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Estimation of particle acceleration and propagation parameters by possible measurements of gamma rays generated in interactions of SEP with upper corona and solar wind matter

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It is well known that some part of solar energetic particles (SEP) escape up into solar wind. We calculate the expected space-time-energy distribution of these particles in the Heliosphere in the periods of great SEP events. On the basis of investigations of cosmic ray (CR) nonlinear processes we estimate also the space-time distribution of solar wind matter. We calculate the generation of neutral pions from nuclear interactions of SEP with the upper corona and solar wind matter, and then GR fluxes (from decay of neutral pions). We found the expected space distribution of GR emissivity and how it changed with time. Then we calculate the expected time variation of the angle distribution and spectra of GR fluxes. It is shown that by simultaneously observations in different directions of GR generated by SEP interactions with upper corona and solar wind matter can be obtained information on SEP energy spectrum in source, on mode and parameters of SEP propagation, what may be useful also for radiation hazard forecasting.

1. Introduction

The generation of gamma rays (GR) by interaction of solar energetic particles (SEP) with corona and solar wind matter is determined mainly by 3 factors:

1st- by space-time distribution of SEP in the Heliosphere, their energetic spectrum and chemical composition.

2nd- by the solar wind matter distribution in space and its change during solar activity cycle; for this distribution will be important also pressure and kinetic stream instability of galactic cosmic rays (CR) as well as of SEP (especially in periods of very great events).

3rd- by properties of SEP interaction with solar wind matter accompanied with GR generation through decay of neutral pions.

After consideration of these 3 factors we will calculate expected GR emissivity space-time distribution, and then expected fluxes of GR for measurements on the Earth's orbit.

2. Space-time distribution of SEP

In the first approximation according to numeral data of observations of many events for about 5 solar cycles the time change of SEP and energy spectrum change can be described by the solution of isotropic diffusion (characterized by the diffusion coefficient $D_i(E_k)$) from some pointing instantaneous source $Q_i(E_k,\mathbf{r},t)=N_{oi}\delta(\mathbf{r})\delta(t)$ of SEP of type *i* (protons, $\alpha-$particles and heavier particles, electrons) by

$$N_i(E_k,\mathbf{r},t)=N_{oi}(E_k)\left[2\pi^{1/2}\left(D_i(E_k)t\right)^{3/2}\right]^{-1}\exp\left(-\mathbf{r}^2/\left(4D_i(E_k)t\right)\right), \qquad (1)$$

where $N_{oi}(E_k)$ is the energetic spectrum of total number of SEP in the source. At the distance $r=r_1=1AU$ the maximum of SEP density will be reach according to Eq. (1) at the moment

$$t_1(r_1, E_k) = r_1^2 / 6D(E_k). \quad (2)$$

3. Space-time distribution of solar wind matter

If we assume for the first approximation the Parker's [1] solar wind model, the matter distribution will be described by the relation

$$n(r,\theta,t) = n_1(\theta,)u_1(\theta)r_1^2 / \left(r^2 u(r,\theta)\right), \quad (3)$$

where $n_1(\theta)$ and $u_1(\theta)$ are the matter density and solar wind speed at the helio-latitude θ on the distance $r = r_1 = 1$ AU from the Sun. The dependence $u(r,\theta)$ is determined by the interaction with galactic CR, with interstellar matter and magnetic field, with neutral atoms penetrating from interstellar space inside the Heliosphere, by the nonlinear processes caused by these interactions (see [2, 3]). According to [3] the change of solar wind velocity can be described approximately as

$$u(r) \approx u_1(1 - b(r/r_o)), \quad (4)$$

where the distance to the terminal shock wave $r_o \approx 74$ AU and parameter $b \approx 0.13 \div 0.45$ in dependence of sub-shock compression ratio (from 3.5 to 1.5) and from injection efficiency of pickup protons (from 0 to 0.9). From analysis of CR-SA hysteresis phenomenon we estimate $r_o \approx 100$ AU [4].

4. Generation of neutral pions

According to [5] the neutral pion generation caused by nuclear interactions of energetic protons with hydrogen atoms through reaction $p + p \rightarrow \pi^o +$ anything will be determined by

$$F_{pH}^{\pi}(E_\pi, r, \theta, t) = 4\pi n(r,\theta,t) \int_{E_{k\,\min}(E_\pi)}^{\infty} dE_k N_p(E_k, r, t) \langle \varsigma\sigma_\pi(E_k)\rangle \left(dN(E_k, E_\pi)/dE_\pi\right), \quad (5)$$

where $n(r,\theta,t)$ is determined by Eq. (3), $E_{k\,\min}(E_\pi)$ is the threshold energy for π^o production, $N_p(E_k, r, t)$ is determined by Eq. (1), $\langle \varsigma\sigma_\pi(E_k)\rangle$ is the inclusive cross section for π^o generation in reactions $p + p \rightarrow \pi^o +$ anything, and $\int_0^\infty \left(dN(E_k, E_\pi)/dE_\pi\right) dE_\pi = 1$.

