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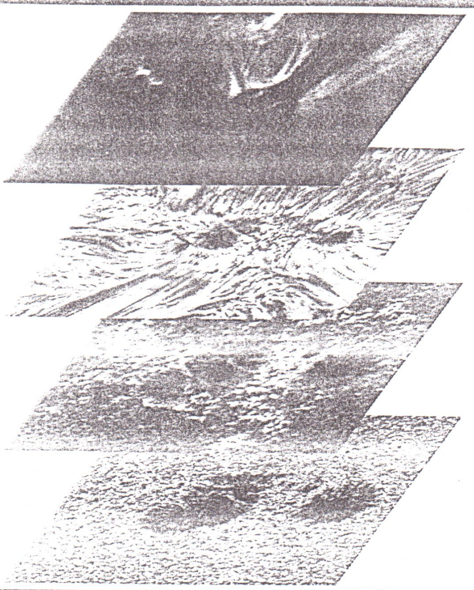

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ENERGY DEPENDENCE OF THE SOLAR PROTON EVENTS AT 1 AU

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ABSTRACT

As has been recognized recently, data on size (frequency) distributions for different sets of solar flare parameters are very helpful for modeling flare and acceleration processes. In this work we analyze long-term data (1970-2001) verifying carefully published catalogues of Solar Proton Events (SPEs) and real measurements that were carried out onboard several Spacecraft. We have separated at first 232 events above 10MeV with proton flux>10pfu (particles $\cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}$) associated with identified sources (flares). We have also created catalogues of these events identified the proton fluxes for the energy threshold >10MeV, as well as for proton fluxes >30MeV, >60MeV and >100MeV above 10^{-2} pfu. Differential size distributions of the peak values of these events have been constructed separately for each energy integral threshold and have been fitted by power law with indices between 1.28 and 1.35 depending on energy. Then, within this database of SPEs a second set of events originated only from flares with longitude >25^0W , was formed. The slopes of the responding size distributions in the energy range 10-100 MeV seem to be greater than the other ones including full disk flares-related events. Moreover it was found that a certain difference exists in the slopes at >10MeV and >500MeV in the size distributions constructed on the base of those solar proton events associated with ground level enhancement (GLE) in Neutron Monitors network (E > 500MeV). This may point to a dependence of slope on the proton energy under consideration.

1. INTRODUCTION

Data on size distributions of different sets of solar flare parameters (peak fluxes and /or energy fluences in X-ray and radio wave bursts, in proton and electron emissions, etc.) have been extensively reported in recent decades [1],[2],[6]. These data were recognized to be very helpful for the resolution of some problems related to flare modeling [3],[4] and particle acceleration[5],[6]. It has been found that the frequency distributions of various solar flare phenomena show a power-law shape consistent with the stochastic model of [3] suggesting that the flare energy build-up is governed by exponential growth. In the development of the avalanche model of solar flares, [7] suggested to take into account the finite size of active regions, while [8] used the energy release through magnetic connection in multiple current sheets as an alternative suggestion to the avalanche model for flares. The slope of the distribution functions however, is dependent on the flare parameter under study. Typically, the slopes are of 1.7-1.8 for peak flux, 1.4-1.6 for flare energies and about 2.0 for flare duration. As to the proton peak flux distributions at the Earth's orbit, they turn out to be significantly flatter than those obtained for other parameters of solar flares more representative of the total flare energy. Setting the differential distribution in a power-law form the following slopes have been obtained: 1.15±0.15 in the energy range of 20-80MeV [9]; 1.40±0.15 at >10MeV [10]; 1.35±0.15 at>25MeV [1]; 1.13±0.04 in the range of 24-43 MeV [11]; 1.47 and 2.42 at >10MeV [12] at the peak flux intensity below and above 10^2p.f.u., respectively; 1.27±0.02 and 1.38± 0.03 [13] at the peak fluxes of the >10MeV protons above 1p.f.u.and 10pfu respectively; 1.3±0.2 at the proton energy >10MeV and peak fluxes >10pfu [14].

The clear differences between the slopes of size distributions for proton, electron and electromagnetic flare emissions are very important to interpret the initial stage of acceleration of solar cosmic rays. In the light of a new arising paradigm of particle acceleration at different sources at/ near the Sun (flares, shock waves etc) an extended statistical study of solar proton events (SPEs) has started during last years.

