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# On the correlation between the solar gamma-ray line emission, radio bursts and proton fluxes in the interplanetary space

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It is shown that the correlation takes place between the 4—7 MeV gamma-ray line flare fluence $F_{4-7}$ and the intensity of the >10 MeV proton flux in the interplanetary space as well as between $F_{4-7}$ and the peak flux density of microwave bursts. Besides, the energy spectral index of protons displays the definite dependence from parameters of the radio burst frequency spectrum. These testify that: a) there is a close physical association between the acceleration of electrons and protons in flares; b) protons, giving gamma-ray lines, and ones, registered in the interplanetary space, belong to the same population.

Es wird gezeigt, daß der Fluß $F_{4-7}$ der Gammastrahlung (Bereich 4—7 MeV) sowohl mit der Intensität des Protonenflusses > 10 MeV im interplanetaren Raum als auch mit der Flußdichte in den Maxima der Mikrowellenausbrüche korreliert ist. Außerdem weist der spektrale Energieindex der Protonen eine deutliche Abhängigkeit von den Parametern der Radiostrahlungsausbrüche im Frequenzspektrum aus. Daraus folgt, daß a) ein enger physikalischer Zusammenhang zwischen der Beschleunigung von Elektronen und Protonen während Eruptionen besteht, b) Protonen, die Gammastrahlung erzeugen und solche, die im interplanetaren Raum nachgewiesen werden, zur gleichen Population gehören.

*Key words*: sun — atmosphere — gamma ray line flare — proton flux — microwave bursts

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## 1. Introduction

Proton fluxes observed in the interplanetary space after large solar flares have the power-law energy spectrum $J(>E) = J_E \propto E^{-\gamma}$ with the index $\gamma \sim 1$—4 in the range of tens of MeV. On the other hand, protons of the same energies interacting with the solar atmosphere matter, excite the gamma-ray line emission with the whole flux $F_{4-7}$ in the range of 4—7 MeV. The acceleration of electrons taking place simultaneously, is accompanied in particular by the generation of microwave bursts with the peak flux density $S_f$ and the spectral maximum frequency $f_m \sim 3$—15 GHz (see CHUPP 1984, KOCHAROV 1987, CRANNELL et al. 1989).

The analysis of the correlation between the indicated parameters of gamma-rays, radio bursts, and proton fluxes is very important for a solution of two of principle and connected problems:

— does the observed dependence between the interplanetary proton fluxes and the flare radio emission mean the close relation between the acceleration of electrons and protons or does it reduces to the "Big Flare Syndrome", i.e. to a simple correlation which may exist between any (even wittingly independent from the physical point of view) parameters reflecting the flare energetics (KAHLER 1982)?

— do the protons, giving gamma-ray lines, and the interplanetary proton fluxes belong either to the same particle ensemble or to the different populations of which the former is accelerated directly in the region of the initial energy release, and the latter — in the shock wave propagating through the corona together with the coronal mass ejection (see LIN 1987)?

## 2. Gamma-ray fluence and proton flux

FOMICHEV and CHERTOK (1985), basing on the analysis of the radio emission from large flares and on the quantitative proton flare diagnostics technique, showed that the gamma-ray line flares, in contrast to the wide spread opinion, do not differ by a deficit of protons in the interplanetary space among the whole class of large flares. In the present paper the question on the correlation between gamma-ray bursts and proton fluxes is considered using the quantitative characteristic of the gamma-ray line emission — the fluence $F_{4-7}$. The corresponding data are published, for example, by HUA and LINGENFELTER (1987). As it is done in the analysis of other types of the flare emission, in particular microwave bursts, as in the investigation of the corresponding dependences one must consider only the flares which satisfy the proton flare criterion, i.e. large nonimpulsive flares with a significant metric component (FOMICHEV and CHERTOK 1985).

Shown in Fig. 1 is the relation between the gamma-ray fluence $F_{4-7}$ and the interplanetary proton flux $J_{10}$ for 15 such flares. For the west half of the disk and for the August 4, 1972 flare (E 09) the proton fluxes directly observed near the Earth are admitted as $J_{10}$ (Solar-Geophysical Data; LOGACHEV 1986). For the east flares the proton flux values are recalculated to the Earth using the generalized helio-longitude attenuation functions which have been obtained in frames of the proton flare diagnostics technique by radio bursts (see AKINYAN et al. 1981). One can see from Fig. 1 that the clear dependence takes place between the whole gamma-ray line flux and the interplanetary proton intensity for the west and east flares separately as well as for the whole totality of the events. When $F_{4-7}$ increases from 4 up to 700 cm$^{-2}$, $J_{10}$ grows on the average from 5 to $3 \cdot 10^4$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The correlation coefficient between logarithms of these parameters is $r \sim 0.87 \pm 0.06$.

The visible scatter of points is explained by that the gamma-ray emission characterizes the quantity of accelerated particles only, and the escape conditions (at least for the west events) as well as some other factors remain leaving out of account.