5. Space-time distribution of gamma ray emissivity

GR emissivity because of nuclear interactions of SEP protons with solar wind matter will be determined according to [5] by

$$F_{pH}^{\gamma}(E_\gamma, r, \theta, t) = 2 \int_{E_{\pi\,\min}(E_\gamma)}^{\infty} dE_\pi \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} F_{pH}^{\pi}(E_\pi, r, \theta, t), \quad (6)$$

where $E_{\pi\,\min}(E_\gamma) = E\gamma + m_\pi^2 c^4 / 4E\gamma$. Let us introduce Eq. (1) in (5) and (6) by taking into account Eq. (3):

$$F_{pH}^{\gamma}(E_\gamma, r, \theta, t) = 3^{3/2} 2^{7/2} \pi^{1/2} n_1(\theta, t)\left(r_1^2 u_1(\theta, t)/r^2 u(r, \theta, t)\right) \int_{E_{\pi\,\min}(E_\gamma)}^{\infty} \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} dE_\pi \times$$
$$\times \int_{E_{k\,\min}(E_\pi)}^{\infty} N_{op}(E_k) \langle \varsigma\sigma_\pi(E_k)\rangle (t/t_1)^{-3/2} \exp\left(-3r^2 t_1 / 2r_1^2 t\right) dE_k, \quad (7)$$

where t_1 is determined by Eq. (2). The biggest GR emission is expected in the inner region

$$r \le r_i = r_1 (2t/3t_1)^{1/2}\,, \tag{8}$$

where the level of emission $\propto r^{-2}(t/t_1)^{-3/2}$; out of this region GR emissivity decreases very quickly with r as $\propto r^{-2}\exp\left(-(r/r_i)^2\right)$.

6. Angle distribution and time variations of gamma ray fluxes

Let us assume that the observer is inside the Heliosphere, on the distance $r_{obs} \le r_o$ from the Sun and helio-latitude θ_{obs} (here r_o is the radius of Heliosphere). The sight line of observation we can determine by the angle θ_{sl}, computed from the equatorial plane from direction to the Sun to the North. In this case the expected angle distribution and time variations of GR fluxes will be

$$\Phi^{\gamma}_{pH}\left(E_\gamma, r_{obs}, \theta_{obs}, \theta_{sl}, t\right) = \int_0^{L_{\max}(r_{obs},\theta_{obs},\theta_{sl})} F^{\gamma}_{pH}\left(E_\gamma, L, t\right) dL\,. \tag{9}$$

In Eq. (9) gamma-ray emissivity

$$F^{\gamma}_{pH}\left(E_\gamma, L, t\right) = F^{\gamma}_{pH}\left(E_\gamma, r, \theta, t\right) \tag{10}$$

is determined by Eq. (7) taking into account that

$$r = \left(r_{obs}^2 + L^2 + 2r_{obs}L\Delta\theta\right)^{1/2},\ \ \theta = \theta_{obs} + \arccos\left(\frac{r_{obs}^2 + r_{obs}L\Delta\theta}{r_{obs}\left(r_{obs}^2 + L^2 + 2r_{obs}L\Delta\theta\right)^{1/2}}\right), \tag{11}$$

where $\Delta\theta = \theta_{sl} - \theta_{obs}$. In Eq. (9)

$$L_{\max}\left(r_{obs}, \theta_{obs}, \theta_{sl}\right) = \frac{r_o}{\sin\Delta\theta}\sin\left[\Delta\theta - \arcsin\left(\frac{r_{obs}}{r_o}\sin\Delta\theta\right)\right]. \tag{12}$$

In the case of spherical symmetry we obtain

$$\Phi^{\gamma}_{pH}\left(E_\gamma, r_{obs}, \varphi, t\right) \approx F^{\gamma}_{pH}\left(E_\gamma, r = r_{obs}\sin\varphi, t\right)\left(\theta_{\max} - \theta_{\min}\right) r_{obs}\sin\varphi\,, \tag{13}$$

where φ is the angle between direction on the Sun and direction of observation, and

$$\theta_{\min} = \begin{cases} -\arccos\left(r_{obs}\sin\varphi / r_i\right) & \text{if } r_{obs} > r_i \\ \varphi - \pi/2 & \text{if } r_{obs} \le r_i \end{cases};\quad \theta_{\max} = \arccos\left(r_{obs}\sin\varphi / r_i\right), \tag{14}$$

where r_i is determined by Eq. (8). For the great solar event with the total energy 10^{32} ergs Eq. (13) gives

$$\Phi^{\gamma}_{pH}\left(E_\gamma > 0.1\,\text{GeV}, r_{obs} = 1AU, \varphi, t\right) \approx \frac{6.7\times 10^{-6}}{\sin\varphi}\left(\frac{t}{t_1}\right)^{-\frac{3}{2}} \exp\left(-\frac{3t_1\sin^2\varphi}{2t}\right) \text{photon.cm}^{-2}.\text{sr}^{-1}.\text{sec}^{-1}. \tag{15}$$

