X-ray flare characteristics and probability of solar proton events

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Abstract: The relation between solar particle enhancements near the Earth and solar flares properties is studied using as a working tool an extensive database of X-ray flares and proton events. This database includes about 63000 flares observed by GOES satellites and >1200 proton enhancements over the period of 1975-2007. Feasible for usage in the real time regime models of probability for the different types of proton enhancements are proposed based on the X-ray flare location and importance.

Introduction

Flares and acceleration processes are in the one complex of sporadic solar events (together with CME generation, radio bursts, magnetic field dissipation and reconnection). This supposes the connection (if not physical, but at least statistical) between characteristics of the proton events and flares. Belov et al., [1] have shown on the basis of study of large experimental material, that the main properties of proton enhancements near Earth are tightly related with the parameters of associated X-ray (first of all, with their power and heliolongitude).

The models allowing predict a probability and properties of proton enhancements near Earth by the flare and radio burst observations, were actively elaborated in 70-80 of the last century [2-7], and they are used at present, for example, in SEC/NOAA[8]. Already the first versions of these models proved their practical validity. Since that time a considerable volume of data is accumulated and more than 1200 proton enhancement near Earth have been selected [1] that gives a chance to obtain model parameters more correctly and to extend an area for usage of models.

In this work we use data on the flares and spacecraft and ground level proton enhancements (GLEs), collected over the period of regular solar soft X-ray observations by GOES satellites. The models of probability of the various proton events are constructed and optimized for real time prognosis of proton enhancements.

Data and Methods

This work is performed on the database of X-ray flares and proton enhancements (see [1], where the method of the event selection and identification with flares is described). Data on the soft X-ray (SXR) is obtained onboard GOES satellites. At present this database includes all X-ray flares observed from the end of 1975 to the beginning of 2007 in a region of 1-8Å wavelengths. Solar proton enhancements were selected by authors from the proton flux measurements of >10 MeV and >100 MeV (IMP-8 and GOES). During this period the 1274 proton enhancements with energy >10 MэВ were observed. We are succeeded in identifying of 679 events with solar sources. The first event regards to November 1975, the last one – to December 2006. The enhancements associated with solar sources allow us to study diverse relations and to establish quantitative correlations between flare characteristicscs on the Sun and properties of proton events near Earth. These dependencies, in particular, allow a creation of model of the proton event probability.

The model of a probability p_s of the proton event has been searched as $p_s(I_x,\varphi) = f_x(I_x)\, f_\varphi(\varphi)$, where $f_x(I_x)$ and $f_\varphi(\varphi)$ – are the functions of importance and longitude of SXR flare. Several versions of these functions were tested, and we chose finally the following shape:

$$p_S(I_x,\varphi)=\begin{cases}\left(\dfrac{I_x}{I_0}\right)^{\gamma}\exp\left[-\left(\dfrac{(\varphi-\varphi_0)}{\sigma_\varphi}\right)^4\right] & (I_x<I_0)\\ \exp\left[-\left(\dfrac{(\varphi-\varphi_0)}{\sigma_\varphi}\right)^4\right] & (I_x>=I_0)\end{cases} \quad (1)$$

Parameters I_0, γ, φ_0, σ_φ were derived using all the flares with importance >B5. The observed probability was equal to 1 if flare was associated with treated type of proton events, and it was 0 in all other cases. Calculations were carried out for different kinds of proton enhancements, some of properties of which are given in Table 1.

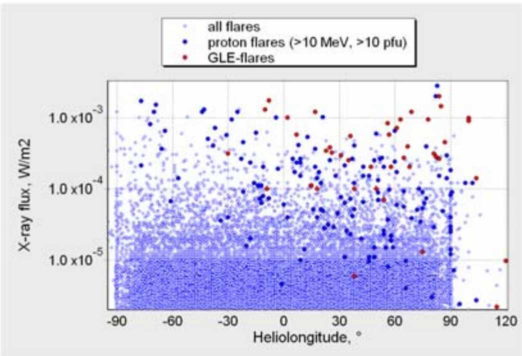

Figure 1. Distributions by importance and by heliolongitude of all SXR flares; flares associated with >10 MeV proton flux >10 pfu and flares associated with GLE.

