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Statistical analysis of solar proton events in different energy channels

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Abstract. A new catalogue of the solar proton events in the energy channels >10 MeV, >30 MeV, >60 MeV and >100 MeV and GLE for the period 1976-2000 was created.
Solar proton events (SPEs) for three complete 11-year solar cycles (1976-2000) have been studied. Longitudinal distribution of the 168 identified Hα solar flares and peak size distributions of all 200 events with proton energy >10 MeV and peak intensity >10 pfu (particle $cm^{-2}s^{-1}sr^{-1}$) observed at 1 AU were obtained. In addition, to examine the energy dependence of the proton event frequency we have constructed the peak size distributions for three energy thresholds of protons >30 MeV, >60 MeV and >100 MeV for the time interval 05.1987÷10.1995.

1 Introduction

Solar proton events having a flux of 10 MeV protons ≥10 sfu are the subject of the big amount of works and have been studied by many authors (Feynman et al., 1990; Mendoza et al., 1997; Crosby et al., 1993). The first approach to understanding the variability in the proton production, escaping into interplanetary space and propagation processes of the energetic particles has been a statistical study of a large number of solar particle events and the associated solar flares is the work of Van Hollebeke et al. (1975). The authors studied the procedures for identifying the parent flare for proton events and summarized the properties of the 125 events for which the location of the initiating flare could be established. The most important characteristics were found to be the maximum particle intensity I_{max} at a given energy and the slope of differential energy spectra constructed with these I_{max} (measured in different time intervals). By studying the variation of these parameters with the heliolongitude of the parent flares the existence of a “preferred connection region” from 20°W to 80°W has been established.

Several catalogs of the proton events have been created recently. Gerontidou et al. (2001) presented an updated catalogue of solar proton events for the period 1987-1996 and separated the events into ordinary and anomalous events with respect to their sources at the Sun, their peak intensity and their ground level enhancements.

The best one and the most complete is the catalog edited by Logachev (Basilevskaya et al, 1983, 1986, 1990, 1998), which covers 1970÷1996 period and contains a lot of additional information.

In this report we present the first results based on the new data set created for the purposes of the statistical study of high energy events measured in the interplanetary space. Our catalog covers time interval from the 1976 till now, is based on the catalog (Logachev ed., 1983, 1986, 1990, 1998) and on the GOES data. The detailed description of our catalog will be published soon.

2 Data Description

The new data base contains onset time for flux of 10 MeV protons ≥10 $\{cm2\text{-}sec\text{-}ster]^{-1}$, values I_{max} for Ep>10 MeV, and in addition a column with GLE (ground level enhancement) events, start, peak times, duration and accumulated fluence for the parent soft X-ray flares, and importance and coordinates for Hα parent flares. We included in the catalog the I_{max} values for Ep>30, >60 and >100 MeV for the period since 05.1987 to 10.1995.

Each discrete solar proton increase was considered as “one” event. Increases associated with arrival of an interplanetary shock at the Earth were included into our listing if the solar flare producing the interplanetary disturbance has been identified. It should be kept in mind that the identification of the parent solar flares and definition of the peak flux value for the flares situated on the East part of the solar disk are mostly intuitive and based on the criteria which are not comprehensible to all. In

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particular we sometimes adopted the peak flux values for 10 MeV protons measured within the time of SC disturbance as I_{max} value. Actually in such a case we measure the combined flux, which has been influenced by acceleration caused by the interplanetary shock and propagation effects.

We are guided in our choice by the supposition that proton flux near the Earth is connected with the total energy release during the parent flare development. As a result of that energy release direct particle acceleration takes place and, an additional acceleration on the shock front in the solar corona and in the interplanetary space form the particle fluxes and energy distribution near the Earth.

