ESWW-2

Forecasting of great radiation hazard: 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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ABSTRACT

It is well known that in the periods of particle acceleration in the solar corona connected with solar flare events, some part of solar energetic particles (SEP) go down and as result of their interactions with dense matter in chromosphere and photosphere gamma rays are generated. These gamma rays, generated practically simultaneously with the process of SEP acceleration, are regularly measured many years and gave important information on the acceleration processes. The other

part of SEP escaped up into solar wind. We calculate the expected space-time-energy distribution of these particles in the Heliosphere in the periods of SEP events. On the basis of investigations of cosmic ray nonlinear processes we estimate also the space-time distribution of solar wind matter. For great solar flare events we calculate the generation of neutral pions generated in nuclear interactions of SEP with the upper corona and solar wind matter, and then gamma-ray fluxes (from decay of neutral pions) in periods of great SEP events from upper solar corona and solar wind. We found the expected space distribution of gamma-ray emissivity and how it changed with time. Then we calculate the expected time variation of the angle distribution and spectra of gamma ray fluxes. For some simple diffusion models of solar SEP propagation we obtained analytical approximation described the time evolution of gamma ray flux angle distribution as well as time evolution of gamma ray spectrum. It is shown that by simultaneously observations in different directions of gamma rays generated by SEP interactions with upper corona and solar wind matter can be obtained important information on SEP energy spectrum in source, on mode of SEP propagation. On the basis of this information can be made forecasting of expected SEP fluxes and total fluency, and then to estimate the expected radiation hazard. In cases of expected dangerous situation for some type of satellites and aircrafts, may be sending corresponding Alerts.

Introduction

The generation of gamma rays (GR) by interaction of flare energetic particles (FEP) with solar wind matter shortly was considered in Dorman (1996, 1997). Here we will give a development of this research with much more details and applications to space weather. The phenomenon is determined mainly by 3 factors:

1st- by space-time distribution of solar FEP in the Heliosphere, their energetic spectrum and chemical composition (see review in Dorman, 1957, 1963, 1978; Dorman and Miroshnichenko, 1968; Dorman and Venkatesan, 1993; Stoker, 1995; Miroshnichenko, 2001).

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 solar FEP, especially in periods of very great events (Dorman, 1995; Le Roux and Fichtner, 1997).

3rd- by properties of solar FEP interaction with solar wind matter accompanied with GR generation through decay of neutral pions (Stecker, 1971; Dermer, 1996a,b).

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 in dependence of time after the moment of FEP generation for different directions of GR observations. We calculate expected fluxes also for different distances from the Sun inside the Heliosphere and outside.

Observations of GR generated in interactions of solar FEP with solar wind matter can give for the periods of great events valuable information on solar wind matter 3d-distribution as well as on properties of solar FEP and its propagation parameters.

FACTOR 1: FEP SPACE-TIME DISTRIBUTION

The problem of solar FEP generation and propagation through the solar corona and in the interplanetary space as well as its energetic spectrum and chemical and isotopic composition was reviewed in Dorman (1957, 1963, 1978), Dorman and Miroshnichenko (1968), Dorman and Venkatesan (1993), Stoker (1995), Miroshnichenko (2001). In the first approximation according to numeral data of observations of many events for about 5 solar cycles the time change of solar FEP 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 solar FEP 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 solar FEP in the source. At the distance $r = r_1 = 1AU$ the maximum of solar FEP density will be reach according to Eq. (1) at the moment

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

and the space distribution of solar FEP density at this moment will be

$$N_i(r, E_k, t_1)/N_{oi}(E_k) = 4.15 r_1^{-3} \exp\left(-3r^2/2r_1^2\right). \qquad (3)$$

FACTOR 2: SPACE-TIME DISTRIBUTION OF SOLAR WIND MATTER

The detail information on the 2nd-factor for distances smaller than 5 AU from the Sun was obtained in the last years by the mission of Ulysses. Important information for bigger distances (up to 60-70 AU) was obtained from missions Pioneer 10, 11, Voyager 3, 4 , but only not far from the ecliptic plane. Let us assume for the first approximation the Parker's (1963) solar wind model. In this case the matter distribution will be described by the relation

$$n(r,\theta,t) = n_1(\theta,)u_1(\theta) r_1^2/\left(r^2 u(r,\theta)\right), \qquad (4)$$

where $n_1(\theta)$ and $u_1(\theta)$ are the matter density and solar wind speed at the helio-latitude θ on the distance $r = r_1$ from the Sun $(r_1 = 1AU)$. The dependence $u(r,\theta)$ is determined by the interaction with galactic cosmic rays, 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 Dorman, 1995; Le Roux and Fichtner, 1997). According to calculations of Le Roux and Fichtner (1997) the change of solar wind velocity with the distance from the Sun can be described approximately as

$$u(r) \approx u_1\left(1 - b\left(r/r_o\right)\right), \tag{5}$$

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 (Dorman, 2003). Therefore we will use in Eq. (5) $r_o \approx 100$ AU and $b \approx 0.3$.