Solar proton events having a proton flux with energy >10MeV and peak intensity ≥10pfu are the subject of the big amount of works [15],[13]. 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 [9]. 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. The purpose of this work is to compile a homogeneous of time in order to obtain the size distributions for proton

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events relying upon more abundant SPE statistics than in previous works. In order to examine the energy dependence of the proton events, peak size distributions in different energy thresholds of protons (>30, >60, >100MeV and >500MeV) have been constructed. The same analysis performed on the database of proton events originated only from flares of the west disk of the Sun. New catalogues of solar proton events covering the Time interval from 1970 till now that means three complete solar cycles, are used for the purposes of this study. These catalogues are based on the Moscow State University catalogue [16],[17] and on NOAA list from the GOES data. The Neutron Monitor data base of IZMIRAN is also used for identification of the GLEs.

2. DATA DESCRIPTION

In a recent work, Gerontidou et al. (2002) presented an updated catalogue of solar proton events for the period 1987-1996 separated the events into ordinary and anomalous events with respect to their sources at the Sun, their peak intensity and their ground level enhancements. This catalogue has been extended from 1970 up to 2001 separated the well-identified events for five different energy channels (>10, >30, >60, >100, >500 MeV). The new data base of solar proton events contains the start time, the time and the duration of the peak intensity, the accumulated fluence for the parent soft X-ray flares, the importance and coordinates for H-alpha parent flares, the onset time for flux with proton energy >10MeV and peak intensity ≥10pfu, the maximum intensity for proton energy >10MeV. In addition, solar proton events associated with GLE recorded by Neutron Monitors are given. The maximum intensity for E>30, >60 , >100, >500MeV for the period 1970 up to 2000 has also been included in the catalogues.

Each discrete solar proton increase was considered as "one" event. Increases associated with arrival of the interplanetary shock at 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 in the flares situated on the eastern part of the solar disk are mostly intuitive and based on the criteria which are not comprehensible to all. In particular, we adopted sometimes 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 as well. We are guided in our choice by the assumption that proton flux near the Earth is connected with the total energy release during the parent flare development. As a result of the energy release, direct particle acceleration and the 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.

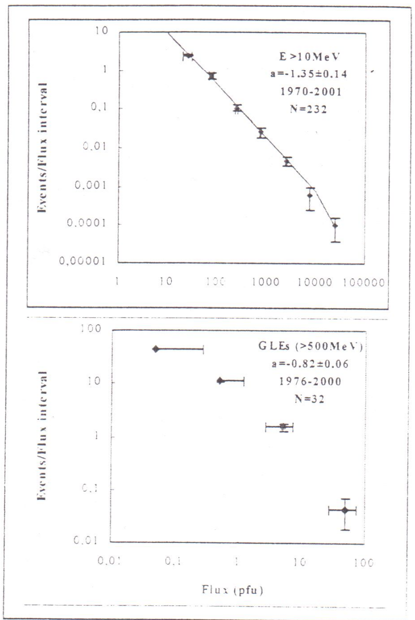

Fig.1 Size distributions of solar proton events with E>10MeV and peak intensity >10pfu (upper panel) and Ground level enhancements with E>500MeV (lower panel).

3. RESULTS

From our analysis we identified 232 proton events with E >10MeV and I >10pfu associated with SXR GOES flares for the time interval 1970-2001. Moreover 316 proton events extended up to E>30MeV, 256 events up to E>60MeV and 218 events up to E>100MeV with peak intensity >10^{-2}pfu were determined. For this time interval 32 solar proton events were accompanied by GLEs (E>500 MeV). The time distributions of these data sets appear a clearly 11-year variation, while the large number of powerful solar flares with importance >M4 characterizing the solar cycle 22, is resulting in the increasing occurrence rate of proton events during this cycle [14],[18]. There is a kind of connection between the evolution of solar activity, the magnetic field of the

Sun as a star and the efficiency of powerful proton production.

The frequency distribution of the data set at the threshold proton energy of 10MeV and peak intensity >10pfu represented by a power law at the form $dN/dI=I^{-a}$ where N is the number of events per flux interval and I is the mean particle flux in that interval at energy >10MeV is presented in Fig.1. Using least-square fitted power-law functions, we have calculated the slope of these distributions given analytically in the Table I. Each point is a weighted fit of all the events in each chosen interval. It is noteworthy that the slope of these distributions of proton events is consistent with the values calculated by other authors within uncertainties in different time intervals [13],[5],[14]. A similar procedure was performed with the SPEs at the threshold proton energies 30, 60 and 100MeV and peak intensity $>10^{-2}$ pfu. The slopes are 1.28±0.01, 1.30±0.05 and 1.30±0.10 respectively (Fig.2). It is noteworthy that during the energy range under consideration there is no certain differences from one energy channel to another one. The size distribution of flare-associated particle events represented by a power-law form at a given energy 20-80 MeV was reported with a slope 1.15±0.05 for the time interval 1967-1972[2], while at an energy >25MeV was found 1.45±0.05 for the time interval 1981-1982 [1]. In the integral size distributions at >10MeV and > 500 MeV a difference was also found to exist for the time period 1955-1996 [19].

