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Statistical Characteristics of FEP Events and their Connection with Acceleration, Escaping and Propagation Mechanisms

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Abstract

Statistical characteristics of solar cosmic ray fluences (obtained on the basis of satellite and ground-based observations during about four solar cycles) in dependence of solar activity level are discussed in the frame of models of energetic particle acceleration, escaping and propagation mechanisms.

1 Introduction:

Which factors could influence the formation of FEP and their statistical properties, particularly the statistical dependence of frequency of FEP on total energy? There are several possibilities:

i) Accumulation of the necessary magnetic energy in the vicinity of singular points/current sheet of the magnetic structure above the active region.

ii) Efficiency of the trigger's mechanisms of the flare - near threshold of critical state of current percolation through random resistors' net of turbulent elements in current sheet.

iii) Efficiency of solar cosmic ray ejection into the solar wind resulting from: a) a direct run-away in the open part of the magnetic fields; b) a global instability of the magnetic trap with CME events; c) an anomalous diffusion of accelerated cosmic ray particles from closed magnetic field into the open region.

iiii) FEP particles propagation to the Earth.

The final probability of FEP events in dependence of their energy content will be determined as convolution of partial probability functions of different components.

2 Frequency of FEP Events vs. Fluence of Particles with Energy > 10 MeV:

Average results for several solar cycles are shown in Fig. 1 and for different solar activity levels in Figure 2.

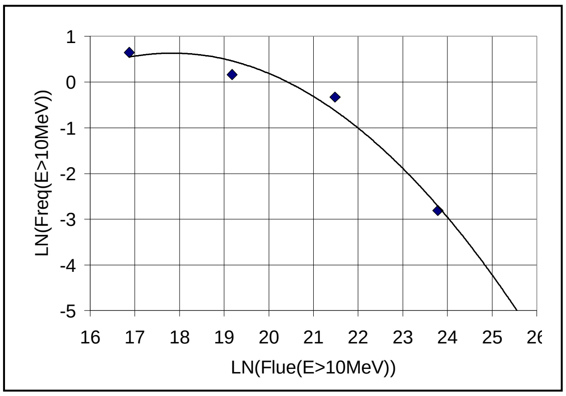

Figure 1: Average for some solar cycles, E>10 MeV.

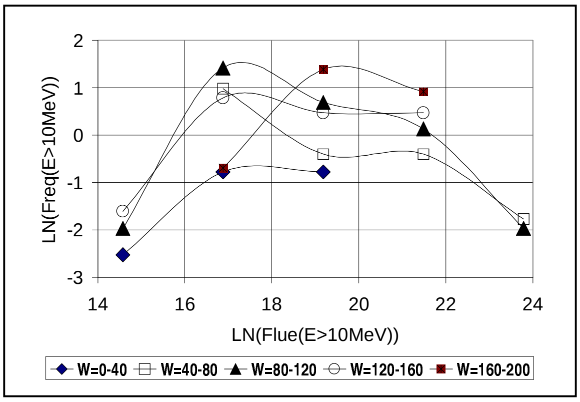

Figure 2: Averaged for different levels of solar activity, E>10 MeV.

In this paper we continue our analysis on the statistical properties of FEP events (Dorman et al. 1993; Dorman & Pustil'nik 1995). We use mostly observation data on FEP events reviewed by Dorman & Venkatesan (1993); the resulting statistical dependencies can be compared with those obtained for solar flares in optical and hard X-ray ranges, as well as for some nearby flare stars (Grosby et al. 1993; Gershberg & Shakhovskaya 1983; Gershberg et al. 1987; Korotin & Krasnobabcev,1985; Kurochka 1987).

The dependence showed in Figure 1 can be approximated by a parabolic function:

$$\nu = aF^{-\gamma}\ ,\ \ a = 1.702\times 10^{-13},\ \ \gamma = 0.0945\ln F - 3.369,\ \ (1)$$

where ν is the frequency of FEP events (in year^{-1}) and F is the fluence (in *particle x cm*$^{-2}$), which is nearly proportional to the total energy of solar flare. Figure 2 shows that the frequency of FEP events increases with the increasing of solar activity for great fluences (LN(Flue)=18-22), but the greatest fluences (LN(Fluence) ≈ 24) happened in periods of intermediate solar activity levels (W=40-80 and W=80-120).

3 Frequency of FEP Events vs. Fluence of Particles with Energy > 30 MeV:

Results for the case E > 30 MeV are shown in Figures 3 and 4.

