ELECTRONS AND X-RAY EMISSION OF SOLAR FLARES

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ABSTRACT
A statistical analysis of solar flare X-rays and interplanetary particle fluxes, measured onboard VENERA-13, 14 Spacecraft, was performed. The correlation of fluences for different manifestations of solar flares is strong, especially for fast electrons and hard and soft X-ray emissions. Frequency dependence on fluence value ε_i for practically all kinds of solar flare emission can be described by power law $\nu\ (\varepsilon > \varepsilon_0) \sim \varepsilon^{-0.45 \pm 0.15}$ which does not change significantly with solar activity. For different H_α flare importances the values of ε_i were obtained. It is proposed that appearance of certain energy flare frequency is strongly dependent on some scale factor.

1. INTRODUCTION.

Complex experiments have been carried out during the last few years measuring various flare manifestations in a wide range of wave lengths. It was shown that the full energy impacted in the flare volume by fast electrons with kinetic energy above 25 keV can be comparable with the total emission energy of the low and high temperature flare regions. These results are very important and new. But one should remember that only for seven flares such experiments have been done, which is not enough to draw general conclusions [1].

But there is another way to solve the problem. For different kind of solar flares emissions the maximum burst amplitude (P), its duration (ΔT) and total photon numbers or fluence (ε) can be easily obtained from experiment. If we disregard the peculiarity of each event, we can obtain statictics for these features, which can be measured in a large number of experiments.

As a result of a statistical procedure we can obtain the frequency of the phenomena with known fluence and some size distribution functions. This statistical approach allows us to obtain if not precise then at least proper quantitative ratios, which relate the different emissions among themselves. These relations can be used to obtain the energy balance during the flare for determination of the role of fast electrons and construction of a phenomenological model of the flare process.

The present work summarizes our statistical investigations based on measurements of solar flare hard X-ray and energetic particles fluxes in the interplanetary space, which were carried out onboard the VENERA-13, 14 Spacecraft in 1981-1983 [2-10]. The main results will be described below.

2. CORRELATION ANALYSIS. .

As a result of measuring N solar flares events we get the following values: Pxh = X-ray peak flux for Exh > 55 keV; Pxt = peak flux

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for 0.5 < Ex < 5 keV; PHα = Hα peak flux which is proportional to Hα importance, Pe = electrons peak flux; ε_{xh}, ε_{xt}, ε_H = the total quanta number or burst's fluence for Xh, Xt, Hα - emission and so on. For some couples (x, y) of these values we calculated the correlation coefficients. Some of these correlation diagrams are shown on Fig. 1.

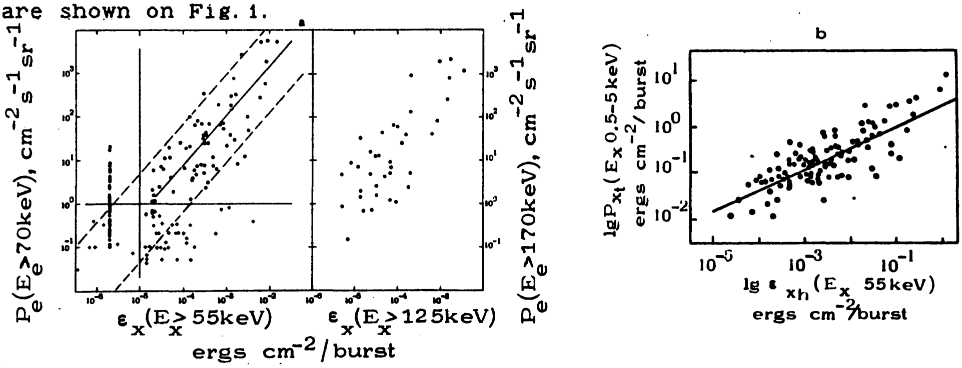

Fig. 1a. Correlation diagrams of the electron peak flux Pe with Ee>70 keV versus the X-ray with Ex > 50 keV fluence ε_{xh} (and for Ee>170 keV versus Ex > 125 keV). The vertical and horizontal lines show Pe and ε_{xh} values, within which selection effects exist.

Fig 1b. Scatter plots of the X_t peak flux Pxt versus the Xh (Ex>50 keV) fluence ε_{xh}.

By correlation analysis it was shown that if the number of events N exceeds 50, formally all of the correlation coefficients take the values: r_{oxy} > 0.5, and are "high-significant".

A list of results for strong correlations coefficients with r_{oxy} >0.75 is shown in Table 1. In this table we can see arrays x, y, value of r_{oxy} and the value of N for each of cross correlations.

Table 1. The results of cross-correlation analysis: y=a+bx.

No	X	Y	r_{oxy}	N	Reference
1.	lg Pxt	lg ε_{xh}	0.79	105	[9]
2.	lg Puv	lg ε_{xh}	0.84	101	[1]
3.	lg ε_e	lg ε_{xt}	0.80	-	[11]
4.	lg ε_{xh}	lg Pe	0.87	87	[8]
5.	lg ε_{xt}	lg Pp	0.83	55	[4]
6.	lg Pp	lg Pe	0.94	54	[10]
7.	lg Pe	lg ε_R	0.84	53	[10]
8.	lg Pp	lg ε_R	0.82	53	[10]

We include in Table 1 the results of Crannel [1, 11].

