Interaction of EHE gamma-rays with the magnetic field of the Sun

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Abstract

The content of EHE gamma-rays in the highest energy cosmic rays can be investigated by observations of high energy cosmic ray showers from the direction of the Sun. Gamma-rays with energies above 10^{19} eV may develope magnetic $e^{\pm}$ pair cascades in the dipole magnetic field of compact objects in the Solar System, i.e. the Earth, the Sun, the Jupiter. If photons are numerous at the highest energies then a deficit of showers with energies $> 10^{19}$ eV and multiple, synchronous showers at lower energies might be detected from the certain circle around the Sun. We investigate these processes by performing Monte Carlo simulations of cascades initiated by EHE photons in the magnetic field of the Sun. Based on simulations we predict that the Auger array may detect multiple, synchronous showers initiated by photons with energies above $\sim 10^{16}$ eV with a rate about one per year if photons are common above 10^{19} eV in cosmic rays.

1 Introduction:

In last years a few cosmic ray events with energies above predicted Greisen-Zatsepin-Kuzmin cut-off at $\sim 4 \times 10^{19}$ eV have been detected (e.g. Efimov et al. 1991, Bird et al. 1994, Hayashida et al. 1994). It is possible that these events are initiated by EHE photons which content in the cosmic rays above $\sim 10^{19}$ eV may be significant due to the interaction of cosmic ray hadrons with the microwave background radiation (e.g. Wdowczyk & Wolfendale 1990, Halzen et al. 1990), or decay of massive particles (e.g. Higgs and gauge bosons) as predicted by some more exotic theories (e.g. Bhattacharjee et al. 1998). The cascades initiated by such energetic photons in the Earth dipole magnetic field have been considered by McBreen & Lambert (1981) and Aharonian et al. (1991). Recently EHE cosmic ray events with energies $> 10^{20}$ eV were analysed under the hypothesis of their photonic origin by Karakuła and coworkers (see Karakuła, Młyńczyk, Tubek 1994, Karakuła & Tubek 1995, Karakuła & Bednarek 1995, Karakuła 1996) and by others (Stanev & Vankov 1996; Kasahara 1997).

In this paper we discuss the observational consequences of cascading of EHE γ-rays in the magnetic field of the Sun. The magnetic field of the Sun is about an order of magnitude stronger than that one of the Earth for which photons have to have energies above $\sim 5 \times 10^{19}$ eV in order to cascade efficiently. Therefore detection of secondary photons from cascades initiated in the magnetic field of the Sun may allow investigation of the photon content in the EHE cosmic ray spectrum at energies about an order of magnitude lower, provided that enough large detector of cosmic ray showers is available.

2 Magnetic $e^{\pm}$ pair cascades in the magnetosphere of the Sun:

The EHE photon with energy E_γ can convert into $e^{\pm}$ pair in the magnetic field B if the value of the parameter $\chi_\gamma = (E_\gamma/mc^2)(B/B_{cr})$, where $B_{cr} \approx 4.414 \times 10^{13}$ G and mc^2 is the electron rest mass, is high enough (Erber 1966). The secondary $e^{\pm}$ pairs can next produce in the magnetic field synchrotron photons, which energies are high enough to produce next generation of $e^{\pm}$ pairs. We simulate the development of such type of cascade by using the Monte Carlo method and applying the rates of $e^{\pm}$ pair production by γ-ray photon and synchrotron emission by secondary $e^{\pm}$ pairs given by Baring (1988). Note that accept Kasahara (1997), all previous simulations of such type of cascade based on the approximate rates of pair production and synchrotron emission given by Erber (1966).

