Longitudinal dependence of solar proton peak intensities using the X-ray and proton data in the period of 22-23 cycles

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Abstract. The calculations of the heliolongitudinal dependence of solar proton peak intensities for protons with energy more than 30 MeV were made. The new method of analysis of a posteriori probability of SPE observations with the proton peak intensities more than the given intensity by condition of observation the associated solar X-ray bursts with peak intensities more than the given intensity was used. It was shown that the heliolongitudinal peak intensity decrease for the event with flares in the western half of solar disk is practically absent, for heliolongitudinal interval from 0° up to 30° E is equal to 30 and for heliolongitudinal interval 30°-90° E is equal to 100-150.

1. Introduction
The research of the peak particle intensity heliolongitudinal dependence of earth-observed solar proton events (SPE) is connected with the problem of studying the solar proton propagation in solar corona and interplanetary space and with the problem of SPE forecast on electromagnetic radiation of solar flares. One must take into account in this research the different nature of formation of the SPE maximum: the formation of maximum due to the diffusion propagation in the interplanetary space and the formation of maximum due to shock acceleration and particle catch in shock waves structures.

We study here the peak particle intensity heliolongitudinal dependence for particle energy exceeding 30 MeV. For such energies the first mechanism of the maximum formation has the advantage [1]. For particle energy about 10 MeV the second mechanism probably plays the basic role.

Three methods may be used for the heliolongitudinal dependence determination. The first one consists of the research of SPE peak intensity distributions and theirs heliolongitudinal dependences. It is proposed in this method that the number of events with the given peak intensity doesn’t vary with heliolongitude if the value of the observed intensity \( J_p \) is corrected with the help of multiplying by the heliolongitudinal decrease coefficient \( k(\varphi) \). That is:

\[
N_\varphi (J_p, k(\varphi)) = N_\varphi (J_p) = \text{const}(\varphi)
\]

(1)
doesn’t depend on heliolongitude \( \varphi \). In this expression \( \varphi_0 \) is the heliolongitude of footpoint of the field line connecting the Earth with the Sun, which is equal to approximately 60° W, \( N_\varphi (J_p) \) – the integral distribution of SPE on peak intensity \( J_p \) for flares with heliolongitude \( \varphi \).
This method has been implemented in [2-3]. The shortcoming of such method is that in reality the number of SPE from flares with given heliolongitude $\varphi$ may appreciably fluctuate due to the fact that event origins are not independent due to the active region and the active longitude existence and the existence of periods in the origin of flares.

The second method means the immediate SPE observations by satellite with different footpoints of the field line connecting the satellite with the Sun. This method has been implemented in [4]. The shortcoming of the method is insufficient statistical availability of the results for various longitudes.

2. The method of research

In this work the third method is proposed – the method of studying the two-dimensional distributions of the SPE peak intensity and the peak intensity of previous X-ray bursts. We used GOES satellite data on X-ray bursts in the spectral band 0.1-0.8 nm and the data on SPE with proton energy more than 30 MeV.

We utilized the two-dimensional integral distributions $N(0, J_x)$, where $J_p$ is the SPE peak intensity in particle/cm² sec sr and $J_x$ is the peak X-ray burst intensity in $10^{-5}$ Watt/m² (the value $J_x=1$ corresponds to peak intensity of the X-ray burst of class M1). The function $N(0, J_x)$ is the integral distribution on peak intensity for all bursts (after which the SPE were observed or were not observed). The function $N(J_p, 1)$ is the integral distribution on peak intensity for SPE after X-ray bursts with classes more than M1. This function practically coincides with integral distribution for all SPE in expression (1), as the SPEs are practically absent after the X-ray bursts with classes below M1.

The function $W(J_p, J_x)=N(J_p, J_x)/N(0,J_x)$ is a probability observation of the burst with peak intensity more than $J_x$ following the SPE with peak intensity more than $J_p$ among all bursts with peak intensities greater than $J_x$. The value of this function doesn’t depend on flare longitude when multiplying the observed proton peak intensity value by heliolongitudinal decrease coefficient:

$$W(J_p, J_x)=N(J_p, J_x)/N(0,J_x)$$

In contrast to (1) $W$ determines the flare property that doesn’t depend on heliolongitude (probability of generation and injection in interplanetary space of the energetic protons) and must fluctuate with longitude significantly less than $N(J_p)$.

We may calculate the heliolongitudinal decrease coefficient by taking the coefficient in expression (2) so that the probability for heliolongitude $\varphi_0$ is equal to the probability for heliolongitude $\varphi_0$ for all $J_x$.