3. QUANTITATIVE RELATIONS BETWEEN SOLAR FLARES EMISSIONS.

Multiple regression analyses have allowed us to establish quantitative relations between Hα flare importance and the most likely value of the energy in optical, hard and soft X-ray emissions and the kinetic energy of the accelerated electrons [1, 9, 11] (see Table 2).

Table 2. Estimates of solar flare emissions energy.

The emission form	Hα importance			
	SN	SB	1N	1B
$\varepsilon_{H\alpha}$	$(2-6).10^{27}$	$(0.4-1.5).10^{28}$	$(2-5).10^{28}$	$(0.4-1.5).10^{29}$
ε_{opt}	1.10^{28}	2.10^{28}	1.10^{29}	$(2-3).10^{29}$
ε_{xt}	$(2-3).10^{28}$	$(0.8-2).10^{29}$	$(2-4).10^{29}$	$(2-5).10^{29}$
ε_e (>25 keV)	$(3-9).10^{28}$	$(1-2).10^{29}$	$(2-3).10^{29}$	$(3-10).10^{29}$

The emission form	Hα importance		
	2N	2B	3B
$\varepsilon_{H\alpha}$	$(2-5).10^{29}$	$(0.5-1.5).10^{30}$	$(0.3-2).10^{31}$
ε_{opt}	$(1.5-2.5).10^{30}$	$(3-5).10^{30}$	$(3-5).10^{31}$
ε_{xt}	$(0.4-1.7).10^{30}$	$(0.9-3).10^{30}$	$(1-4).10^{31}$
ε_e (>25 keV)	$(1-3).10^{30}$	$(2-4).10^{30}$	$(1-3).10^{31}$

These quantitative relations were obtained in usual models of emission generation and the movement of charged particles.

4. DEPENDENCE OF THE NUMBER OF EVENTS ON THE FLUENCE were found for different kinds of flare emission (Fig. 2). All the dependence can be described by power law with an exponent $\beta = 1.45 \pm 0.15$ for wide range of fluences. Only for extremely high fluences the spectra become steeper with $\beta = 1.9-2.0$.

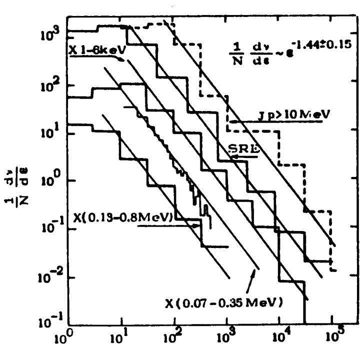

Fig. 2. Frequency dependence (differencial spectra) on fluence values: $(1/N)(d\nu/d\varepsilon)$ for different kinds of solar flare emissions.

5. DISCUSSION.

5.1. The total energy of the fast electrons in the impulsive phase of the flare and the energy of the hot plasma at the end of the impulsive phase, when the plasma temperature reaches its maximum, are practically functionally related: $r_o = 0.8$ [1, 9, 11].

5.2. The X-ray fluence (ε_{xh}) and electrons flux (Pe) are linearly connected (b=0.9 ± 0.10) in such events, where hard X-ray bursts and high energy interplanetary electrons are observed [8]. (Peak flux Pe ~ Ne - total electrons escaping number in the interplanetary space in all particles propagations models). One can explain such ratio if the total number of: hard quanta (Nx) and escaping electrons (Ne) are both proportional to the total number of the accelerated electrons (Ni). Electron escaping efficiency from the source into interplanetary space is described by the ratio Ke = Pe /ε_{xh}. This value K_e can be obtained directly from experiment without any additional suppositions (see Fig. 1a).

5.3. There is a strong correlation between the number of accelerated electrons (Ni) and protons (Mi) in the flare. The escape contidions into the interplanetary space are seemingly analogous [10].

The conclusion of the multifunctional correlation analysis is that the energy emmitted in the soft and hard X-ray range, the photons energy in the optical range of wave length and the energy of accelerated particles are a proportional measure of the total flare energy. From Table 2 can be seen that the energy inserted into the flare volume by energetic particles is comparable to the total emission energy of the low and high temperature plasma regions.

However for the continious spectrum of the accelerated electrons in their energy range Ee<10 keV [14], the true value for εe must be higher. Nearly the same energy can be inserted into the chromosphere by the accelerated protons with Ep>100 keV [15].

5.4. Table 3 shows the exponents of integral spectra obtained in different experiments during last 15 years. There is no reason to believe that the spectra vary significantly in time.

Table 3. Summary of β values for different solar flares emissions.