Figure 1 demonstrates that proton flares are more often presented among the powerful X-ray flares. Going forward to eastern limb the number of proton flares decreases substantially whereas near the western limb there are many such flares. Note that here and further we shall name as "proton" only those flares which are associated with proton enhancement recorded near Earth.

Analysis of all proton SXR flares reveals the common properties of their peak flux (importance) and longitude distributions which are necessary to be accounted under the model elaboration.

Discussion of the results

Proton flares are mainly powerful flares located inside a definite longitudinal sector centered in the western part visible solar disk. There is sufficiently wide belt of western longitudes where probability of proton flare depends weakly on the longitude, but outside of this zone the probability falls quickly. Thus, remote eastern flares and majority flares on the back western side of the Sun have no chance to be registered at Earth as proton ones. Along the SXR importance increase a probability of the flare to be related to the proton enhancement is quickly growing up , and under definite, sufficiently large peak fluxes I_0 it approaches to the upper limit -100 %. It is clear that the further increase of the flare importance (flare energy release) cannot make the probability more high. A distribution of the GLE probability as function on I_x and φ is shown in Figure 2.

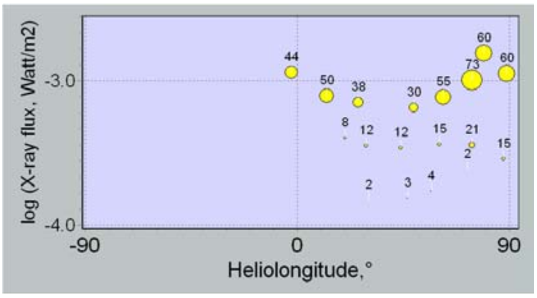

Figure 2. Fraction of GLE-flares among the flares of different power and heliolongitude. Numbers - mean probabilities of GLE observation after the flares in corresponding zone.

Distinction of proton and especially GLE associated flares from usual ones demonstrates Figure 3. Parameters I_0, γ, φ_0, σ_φ are calculated for the model (2) and presented in Table1.

Usual criteria of the model quality, such as dispersion or correlation coefficient value, are not informative in the case of the probability model. To estimate a model quality we calculated mean observed probabilities of the proton events for the cases when $p_s>0.5$ and $p_s<0.01$. These values (Table 1) testify sufficiently successful work of the models for all types of the enhancements.

Table 1. Characteristics of proton enhancements and associated solar flares.

Ep, MeV	$I_{PC,}$ pfu	N	N_I	I_{XM}	$\varphi_{m,}$ °	γ	I_0	φ_0°	$\sigma_{\varphi,}$°	p_s> 0.5	p_s< 0.01	$p_{s1,}$ %
>10	0.05	1274	679	X1.5	36	0.91±0.10	2.4±0.7	35±12	82±12	72.3	0.24	45.93
>10	1	595	430	X2.1	37	0.93±0.10	5.3±1.0	30±12	97±13	72.4	0.11	21.19
>10	10	275	215	X3.3	42	1.06±0.12	8.0±1.3	34±12	101±13	75.6	0.05	11.03
>10	100	100	94	X4.7	46	1.41±0.18	7.8±0.9	42±8	87±8	71.9	0.04	5.52
>100	0.01	637	399	X2.2	43	0.88±0.10	6.4±1.3	35±14	103±14	72.2	0.15	19.52
>100	1	120	107	X4.8	52	1.30±0.16	9.3±1.3	43±14	99±12	78.6	0.03	5.51
>100	10	46	45	X5.6	51	2.00±0.33	8.8±0.7	54±5	63±5	72.2	0.02	1.29
GLE	-	44	44	X5.4	55	2.02±0.30	8.8±0.6	54±5	63±5	72.2	0.02	1.24

Explanations: Ep-kinetic proton energy; Ipc- minimum threshold of the proton flux; N and N_I – number of all and flare associated proton events; I_{XM} – mean importance of the X-ray flares, estimated for the events within E85-W85 longitude range; φ_m – mean longitude of the flares, associated with GLE and large SPEs, and it is median longitude for all other cases.

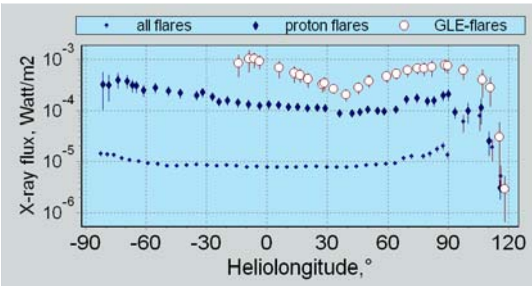

Figure 3. Heliolongitudinal dependence of the mean importance of all SXR flares, flares associated with proton enhancements of >10MeV, and flares associated with GLEs.