The magnetic field of the Sun during the Solar minimum can be well approximated as a dipole with the magnetic moment $M_s \approx 6.87 \times 10^{32}$ G cm^3. We neglect the influence of the active regions on the Sun's

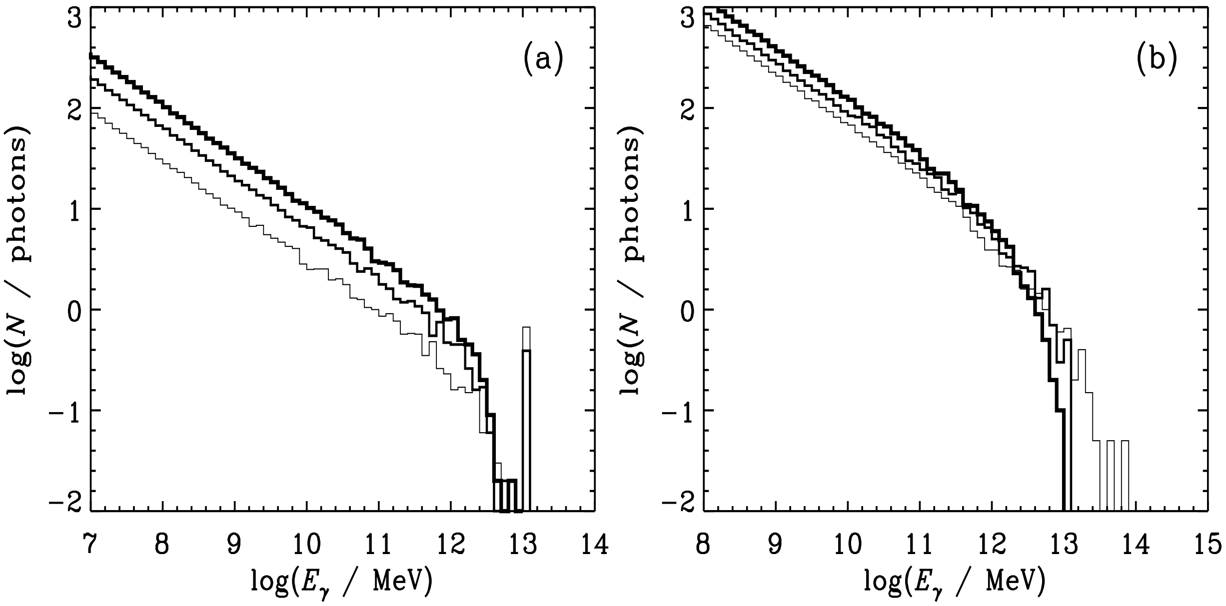

Figure 1: The average number of secondary γ-rays (within Δ log$E_\gamma = 0.1$) from cascades initiated by one hundred primary EHE photons with energies 10^{19} eV (figure **a**), and ten photons with energy 10^{20} eV (figure **b**) which are injected within the circle $s = 1.5r_{\rm s}$ (the thickest full curve), $2r_{\rm s}$, and $3r_{\rm s}$ (the thinnest full curve) around the Sun.

surface (hot spots) with strong magnetic fields, since they dominate only in the Solar chromosphere. Cosmic ray EHE photons may initiate cascades in the dipole magnetic field of the Sun if their energies are

$$E_\gamma > E_{\gamma,\rm min} = \chi_{\gamma,\rm th} mc^2 B_{cr} r_{\rm s}^3/M_{\rm s}\sqrt{1+3\cos^2\varphi} \approx 1.13\times 10^{12}/B_{\rm s,sur}\sqrt{1+3\cos^2\varphi}\,{\rm MeV},$$

where $\chi_{\gamma,\rm th} = 0.05$ is the applied threshold for which photons have chance to cascade efficiently, $B_{\rm s,sur}$ is the magnetic field at the surface of the Sun, and φ is the zenith angle of the photon at the moment of its closest approach to the center of the Sun.

It is assumed that photons are injected randomly within the circle with radius s around the Sun. The number of secondary photons from cascades initiated by primary photons with energy 10^{19} and 10^{20} eV, within the circle $s = 1.5, 2$ and $3r_{\rm s}$ around the Sun (where $r_{\rm s}$ is the radius of the Sun) are shown in Figs. 1a,b. These secondary photons are grouped into bins $\Delta(logE_\gamma) = 0.1$, and the results are averaged over 100 simulations in the case of 10^{19} eV primary photons, and 10 simulations in the case of 10^{20} eV photons. Note that all primary photons with energy 10^{19} eV, injected within the circle $s = 1.5r_{\rm s}$ from the Sun, cascade but only part of such photons interact if injected within larger circle (61% for $s = 2r_{\rm s}$, and 33% for $s = 3r_{\rm s}$). All primary photons with energy 10^{20} eV cascade if injected within considered range of parameter s.