Emission, energy	Spectral index	Reference	Emission, energy	Spectral index	Reference
	electrons				
Ee>0.17keV	0.5±0.2	[16]	Rμ bursts	0.49±0.15	[4,19]
Ee>0.45keV	0.5±0.2	[17]	X-ray		
Ee>0.70keV	0.35±0.15	[8]	Ex 1-6keV	0.44±0.15	[4,12,13]
Ee>500keV	0.46±0.15	[17]	Ex>30keV	0.45±0.2	[20]
	protons		Ex>55keV	0.44±0.15	[4]
Ep>10MeV	0.15±0.1	[18]	Ex>300keV	0.50±0.15	[3,4,21]
Ep>10MeV	0.45±0.15	[17]	Optical band		
Ep>25MeV	0.35±0.15	[4]	of wavelength	0.80±0.10	[22]

Flare frequency with fluence higher than εo, has a simple dependence upon this energy ν $(\varepsilon > \varepsilon_o) \sim \varepsilon^{-\beta}$, with rather narrow β range. For extreme values of flares energy β increases up to 0.9-1.5.

This universal relation shows the existence of some deep and common objective regularities. These regularities demonstrate that the appearance of certain energy flare frequency is strongly dependent on some scale factor.

Pustilnik suggested [23] a possible explanation of this relation. In existing theories of stars convection the turbulence velocity ν_{turb} is described by usual relation:

$\nu_{turb}(l) \sim l^{-s}$, l - the size of turbulence cell.

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The spectrum index s varies within rather small values: from s=1/2 (for convection with magnetic field) and s = 1/3 (for Kolmogorov's turbulence) to s = 1/4 (spectrum of acoustic's and Alfven's waves turbulence, Kaplan). As a result Pustilnik obtained the dependence on flare frequency with energy higher than Eo:

$$\nu_{flare}(E>Eo) \sim \begin{cases} E^{-1.0+s/2} \sim E^{-(0.88-0.75)} & \text{(a)} \\ E^{-0.66+s/3} \sim E^{-(0.5-0.58)} & \text{(b)} \end{cases}$$

a) - fast magnetic field decrease with increasing altitude.
b) - slow magnetic field decrease with increasing altitude.

Thus we naturally come to distribution function of flare frequency $\nu_{flare}(E>Eo) \sim Eo^{-\beta}$, with index β which corresponds well to experimental data. This is not the only possible interpretation of solar (star) flare appearance frequency dependence. However, the possibility of obtaining experimental data which can give us information about the internal solar structure, make accumulation of such kind of data very important.

REFERENCES.

1. Crannel C.J., Hudson H.S. (1986)'Energetic phenomena on the Sun', Ed. Woodgate B.E. and Kundu M.R. (NASA CP-243a).
2. Barat C., Chambon G., Harley K., et al. (1981), Sp.Sci. Instr. 5, p 229.
3. Data from sol. hard X-ray monitor SIGNE-2M on VENERA-13,14 (1987) Sov. Geoph. Commit. A.N. of the USSR, Moscow, Ed. Kurt V.G.
4. Kurt V.G. (1989), In Sol. Plasma Physics, M. Nauka, p 138.
5. Melnikov V.F., Kurt V.G., et al. (1988), Sol.Max. Analysis (17-24 June, 1985, Irkutsk, USSR) Add. Issue, Novosibirsk, Nauka, p 366.
6. Daibog E.I., et al. (1987), 20th Int. Cosm. Ray Conf., V.3, p 45.
7. Daibog E.I., Kurt V.G., et.al. (1988), Izv. A.N. USSR, ser. fis. 52, p 2403.
8. Daibog E.I., et al. (1989), Sov. Cosm. Res. 27, p 113.
9. Kurt V.G., et al. (1989), Sov. Cosm. Res., 27, p 425.
10. Melnikov V.F., et al. (1990), presented at 21th ICR Conf., V5, Adelaida, Australia.
11. Crannel C.J., et.al. (1982), Ap. J. Lett., 329, p 969.
12. Teske R.G., Thomas R.J. (1972), Sol. Phys., 16, p 431.
13. Mayfield E.B., Lawrence J.K. (1985), Sol. Phys. 96, p 243.
14. Lin R.P., L. de Pan, Kane S.R. (1984), Sol. Phys., 91, p 345.
15. Daibog E.I., Kurt V.G. et al. (1983), Sov. Cosm. Res., 21, p 704.
16. Potter D.W., Lin R.P., Anderson R.A. (198), Ap. J. L., 226, L97.
17. Belovskiy M.N., Kurt V.G., et al. (1979), Sov. Cosm. Res., 17, p 906.
18. V. Hollebeck MAI, et. al. (1975), Sol. Phys. 41, p 189.
19. Neidig D.F. (1978), Sol. Phys., 57, p 385.
20. Pearson D.H. et al. (1989), Ap. J. 336, p. 150.
21. Vestard T. et.al., SMM observ. Gamma ray Astr. Group Phys. Dep. Univ. of Hampshire. Preprint N HO3224.
22. Kurochka L.N. (1987), Sov. Astronom. J. 64, p 443.
23. Pustilnik L.A. (1988), Sov. Astrom. J. Let., 14 p 940