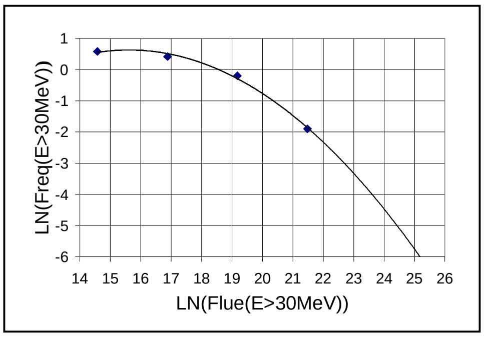

Figure 3: Averaged for several solar cycles, E>30 MeV.

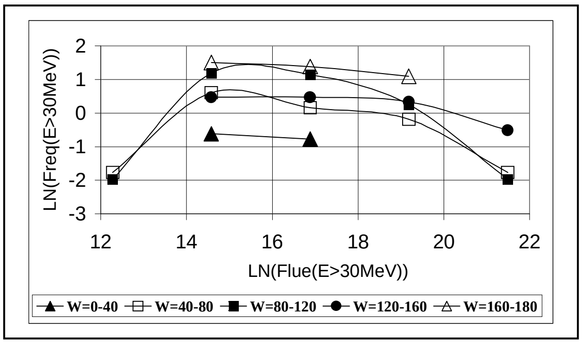

Figure 4: Averaged for different levels of solar activity, E>30 MeV.

The dependence showed in Figure 3 can be approximated by a parabolic function as in (1), with parameters:

$$a = 4.07\times 10^{-8},\ \ \gamma = 0.0724\ln F - 2.2604,\ \ (2)$$

Figure 4 shows that for great fluences (LN(Flue) = 14-20) the frequency of FEP events increases with the increasing of solar activity, but the biggest observed fluences (LN(Flue) about 21-22) happened in periods of intermediate solar activity (W=40-80, W=80-120, and W=120-160).

4 Results for Different Levels of Solar Activity:

Some dependencies showed in Figures 3 and 4 can be also approximated in a first approximation by parabolic functions, as in (1), but with parameters depending on the level of solar activity (see Table 1).

Table 1: Parameter γ in Eq. (1) in dependence of solar activity for cases E>10 Mev and . E>30 MeV

CASE	W=40-80	W=80-120	W=120-160	W=160-200
E>10 Mev	-0.0005lnF+0.380	0.0646lnF-2.1604	0.1131lnF-4.3341	0.2404lnF-9.5725
E>30 MeV	0.0537lnF-1.6109	0.1025lnF-3.2466	0.3995lnF-1.3070	0.01602lnF-0.4528

At great fluences the type (1) dependencies will be of power-law type with γ increasing with the increasing of the fluence. The obtained dependencies are in good agreement with those determined from solar and stellar flares (see the Introduction).

5 Discussion and Conclusions:

To estimate a possible cosmic ray flux from the flare and the probability of FEP events it is necessary to perform a convolution of probability functions in the multi-dimension space of physical parameters of active region, which take into account the main processes of flare energy accumulation, trigger, release, escaping into solar wind and transport to the Earth:

$$P_{cr} = \prod_i P_i(x_i)\,. \quad (3)$$

Indeed, in each real observation we are able to test a small part of the dependencies in this multi-dimension space. Usually, we obtain from real data analysis only some projection of parameters on a chosen plane:

$$P_{cr}^{j} = \iiint_{x_i} \prod_{i \neq j} P_j dx_j\,. \quad (4)$$

In principle, this division of variables allows to built a global probability function which can be useful for real estimations. It is necessary to analyze many main factors of influence and compare a part of them with observational data and statistical dependencies.

Solar cosmic ray generation in flares comprises several different processes:

(i) Accumulation of strong non-potential magnetic fields in the active region caused by penetration of convection cells into an old magnetic structure. This process leads to the creation of current, accumulated in the transition layer between old and new field tubes. The probability of this process can be described by the function $P_1(\Phi,\varphi,\lambda,\theta)$, which depends on the phase of 11-year solar activity Φ, on the phase of the development of active region itself φ, on its coordinates λ,θ (active latitudes and longitudes effects).

(ii) Modern approach to flare, as to anomalous magnetic field dissipation with threshold of action caused by current density in the current sheet, leads to some threshold dependence of probability of flare trigger. It depends on gradient of photospheric field and rate of its change with time (space-time gradients of the magnetic configuration with singular points $\nabla_{\mathrm{r,t}}\mathrm{H}$). Permanent current instability disrupts this narrow sheet with current into numerous "good resistors" of high conductive normal plasma - "bad resistors" of turbulent plasma. The resulting current propagation converts into percolation mode and leads to critical phenomenon behavior. Some precursor-like manifestations, as short life bursts of energy release, may be used as immediate sign of critical state. The correspondent probability function $P_2(\nabla_{\mathrm{r,t}} \cdot \mathrm{H}, \mathrm{A_i}, \Delta \mathrm{t_i})$ depends on the observed field gradients and precursory events with amplitude $\mathrm{A_i}$ and time of preceding as $\nabla \mathrm{t_i}$.