Next we consider the possibility that EHE cosmic ray spectrum $> 10^{19}$ eV, contain significant proportion of photons. We compute the spectra of secondary cascade γ-rays assuming that the primary photons, which enter the magnetosphere of the Sun at certain circle s, have a power law spectrum with the spectral index -2.7 and a cut-off at different energies. In Fig. 2a are shown the spectra of secondary photons (multiplied by the photon energy square) from cascades initiated by primary EHE photons injected within $s = 1.5, 2, 3r_{\rm s}$. The primary photon spectrum extends up to $E_{\rm max} = 3\times 10^{20}$ eV and is normalized to the observed cosmic ray spectrum at 10^{19} eV. The observed cosmic ray spectrum is marked schematically by the dashed curve. The primary photon spectrum which extends above 10^{18} eV is marked by the dotted curve. In Fig. 2b we show

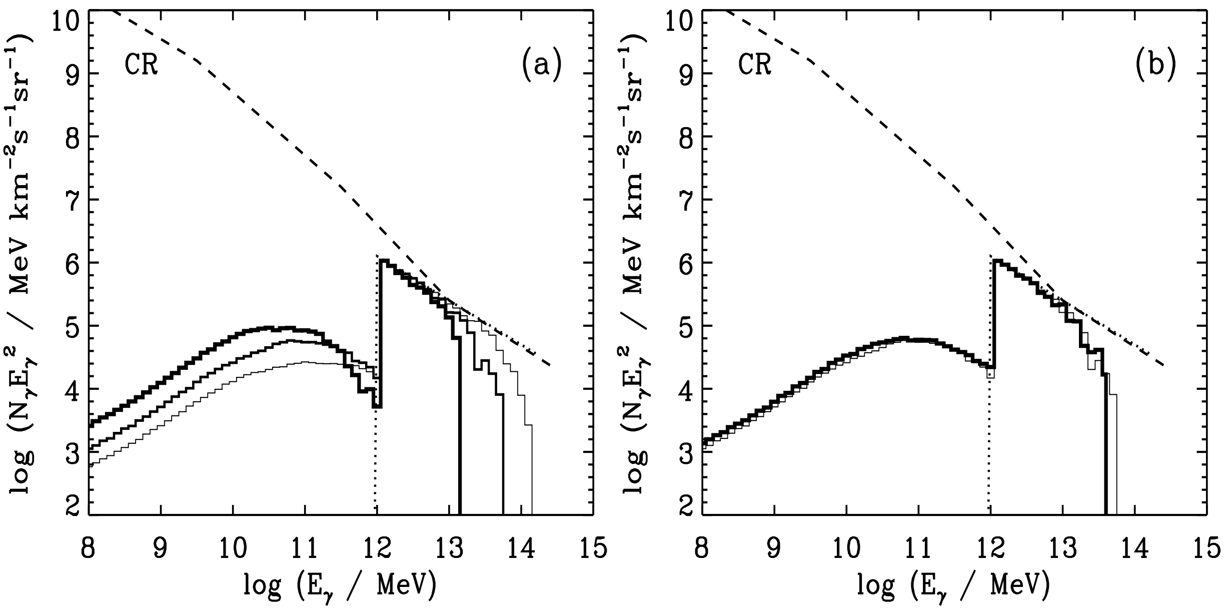

Figure 2: The spectra of secondary γ-rays (multiplied by the square of the photon energy) from the cascades initiated by the primary photons with the power law spectrum and spectral index -2.7 above 10^{18} eV and the cut-off at 3×10^{20} eV (marked by the dotted curve). The spectra emerging from the Sun's magnetosphere are shown for primary photons injected within the circle $s = 1.5r_{\rm s}$ around the Sun (the thickest full curve), $2r_{\rm s}$, and $3r_{\rm s}$ (the thinnest curve). **(b)** As in Fig. 2a but for the primary γ-ray spectrum injected within $s = 2r_{\rm s}$ and extending up to 3×10^{20} eV (thin curve) and 3×10^{21} eV (thick curve). The observed cosmic ray spectrum (CR) is schematically marked by the dashed curve.