For example, in 13 of 18 events where calculated GLE probability was >0.5, the ground proton enhancements were really observed. And of 31173 events with p_s<0.01 the GLEs were recorded only in 5 cases. We can judge about accordance of simulated and experimental probabilities of proton events by Figures 4 and 5. The obtained models are approximately equally effective to all types of enhancements. Along with it the parameters of these models strongly differ. One can see that probability of the large enhancements depends stronger on the SXR flare importance than that for the small ones. Index for the smallest enhancements is $\gamma\approx0.9$ and it is about 2 for the largest events. By the similar way (from X2.4 to ≈X9) changes critical peak flux of the SXR flare I_0, which is sufficient to provide the 100% probability of the small and large proton enhancements after ideally located flares. In a whole, the weaker proton enhancements the wider longitudinal zone associated flares occupy (parameter σ_φ varies from 63° for large proton events and GLEs up to ≈100° for bigger part of other types of enhancements).

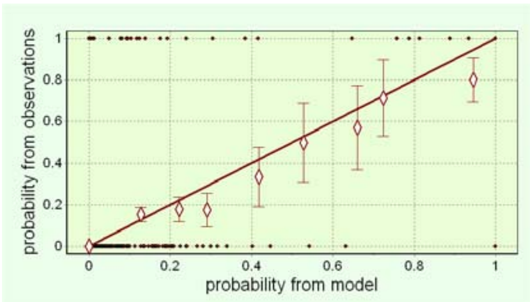

Figure 4. Correlation between simulated and observed GLE probabilities. Points mark flares associated and not associated with GLE. Diamonds are averaged experimental probabilities corresponded to different ranges of p_s.

Srector of the effective heliolongitudes is located most to the west (φ_0=54°) for large and ground level enhancements. For relatively small enhancements this region is shifted more close to the central meridian and φ_0=30-35°. To make a dependence of calculated probability on energy threshold and magnitude of the proton enhancement more presentable, we added in Table 1 a probability p_1, calculated for definite flare of importance X1 and longitude W45. For such flares model forecasts weak proton enhancements (above the background for >10MeV) almost in a half number of events. At the same time for such flares the most outstanding enhancements (large and GLE) are expected only in one case from 80.

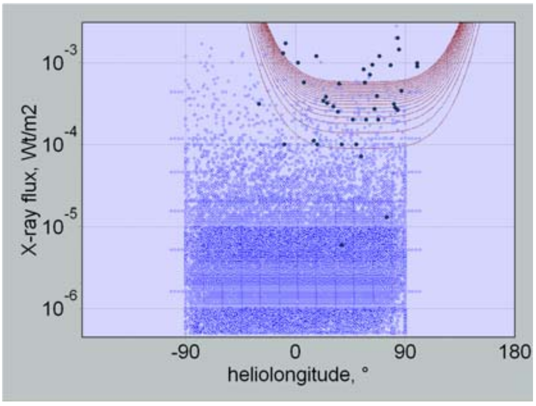

Figure 5. SXR flare distribution (light points) by flare importance and by heliolongitude. Dark points of larger size represent the flares, associated with GLEs. Contour curves are depicted for equal p_s; inside contour corresponds to probability of 50%, outside one – to 1%.

Conclusion

The model of probability for different proton event subsets is created on the basis of all data on X-ray flares and proton enhancements. Model is suitable both for a short time forecasting from X-ray observations, and for a more long time forecasting in combination with flare forecast. At the same time we do not consider supposed model as the best one. We tried only several of possible dependencies, and probably, a longitudinal dependence may be improved. It seems, the model may be improved with addition the information about initial phase of the X-ray flare. It may be useful also to replace or supplement X-ray power by the characteristics of solar radio bursts, which are more directly related to acceleration processes than X-rays.

It is clear that probability model should be supplemented by estimations of maximum proton flux and its time delay respectively to the solar event. It may be realized using the same data and similar approach to their processing, obtaining in result a possibility of more detailed forecasting of proton events.

Acknowledgement

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