(iii) The next group of factors of influence on the cosmic ray content of solar flare depend on the position of the current sheet into the magnetic configuration and of the active region on the disc.

Naturally, the direct run-away of particles from the flare region may take place only if the current sheet is situated in the open part of the magnetic flux in the external part of the magnetic field. At the same time we believe that high power of the flare may take place only in the central part of the magnetic flux over the magnetic spot, where the field is strong enough. These two conditions can be obtained simultaneously only in the rare magnetic configuration with new field penetration directly into the spot. The name of this rare magnetic configuration is δ-configuration and it is a well known phenomenological necessary condition of proton flares events. Then, the probability function for this kind of flare's cosmic rays is $P_3(\xi,\Psi)$, where ξ,ψ are the magnetic coordinates in the system of magnetic poles.

In the case of "inner" current sheet, when accelerated particles are confined in the magnetic trap of closed magnetic lines, the direct run-away is not possible, but two ways of particles ejection are conserved:

a): Instability of the trap itself with ejection into the solar wind magnetic "bubble" with solar cosmic ray into. The probability of this event depends on cosmic-ray/hot-plasma density relative to the energy density *w*(c.r.), *w*(pl) and size of the active region *L*(a.o.) (criteria of balloon mode instabilities) and it is described by a probability E-function with transition on the threshold of stability (E(x)=0 for x<1, E=1 for x>1):

$$P_4(\mathrm{w_{c.r.}}, \mathrm{w_{pl}}, \mathrm{H}, \mathrm{L_{a.o.}}) \propto \mathrm{E}((\mathrm{w_{c.r.}} + \mathrm{w_{pl}})/\mathrm{H}^2)/\beta_{cr}(\mathrm{L}))\ . \ (5)$$

This instability leads to coronal mass ejection (CEM) with creation of cloud "solar cosmic rays-magnetic trap" expanding into solar wind with super Alfven shock wave on the front.

b): Slow diffusion across magnetic field by the anomalous scattering "fast particles-plasma waves" which leads to percolation of remaining particles into open part of magnetic configuration and next run-away into the solar wind. This probability function $P_5(\xi, \Psi, \mathrm{w_a})$ is caused by the position of flare's current region relative to the separating surface between closed and open fields (magnetic coordinates ξ, ψ) and level of plasma wave oscillation w_a (mainly whistlers and magnetic sound/Alfven waves).

(iiii) Another group of processes of flare creation is "trigger mechanisms" caused by external agents which disturb metastable current region near critical state and transit it into unstable state (induced catastrophe). The most known objects for this role are quiet prominence and coronal condensation /arc. Both of them are able to excite into strong oscillation as a result of mass accumulation or overheating. These disturbances probability $P_6\,(\mathrm{L,d;\,w_g}\ \&\ \mathrm{w_{th}}/\mathrm{H}^2)$. is caused by their size and ratio of gravitation/pressure forces to the magnetic stretching, which stabilized it

On the basis of these results it can be estimated the multidimensional "dangerous" region in the space of characteristics of solar activity region position, its field geometry, the evolutionary stage of corona above, solar wind characteristics and energetic particles propagation parameters. As an example of this approach we consider the influence on $P_1(\Phi,...)$ variation of convection characteristics during 11-year cycle and their manifestations. Investigations of active region origin during cycle show that the character of regions are changing with phase. In spite of sin(t)-like variations in the number of spots/active regions, its compactness, magnetic flux and field gradients change differently. Typical state of the photosphere fields in the maximum of 11-year cycle is the high number of active regions, up to ten, with magnetic fluxes of intermediate amplitude and dispersed field distribution (low gradients). On the contrary, in the stage of increasing-decreasing activity (especially in increasing state) it is often observed single active region of large size characterized by a complex inner magnetic structure (including δ-configuration) and fast dynamics. As a limit case we mention the unique events (existing in each cycle) with very strong proton flares in the deepest state of the minimum of activity, created by a strong active region arising suddenly for a short time (in the last minimum there was the giant X-ray/radio flare of 09 July 1996 with direct particles ejection and CME/shock wave). The physical reason of this difference may be caused by transition of convection during 11-year cycle from unstated condition with sporadic generation of strong covective cells into developed state of numerous well organized cells of intermediate amplitude. This difference should come out in the distribution of number of cosmic ray events of high fluence for different particle energies. Namely, we may wait excess of large fluence events, generated by flare-monsters not in maximum of activity, but in an intermediate stage of increasing or decreasing Wolf-numbers. This could be the reason of the well known attraction of all observed giant events out of the maximum phase of solar activity.

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