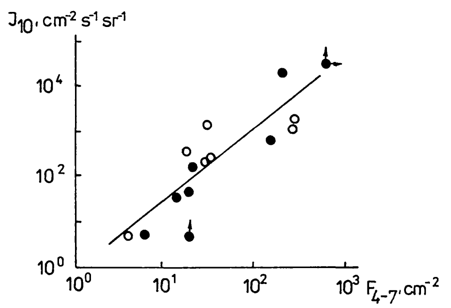


Fig. 1. The relation between the gamma-ray line fluence and the >10 MeV interplanetary proton flux for the west (●) and east (○) flares satisfying the proton flare criterion.

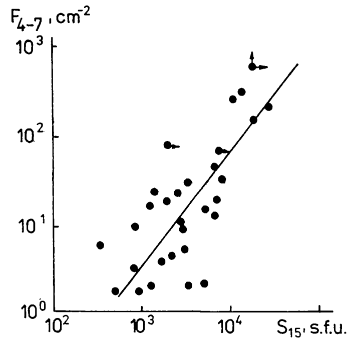


Fig. 2. The correlation between the gamma-ray fluence and peak flux density of microwave bursts at 15 GHz.

## 3. Gamma-ray fluence and microwave burst intensity

For clearing of the questions under consideration it is reasonable to analyse one more aspect: the comparison of the gamma-ray fluence $F_{4-7}$ with the peak intensity of microwave bursts, for example at 15 GHz, i.e. $S_{15}$. In such comparison one can use already the data on all 30 events with the known gamma-ray fluence without taking into account other characteristics of bursts and flares. From Fig. 2, in which the corresponding dependence is shown, it is revealed that the parameters $F_{4-7}$ and $S_{15}$ correlate well, too. The correlation coefficient between logarithms of $F_{4-7}$ and $S_{15}$ is $r \sim 0.72 \pm 0.08$. Of course the dependence between these parameters has a statistical character, and the scatter of point reflects variations of the acceleration efficiency of electrons and protons from one event to another as well as different conditions of the generation by ones of microwave bursts and gamma-ray line emission, respectively.

As it is known (AKINYAN et al. 1981), when the proton flare criterion is taken into account, the microwave burst intensity, in particular parameter $S_{15}$, displays a good relation with the interplanetary protons and is used with a success for the quantitative diagnostics of proton flares. Therefore, the correlation between $F_{4-7}$ and $S_{15}$ indicated above is an indirect evidence of the positive relation between the gamma-ray line emission and the interplanetary protons as well.

## 4. Energy spectrum of protons and frequency spectrum of radio bursts

It is highly important to consider as well the relation of the qualitative physical parameters of the frequency spectrum of radio bursts and the energy spectrum of protons, in particular the spectral maximum frequency $f_m$ and the index $\gamma$. Here about 40 proton events are analyzed which have the peak intensity near the Earth $J_{10} \gtrsim 5$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and are identified with the flares within the optimum longitude interval 20—80° West, where the longitude effects are not essential.

The Fig. 3 demonstrates that, in contrast to KAHLER's (1982) conclusion, the obvious dependence takes place between the frequency $f_m$ and the index $\gamma$. After flares with the relatively hard radio spectrum, when $f_m \gtrsim 9$ GHz, the proton fluxes with the hard energy spectrum are registered, in which the index lies mainly in the range $\gamma \sim 1 - 2$. In this case the increase of $f_m$ up to 70 GHz is not apparently accompanied by any meaningful variations of $\gamma$. On the other hand, for events with

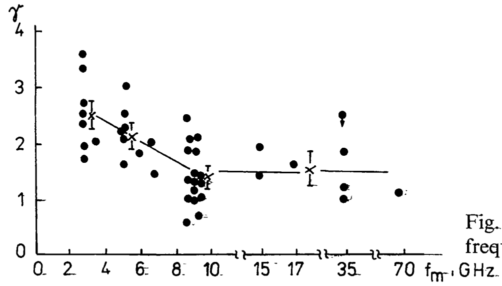


Fig. 3. The energy spectral index of protons versus the spectral maximum frequency of radio bursts.

the soft radio spectrum, when $f_m$ decreases from 9 to 3 GHz, the index $\gamma$ grows from 1.5—2.5 to 2.0—3.5, i.e. the proton energy spectrum becomes more softer. From Fig. 3 it follows as well that almost all proton fluxes with the hardest energy spectrum ($\gamma < 1.5$) were observed after flares with the hard radio spectrum ($f_m \gtrsim 9$ GHz). To the contrary, the flares with the soft radio spectrum ($f_m \gtrsim 7$ GHz) evidently predominate (~75%) among the events with the softest energy spectrum ($\gamma > 2$).

## 5. Conclusion

The undertaken consideration in totality with the results of FOMICHEV and CHERTOK (1985) leads to the conclusion that the gamma ray line emission, in a sense of the relation to the interplanetary proton fluxes, behaves analogously to the other types of the flare emission characterizing the initial energy release. Electrons and protons, accelerated in the flare, are close related with each other by the quantity of particles as well as by their energy spectra. The parameters of the proton fluxes observed in the interplanetary space, are determined largely by the physical conditions in the flare region and for the west flare ones are not distorted strongly in a process of the escape and propagation. As a whole the correlations between the characteristics of gamma-ray lines, radio bursts, and proton fluxes demonstrated above are on important evidence for the common origin of energetic electrons in the flare, protons generating gamma-ray lines, and proton fluxes registered in the interplanetary space.

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