that the spectrum of secondary γ-rays, produced by primary γ-ray spectrum with a cut off at 3×10^{21} eV, is almost the same as in the case of its cut off at 3×10^{20} eV.

3 Discussion:

Our simulations show that significant part of EHE photons with energies above 10^{19} eV should cascade if injected within the circle of $s = 2r_{\rm s}$ around the Sun. However the solid angle corresponding to such a circle on the sky is relatively small ($\sim 2.2 \times 10^{-5}$ sr). The Auger experiment is expected to detect about $50 - 100$ particles $> 10^{20}$ eV per year (Boratav 1997) and about 2×10^4 particles $> 10^{19}$ eV per year. Some showers, initiated by particles with energy $> 10^{19}$ eV, should be detected from the circle of $2r_{\rm s}$ around the Sun within a few years of operation. Let's assume that all these particles above 10^{19} eV are photons. Our simulations show that these photons should cascade in the Sun's magnetic field and as a result of cascading about 12 secondary photons with energy $> 10^{17}$ eV and 50 secondary photons $> 10^{16}$ eV should arrive to the Earth's surface synchronously with a rate corresponding to the number of events with energy 10^{19} expected from the direction of the Sun. We estimated energy weighted perpendicular spread of secondary photons (its half thickness) based on our simulations. It is found that secondary photons from cascade initiated by primary photon with energy 10^{19} eV should fall on the Earth's surface within the circle with average radius ~ 19 km (estimation base on ten simulations). If the primary photons have energy 10^{20} eV, then the secondary photons should be contained within the circle with radius ~ 51 km.

If such synchronous, multiple showers, initiated by photons with energies above 10^{17} eV, can be observed by the Auger experiment, then a bunch containing half of the number of these secondary photons should fall

Table 1: The ratio of cosmic ray photons to cosmic ray particles at energy E from the direction of the Sun.

$E/E_{\rm max}, s$	3×10^{20}eV, $1.5r_s$	3×10^{20}eV, $2r_s$	3×10^{20}eV, $3r_s$
10^{15} eV	5×10^{-6}	$\sim 2 \times 10^{-6}$	$\sim 8 \times 10^{-7}$
10^{16} eV	1.5×10^{-3}	$\sim 6 \times 10^{-4}$	$\sim 2 \times 10^{-4}$
10^{17} eV	3×10^{-3}	$\sim 2 \times 10^{-3}$	$\sim 8 \times 10^{-4}$

on the Auger array with frequency of about one per year. Note that for such photon bunches the effective detection area of the Auger array becomes larger by a factor close to two because of geometrical reasons. Observation of such multiple showers from the direction of the Sun should made possible estimatation of the content of the photons in cosmic rays above 10^{19} eV on a level of 10 percent during years of operation.

The spectra of secondary photons produced within the circle s around the Sun by primary photons with the spectrum observed in cosmic rays above 10^{19} eV (and with normalization to the observed cosmic ray spectrum) are shown in Fig. 2a,b. Based on our computations we estimate the ratio of cosmic ray photons to cosmic ray particles at lower energies (see Table 1). This ratio is of the order of $\sim 10^{-3}$ in the energy range $10^{16} - 10^{17}$ eV if primary photons are injected within the circle of less than $2r_{\rm s}$ around the Sun. However in order to detect one shower initiated in the atmosphere by photon with energy 10^{16} eV from the direction of the Sun, the statistics of showers of the order of $\sim 10^8$ is needed because of small solid angle of the Sun.

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