), AGASA (dotted), Fly’s Eye (thick full). The thin full histogram shows the probability for the case of supposed event with the arrival parameters of the Fly’s Eye event but with the energy $10^{21}$ eV. All results are averaged over $10^4$ simulations.
Figure 5: Magnetic field profiles along direction of motion of EHE photons, defined by the azimuth angle $\phi$ and the zenith angle $Z$, at locations of the Southern and Northern Auger Observatories. The distance from the observatories is given in units of the radius of the Earth $R_e$. Separate curves correspond to the following directions: $Z = 0^\circ$ (full); $\phi = 0^\circ$, and $Z = 30^\circ$ (dotted), and $Z = 60^\circ$ (dashed); and $\phi = 180^\circ$, and $Z = 30^\circ$ (dot-dashed), and $Z = 60^\circ$ (dot-dot-dot-dashed).
Figure 6: Average numbers of secondary photons, per $\Delta \log(E_{\gamma}) = 0.1$, produced in cascades initiated by primary photons with energies $10^{20}$eV (figure (a) and (b)) and $3 \times 10^{20}$eV (figures (c) and (d)) in the magnetic field of the Earth for location of the Southern Auger Observatory. Specific histograms show the results averaged over 100 primary photons. They correspond to different arrival directions defined by the azimuth angle, measured from the South Magnetic Pole, $\phi = 0^\circ$ and the zenith angles $Z = 75^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ$, and $0^\circ$ (figures (a) and (c) from the thickest to thinnest histograms), and $\phi = 180^\circ$, and $Z = 75^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ$ (figures (b) and (d)).
Figure 7: As in Figs. 6 but for location of the Northern Auger Observatory (also the location of the HiRes Fly’s Eye and planned Telescope Array project). The azimuth is now measured from the North Magnetic Pole.
Figure 8: The comparison of the number of secondary photons from cascades initiated by primary photons with energies $10^{20}\text{eV}$ (a), and $3 \times 10^{20}\text{eV}$ (b), arriving to locations of the Southern (full histogram) and the Northern (dotted histogram) Auger Observatories. The results are averaged over 100 primary photons arriving randomly from the sky.
Figure 9: Average number of secondary photons, per $\Delta \log E_\gamma = 0.1$, from cascades initiated by 100 primary photons with energies $10^{19}$ eV (figure a), and 10 photons with energies $10^{20}$ eV (figure b). Primary photons are injected randomly within a circle with the radius $s = 1.5r_s$ around the Sun (the thickest full curve), $2r_s$, and $3r_s$ (the thinnest full curve).
Figure 10: (a) Spectra of secondary $\gamma$-rays (multiplied by the square of the photon energy) from cascades initiated by primary photons with the power law spectrum and the spectral index $-2.7$ above $10^{18}$ eV and the cut-off at $3 \times 10^{20}$ eV (marked by the dotted curve). The spectra emerging from the Sun’s magnetosphere are shown for primary photons injected within a circle with the radius $s = 1.5r_s$ around the Sun (the thickest full curve), $2r_s$, and $3r_s$ (the thinnest curve). (b) As in figure (a) but for the primary $\gamma$-ray spectrum injected within $s = 2r_s$ and extending up to $3 \times 10^{20}$ eV (thin curve) and $3 \times 10^{21}$ eV (thick curve). The observed cosmic ray spectrum CR [33] is schematically marked by the dashed curve.
Figure 11: Perpendicular extent of secondary photons, produced in the cascade initiated by primary photon in the Sun’s magnetosphere, which fall on the Earth’s atmosphere. Specific figures show the number of secondary photons $\Delta N_\gamma$ with energy above $E_{\gamma,s}$ in a ring with the width $\Delta D = 0.2$ km and radius $D$, centered on the direction of primary photon. The parameters of simulations presented in figures (a), (b), and (c) are given in the main text of the paper.