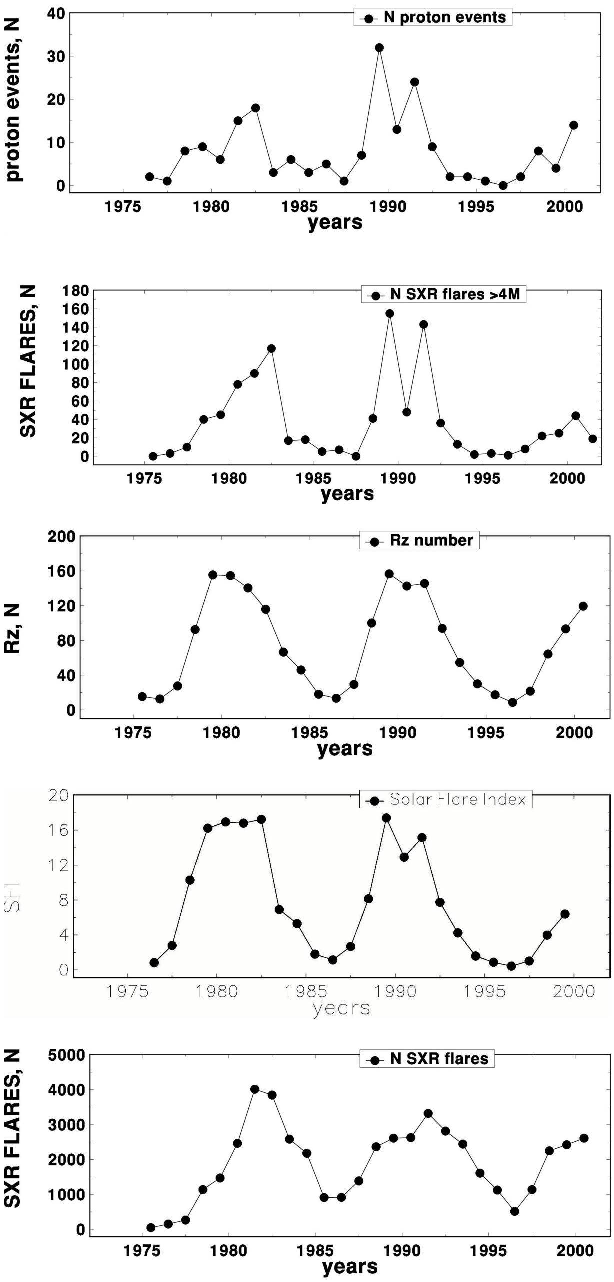

Fig.1 Yearly values of the proton events Ep>10 MeV, number of soft X-Ray flares with importance >4M, all SXR flares number, solar flare index, and sunspot number.

3 Results

1. We identified 200 proton events with E_p>10 MeV and I_p ≥10 pfu with SXR GOES flares and 168 proton events with Hα flares; in 125 events proton energy spectra extended up to E_p>100MeV (I_p >3*10^{-2} pfu) and 27 events were accompanied by GLE (E_p>500MeV).

Fig. 1 represents from top to bottom the yearly values of the 10 MeV proton events, number of SXR flares with importance ≥4M, number of all SXR flares, solar flare index-SFI values and Rz numbers for three solar activity cycles

Correlation coefficients between these solar activity indices and yearly proton events numbers are presented in the TABLE

	SXR>4M	*SXR all*	*SFI*	*Rz*
K_{pi}	*0,94*	*0,64*	*0,79*	*0,76*

It is noteworthy to mention the large value of correlation coefficient of SPEs with SXR flares≥M4.

2. Fig. 2 shows the longitudinal distribution of the parent flares for proton events with energy >10 MeV and >100MeV. The scatter plot of I_{max} for the events with E_p>10 MeV versus the longitude of the parent flare is depicted on the Fig. 3. We know well that interplanetary disturbances accompanied the shock waves occurring after central disk flares are the most efficient near Earth. It means that shock waves help us to see protons with smaller energy and do not influence significantly on the high energy protons propagation. (Smart and Shea, 1996; Bazilevskaya and Sladkova, 2000).

We found that a fraction of the events with Ip >300[cm2-sec-ster]$^{-1}$ in the longitude interval –E40°÷W10° is twice in comparison with the all other longitudinal intervals. This result is useful as a new diagnostic tool for the cosmic weather forecast.

3. The 1987-1995 time interval is known as the most productive for the high energy solar flares. During this period of time we identified 70 protons events with >30 MeV with Ip>0,1 pfu, 66 events with >60MeV and Ip>0,02 pfu, and 52 events with Ip>3*10^{-3} pfu.

Many subsequent observations of different kinds of the solar flares neutral emissions and electron events determined that the frequency size distribution, based on their energies is a power law with the slop values 1,3-1,45 (Datlove, Elkan, Hudson, 1974, Kurt, 1990, Crossby, Aschvanden and Dennis, 1993, Whetland, 2000). For the proton events this slope value has been found between 1,15÷1,45 (Cliver et al, 1991, Feinmann et al,1993, Gabriel, 1996, Kurt, Nymmik, 1997,) for different data sets and for different proton energy ranges. This relatively wide sparse has given a possibility for the speculations with the proton acceleration models (Kuznetzov, Kurt,1991)

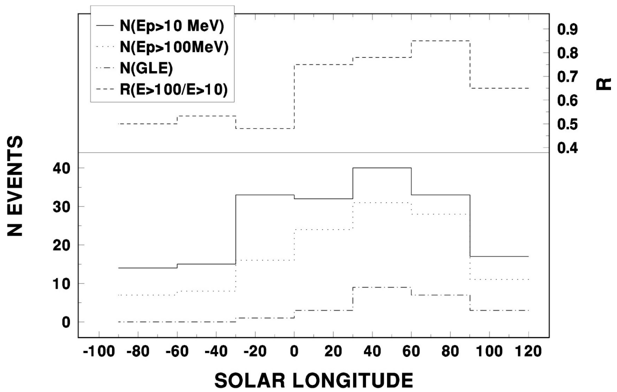

Fig.2. The longitudinal distribution of the parent flares for proton events with energy >10 MeV and >100MeV(bottom part) and ratio of the number of the events with E>100Mev to the number of the events with E>10 MeV9(upper curve).]