FACTOR 3: GAMMA RAY GENERATION BY FEP IN THE HELIOSPHERE

Generation of Neutral Pions

According to Stecker (1971) and Dermer (1976a,b), 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

$$F_{pH}^{\pi}\left(E_\pi, r, \theta, t\right) = 4\pi n(r,\theta,t) \int_{E_{k\,\min}\left(E_\pi\right)}^{\infty} dE_k \times N_p\left(E_k, r, t\right) \left\langle \varsigma\sigma_\pi\left(E_k\right)\right\rangle \left(dN\left(E_k, E_\pi\right)/dE_\pi\right), \tag{6}$$

where $n(r,\theta,t)$ is determined by Eq. (4), $E_{k\,\min}\left(E_\pi\right)$ is the threshold energy for pion generation, $N_p\left(E_k, r, t\right)$ is determined by Eq. (1), $\left\langle \varsigma\sigma_\pi\left(E_k\right)\right\rangle$ is the inclusive cross section for π^o generation in reactions $p+p \rightarrow \pi^o + \text{anything}$, and $\int_0^\infty (dN(E_k, E_\pi)/dE_\pi) dE_\pi = 1$.

Space-Time Distribution of Gamma Ray Emissivity

Gamma ray emissivity caused to nuclear interaction of FEP protons with solar wind matter will be determined according to Stecker (1971) and Dermer (1976a,b) by

$$F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right) = 2 \int_{E_{\pi \min}\left(E_\gamma\right)}^{\infty} dE_\pi \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} F_{pH}^{\pi}\left(E_\pi, r, \theta, t\right), \tag{7}$$

where $E_{\pi \min}\left(E_\gamma\right) = E\gamma + m_\pi^2 c^4 / 4E\gamma$. Let us introduce Eq. (1) in Eq. (6) and in Eq. (7) by taking into account Eq. (4):

$$\begin{aligned} F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right) = B(r, \theta, t) \int_{E_{\pi \min}\left(E_\gamma\right)}^{\infty} \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} dE_\pi \times \\ \times \int_{E_{k \min}\left(E_\pi\right)}^{\infty} N_{op}\left(E_k\right)\left\langle \varsigma \sigma_\pi\left(E_k\right)\right\rangle \left(t/t_1\right)^{-3/2} \exp\left(-3r^2 t_1 / 2r_1^2 t\right) dE_k, \end{aligned} \tag{8}$$

where $B(r, \theta, t) = 3^{3/2} 2^{7/2} \pi^{1/2} r_1^2 n_1(\theta, t) u_1(\theta, t) / r^2 u(r, \theta, t)$ and $t_1 = r_1^2 / 6D_p(E_k)$ is the time in which the density of FEP, at a distance of 1 AU, reaches the maximum value. The space distribution of gamma ray emissivity for different t/t_1 (see Figure 1) will be determined mainly by function $r^{-2}\left(t/t_1\right)^{-3/2} \exp\left(-3r^2 t_1 / 2r_1^2 t\right)$, where t_1 corresponds to some effective value of E_k in dependence of E_γ, according to Eq. (6) and Eq. (7).