7. Expected gamma ray fluxes from great SEP events

Estimations according to Eq. (15) show that in periods of great SEP events with total energy $\approx 10^{32}$ ergs the expected flux of GR with energy > 100 MeV in direction 2° from the Sun at t/t_1 =1/30 reaches $\approx 2\times 10^{-2}$ photon.cm^{-2}.sr^{-1}.sec^{-1}, and at t/t_1 =1/3 reaches $\approx 10^{-3}$ photon.cm^{-2}.sr^{-1}.sec^{-1}. In direction 30° from the Sun expected gamma-ray fluxes are much smaller: the maximum will be at t/t_1 = 1/3 and reaches value only $\approx 10^{-5}$ photon.cm^{-2}.sr^{-1}.sec^{-1}. Expected gamma-ray fluxes are characterized by great specific time variations, which depend from direction of observations relative to the Sun, total SEP

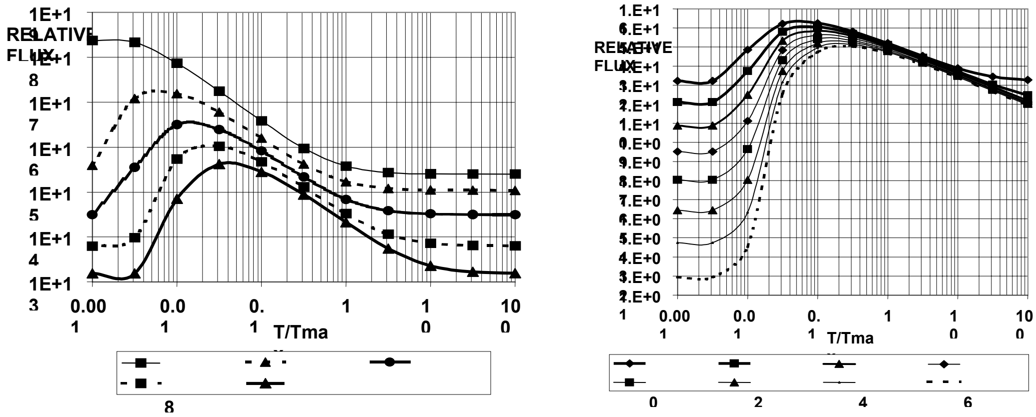

Figure 1. Expected fluxes of GR with energy more than 100 MeV during SEP event with total energy 10^{32} ergs for directions from the Sun φ = 2° to φ = 10° (left) and φ = 12° to φ = 26° (right) in dependence of t/t_1 , where t_1 was determined by Eq. (2).

flux from the source, parameters of SEP propagation (summarized in value of t_1), and properties of solar wind. (as example, see Figure 1 for expected gamma-ray fluxes).

8. Discussion

At energies above about 30 MeV, pair production is the dominant photon interaction in most materials. In GR pair telescopes this process is used to detect the arrival of the GR photon through the electron-positron pair created in the detector. Well known are space-telescopes **COS-B** and **EGRET** (collection area of the last about 1600 cm^2), which gave well energy and spatial resolution [6]. These telescopes can detect objects with GR fluxes with energy bigger than 100 MeV at detection limit of order $10^{-6} - 10^{-7}$ photon.cm^{-2}.sec^{-1}; these fluxes are several order lower than expected from SEP interactions with solar wind matter (see Figure 1). According to [7], further advance in energy and spatial resolution is expected from the Gamma-ray Large Area Space Telescope (**GLAST**). In this telescope will be using solid-state detectors as the tracking material instead of the gas filled chamber. It is planned to launch in 2006. This telescope will allow for improved energy resolution (10% resolution) and spatial location (0.5-5.0 arc-minutes). Figure 1 show that present GR telescopes might measure expected GR fluxes in periods of great SEP events. These on-line observations of GR generated in interactions of SEP with solar wind matter can give important information on solar wind 3D-distribution as well as on properties of SEP generation and propagation parameters, can be useful for forecasting of great radiation hazards.

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