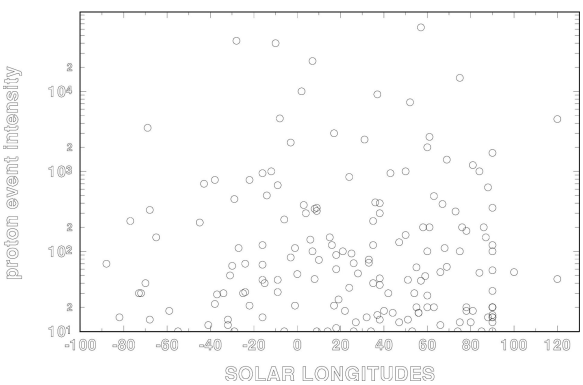

Fig.3. The scatter plot of I_{max} for the events with E_p>10 MeV versus longitude of the parent flare.

We constructed the differential frequency –size distribution of the peak values of the protons events with energy E_p>10 MeV, >30 MeV, >60 MeV, >100 MeV which are based on the mentioned above data set and subset.

On the Fig. 4 we present peak-size distribution for E_p>10 MeV. The best fit for power law slope of the log-log curves outside the low size turnover are: 1.41±0.04, 1.34±0.05, 1.2±0.03 and 1.12±0.12 respectively. This is the small number of events to work with, and an important question to be considered is what types of difference in the individual distributions would be able to detect given this numbers. An important potential problem with this study is the presence of bias in the constructed frequency–size distributions. Two specific biases have already been encountered, namely, the failure to detect small events (the rollover near experimental thresholds) and the difference between the distributions in the high intensities ranges constructed with pure statistics (Higson and Lingefelter, 1985).

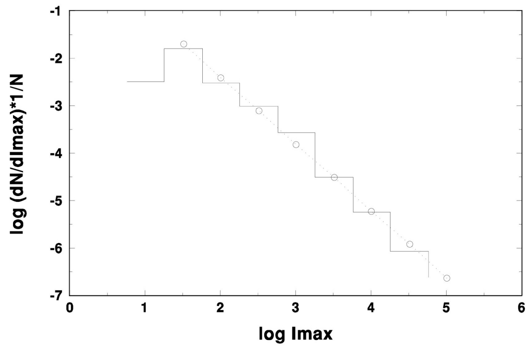

Fig.4. Peak-size distribution and best fit for E_p>10 MeV.

The result of this study is agreeable with the results of the previous works and suggests that the protons events share the same flare emissions frequency–size distribution. (Kurt,1990, Mendoza et al., 1997). The implication is that the flare frequency size distribution is intrinsic to the flare mechanism and every kind of the flare's emission carries away a proportional part of the total flare energy release. It is unlikely, as noted above, that the fine effect of the acceleration efficiency protons up to high energies could be detected given the available statistics, and so the conclusion is that the results are consistent with the avalanche picture (Lu, Hamilton, 1991). The ratio between the numbers of the events having proton energy >100 MeV and >10MeV is R=(125/200) Value of R is in accordance with the more probable value of the differential proton energy spectra slope ~2.5-2.9 in the energy interval of 5÷200MeV. This relation and lack of the significant difference between peak flux distributions obtained for different energy intervals allow us to conclude that in the flares with 10 MeV protons the break in the energy region ~100 MeV does not appear as a rule.

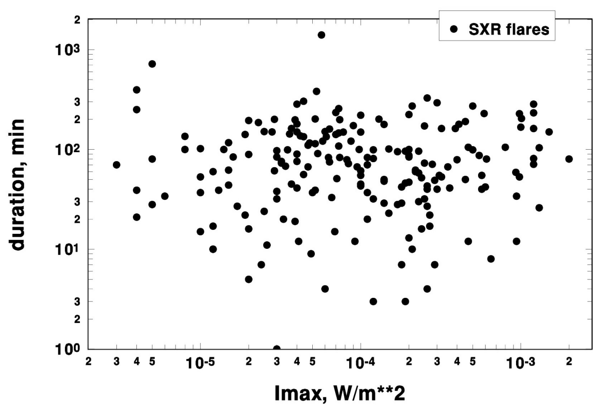

Fig.5. Scatter plot of parent flare soft X- emission duration versus I_{max}

4. Among solar flares the "proton emitting" flares are something exceptional: the high energies particles carry radiation danger. As a rule the total energy released during the flares with a big amount of the run away protons with energy >10 MeV is >(5÷9)*10^{28} ergs and Hα importance >1B (Kurt, 1990).

In Fig. 5 we can see that in the SXR emission the "proton emitting" flares mostly last >10 min and their importance exceeds value 4*10^{-5} Wt*m^2 (importance M4 by GOES classification).

This result together with the value 0.93 for the correlation coefficients between yearly number of proton events and SXR flare number with importance >4M seems is also useful for radiation forecasting.

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