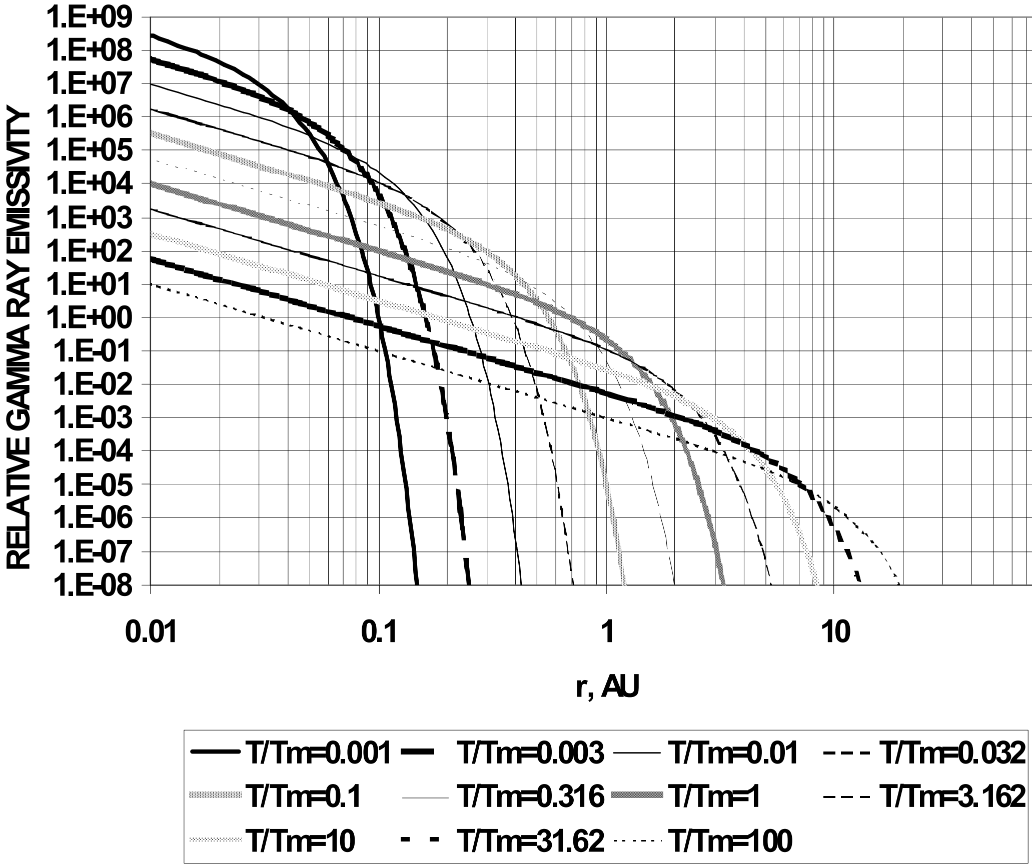

Figure 1. Expected space distribution of gamma ray emissivity for different time T after FEP generation in units of time maximum Tm=t_1 on 1 AU, determined by Eq. (2). The curves are from T/Tm=0.001 up to T/Tm=100.

The biggest gamma ray emission is expected in the inner region $r \le r_i = r_1(2t/3t_1)^{1/2}$ where the level of emission $\propto r^{-2}(t/t_1)^{-3/2}$. Out of this region gamma ray emissivity decreases very quickly with r as $\propto r^{-2}\exp\left(-(r/r_i)^2\right)$. For an event with total energy 10^{32} ergs at $t = t_1 = 10^3$ s, $r_i = 10^{13}$ cm, $n_1(\theta, t) \approx 5\,cm^{-3}$, $D_p(E_k) \approx 4\times 10^{22}\,cm^2/s$ we obtain $F_{pp}^{\gamma}\left(E_\gamma > 0.1 GeV, r\right) \approx 10^8 r^{-2}$ $ph.cm^{-3}s^{-1}$

EXPECTED ANGLE DISTRIBUTION AND TIME VARIATIONS OF GAMMA RAY FLUXES; DISCUSSION OF OBTAINED RESULTS

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 gamma ray fluxes will be

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

In Eq. (9) GR emissivity

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

is determined by Eq. (8) taking into account that

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

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

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

According to Eq. (8) – Eq. (12) the expected angle distribution and time variations of gamma ray fluxes for local observer ($r_{obs} \le r_o$) from interaction of solar energetic protons with solar wind matter will be determined by the energy spectrum of proton generation on the Sun $N_{op}(E_k)$, by the diffusion coefficient $D_p(E_k)$, and parameters of solar wind in the period of event near the Earth orbit $n_1(\theta, \tilde{t})$ and $u_1(\theta, \tilde{t})$. In the case of spherical symmetry we obtain

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

where φ is the angle between direction on the Sun and direction of observation, $\theta_{\max} = \arccos\left(r_{obs}\sin\varphi / r_i\right)$, $\theta_{\min} = -\arccos\left(r_{obs}\sin\varphi / r_i\right)$ if $r_{obs} > r_i$ and $\theta_{\min} = \varphi - \pi/2$, if $r_{obs} \le r_i$. For the great solar event with the total energy in FEP 10^{32} *ergs* for $r_{obs} = 1AU$, Eq. (13) gives

$$\Phi^{\gamma}_{pH}\left(E_{\gamma} > 0.1GeV, r_{obs} = 1AU, \varphi, t\right) \approx \frac{6.7\times 10^{-6}}{\sin\varphi}\left(\frac{t}{t_1}\right)^{-\frac{3}{2}} \exp\left(-\frac{3t_1\sin^2\varphi}{2t}\right) ph.cm^{-2}.sr^{-1}.s^{-1}. \qquad (14)$$

Expected GR fluxes in dependence from t/t_1 are shown in Figures 2 and 3 in units $photon.cm^{-2}.sr^{-1}.\sec^{-1}$.