3. The results of research

We calculated $W(J_p, J_x)$ for various values of $J_p$ beginning with $J_p=0.3$ particle/cm² sec sr in 22 and 23 cycles of solar activity for all X-ray bursts of classes $\geq$ M1 (with known coordinates) for four heliolongitudinal intervals: 1) [90°W-30°W) 2)]30°W-0°) 3) [0°-30° E) 4) [30°E-90°E] (further the lower index indicates the number of interval in expression for $N$ and $W$). For these intervals $N(0,1)=512$, $N(2,1)=183$, $N(3,1)=263$, $N(4,1)=367$ for 23 cycle, and $N(0,1)=564$, $N(2,1)=312$, $N(3,1)=288$, $N(4,1)=405$ for 22 cycle; $N(0,3.1)=55$, $N(2,3.1)=22$, $N(3,3.1)=13$, $N(4,3.1)=7$ for 23 cycle and $N(0,3.1)=37$, $N(2,3.1)=17$, $N(3,3.1)=14$, $N(4,3.1)=5$ for 22 cycle.

In figure 1 and figure 2 the results of calculation for the intervals 1 and 2 are shown. As it follows from these figures the curves for 1 and 2 intervals coincide well for various values of $J_x$ and $J_p$. This means that heliolongitudinal decrease for interval 2 practically is absent in 23 cycle and also in 22 cycle. Then we may unite the intervals 1 and 2 and use only one interval 0-90° W in a further calculation. It follows from these results that probability of SPE after X-ray bursts in 23 cycle is greater (by factor of two) than in 22 cycle.
In figure 3 the results of calculation for the intervals 0-30° E and 0-90° W for 23 cycle are shown. As follows from this figure the curve for \( J_p=0.3 \) for interval 0-30° E coincides well with the curve for \( J_p=10 \) for interval 0-90° W and also do the curves for \( J_p=1 \) and \( J_p=30 \) for these intervals. This means that the heliolongitudinal decrease coefficient for interval 3 is equal to 1/30.

The calculation of propability \( W_{4}(J_p, J_x) \) for interval 4 may not be done in full volume because of a small quantity of SPE observed from flares in this interval. But \( W_{4}(0.3, 1 )=7/367=0.019 \) is approximately equal to \( W_{1+2}(30, 1 )=11/695=0.016 \). This means that the heliolongitudinal decrease coefficient for interval 4 is equal roughly to 1/100.

Figure.1 The dependence of the probability \( W(J_p, J_x) \) on \( J_x \) for 23 cycle. The solid lines (red) are for interval 30-90° W, the dash lines (blue) are for interval 0-30° W. The upper lines are for \( J_p=0.3 \), the lower lines are for \( J_p=1 \).

Figure.2 The dependence of the probability \( W(J_p, J_x) \) on \( J_x \) for 22 cycle. The solid lines (red) are for interval 30-90° W, the dash lines (blue) are for interval 0-30° W. The upper lines are for \( J_p=0.3 \), the lower lines are for \( J_p=1 \).

Figure.3 The dependence of the probability \( W(J_p, J_x) \) on \( J_x \) for 23 cycle. The solid lines (red) are for interval 0-90° W, the dash lines (blue) are for interval 0-30° E. The upper dash line is for \( J_p=0.3 \), the lower line is for \( J_p=1 \). The upper solid line is for \( J_p=10 \), the lower is for \( J_p=30 \).
The dependence of the heliolongitudinal decrease coefficient on heliolongitude is shown in figure 4.

![Figure 4](image)

**Figure 4** The dependence of heliolongitudinal decrease coefficient on heliolongitude. The solid line – the result of this work (23 cycle), dash lines – the results of [4] (upper line), [3] (middle line), [2] (lower line)

### 4. Conclusion

According to this research the heliolongitudinal decrease for intensity of SPE in longitudinal interval 0-30°W is actually absent if compared with interval 30°-90°W. This differs from results [2-4].

The heliolongitudinal decrease for interval 0-30°E is equal to 30, that is appreciably larger than in [4] (there it is equal to 5-6). However for some events connected with flares from this interval the heliolongitudinal decrease must be appreciably smaller. For instance, in the event 19.10.89 and 23.03.91 the proton flux in maximum was equal to $10^4$-4* $10^4$particle/cm²secstr (for energy 30 MeV) and one must suppose with difficulty decrease in 30 times. These are large events with the formation of maximum due to shock waves. This is also in accordance with results [5].

The heliolongitudinal decrease for interval 30°-90°E is equal to 100 with agreement with results [2].

### References

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Adv. in Space Research 17 113-114