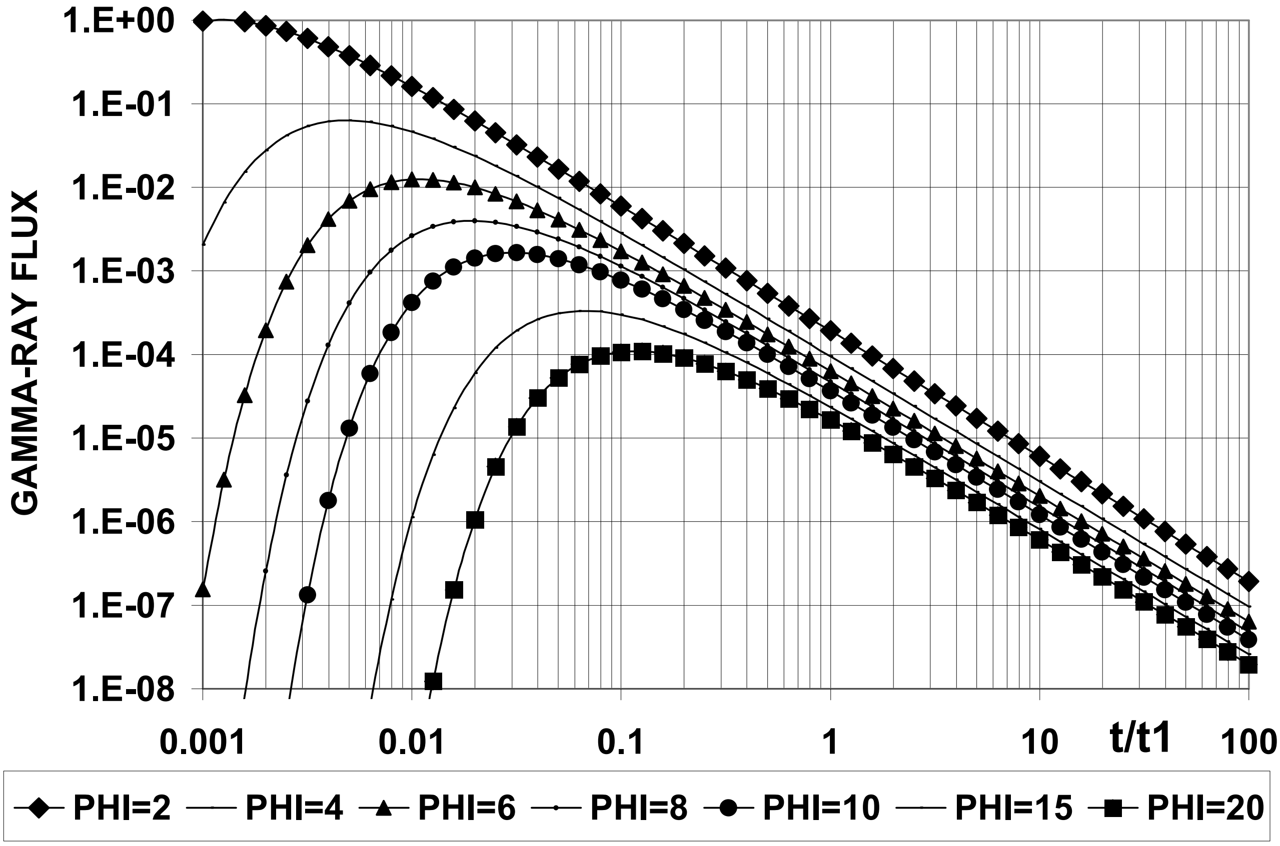

Figure 2. Expected GR fluxes for φ from 2° to 20°

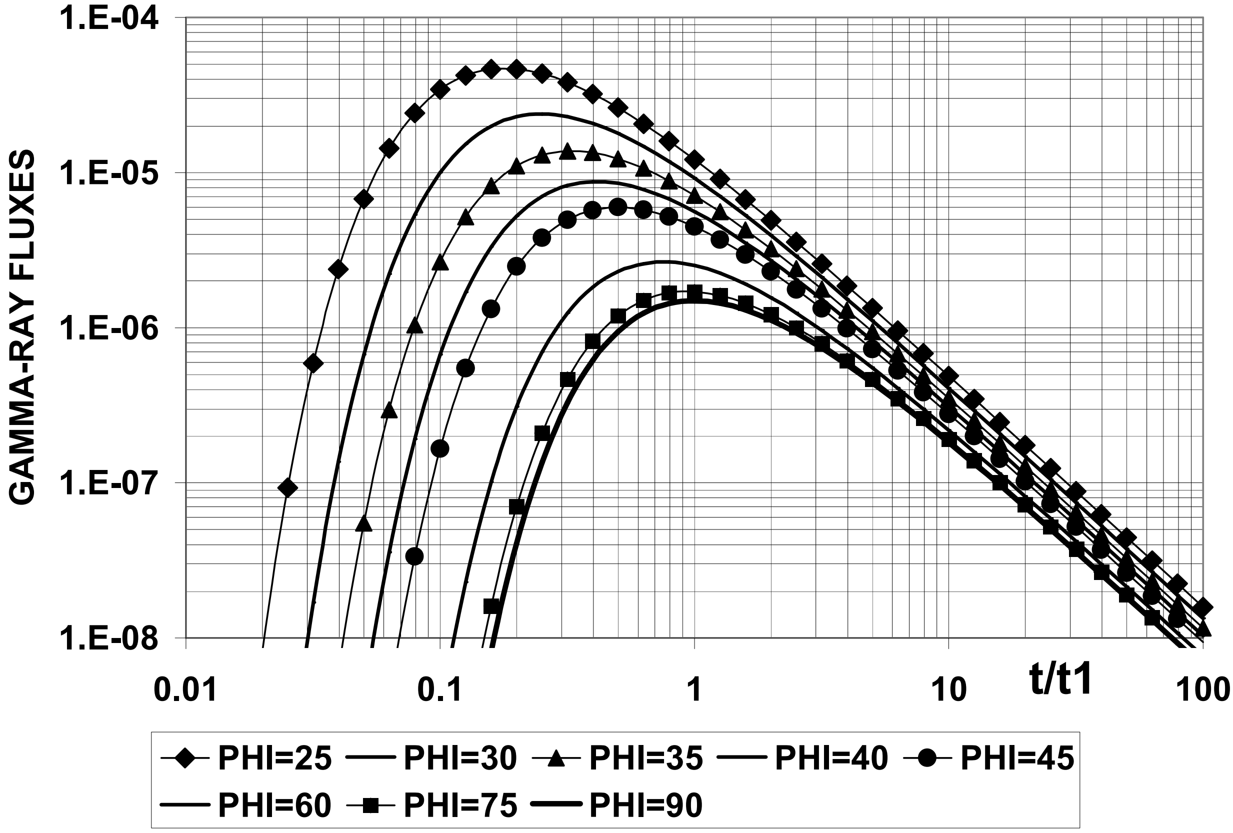

Figure 3. Expected GR fluxes for φ from 25° to 90°

Figures 2 and 3 show that present GR telescopes might measure expected GR fluxes in periods of great FEP events. These observations of gamma rays generated in interactions of FEP with solar wind matter can give important information on solar wind 3d-distribution as well as on properties of solar FEP and its propagation parameters. Moreover, the monitoring of GR observations in directions at few degrees from the Sun can give important possibility to predict expected radiation hazard from FEP on the Earth and in space.

USING GAMMA RAY MEASUREMENTS FOR ESTIMATING OF FEP GENERATION AND PROPAGATION PARAMETERS; FORECASTING OF DANGEROUS SITUATIONS

On the basis of obtained results by existing gamma ray telescopes is possible to determine in the first several minutes of the FEP event beginning the main parameters of FEP generation and propagation. Then we can immediately calculate expected fluxes of FEP the interplanetary space in dependence of particle energies and distance from the Sun. It is important for estimating of expected radiation hazard for space probes.

The same can be made immediately for satellites in the Earth magnetosphere for different orbits with taking into account the change of cutoff rigidity along the orbit, what is important to prevent some part of satellite anomalies.

By using method of coupling functions (Dorman, 1957, 2004) the same can be made immediately for aircrafts and high technology mountain and ground objects in dependence of air absorbed depth and cutoff rigidity. In case of dangerous situations for some aircrafts or/and some high technology mountain and ground objects, may be sent corresponding alerts. This will be help to prevent electronics and people health from radiation hazard.

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