It is well known that interplanetary disturbances accompanied with shock waves originated from flares near the central disk of the Sun are the most efficient near Earth. They help us to see protons with smaller energy and do not influence significantly on the high-energy protons propagation [20],[21]. The longitudinal distribution of the parent flares for proton events with energy >10MeV and >100MeV and the corresponding GLEs (bottom panel) as well as the ratio R of the event numbers with E>100MeV to the event numbers with E>10MeV (upper part of panel) are presented. We can see that the fraction of the events with E>100MeV and in the longitude interval 10°-80° W is double than all other longitudinal intervals and the flares situated in the more wide interval 30°E-90°W have highest "geoeffectiveness" for proton energy >10MeV.

According to this result we have constructed a new data base of SPEs originated from flares with longitude $>25^0$ W for the time interval 1970-1995. The size distributions of the peak values of the events with energies >30, >60 and >100 MeV and threshold intensity 10^{-2}pfu over the entire range of the proton intensities from 10^{-2} to 10^3 pfu were obtained. The slopes of these distributions given in Table II seems to be steeper than that of corresponding distribution of all flare-related events, while there are not significant differences in this energy range.

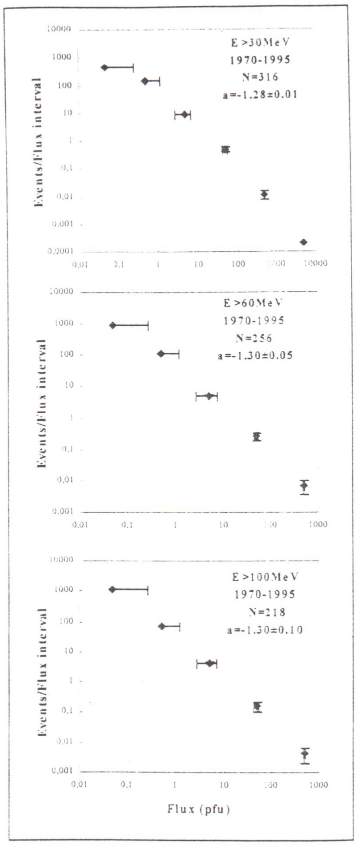

Fig. 2 Size distributions of solar proton events with E>30MeV, >60MeV and >100MeV

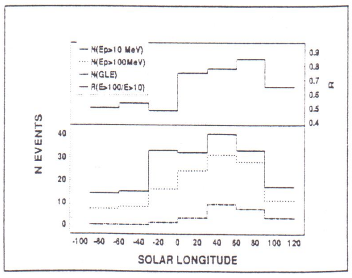

Fig. 3 Longitudinal distribution of the parent flares of the proton events

Table I Solar proton events

Observation period	Proton energy	Peak intensity	Events	Power-law index
1970-2001	>10MeV	>10pfu	232	-1.35±0.14
1970-1995	>30MeV	>0.01pfu	316	-1.28±0.01
1970-1995	>60MeV	>0.01pfu	256	-1.30÷0.05
1970-1995	>100MeV	>0.01pfu	218	-1.30±0.10
1976-2000	>500MeV	>0.01pfu	32	-0.82±0.06

Table II West-flare related Solar proton events

Observation period	Proton energy	Peak intensity	Events	Power-law index
1970-2001	>10MeV	>10pfu	102	-1.82±0.2
1970-1995	>30MeV	>0.01pfu	124	-1.72±0.15
1970-1995	>60MeV	>0.01pfu	92	-1.83÷0.18
1970-1995	>100MeV	>0.01pfu	80	-1.85±0.22

4. CONCLUSIONS

In this work a first attempt to accomplish an extended statistical analysis of solar proton events observed at IAU from 1970 to 2001 in different energy thresholds is performed. Summing up the main results of this study we note that, together with appropriate results published since 1975, our findings provide new important diagnostic information about some features of the Sun's proton productivity and its relation to existing problems of particle acceleration at /near the Sun.

1.- The best power-law fit for the basic sample of 232 proton events is attained at a slope of 1.35±0.14 over the entire range of the proton intensities 10^0-10^5 pfu. This value is consistent with other authors [13[,[14] and contradicts the main conclusion of [7] about a sharp break in the slope at about 10^3pfu.

2.-Differential size distributions at >10MeV and >500MeV demonstrate a big difference. However we can not create a proper distribution with 10-12 intensity bins for the >500MeV events because of very scarce statistic. It means that we did not exclude a selection effect for the small intensity intervals and did not get the weights of the points in the procedure of the fitting.

3.- In order to confirm this tendency, size distributions of proton events at intermediate energies (>30, >60 and >100MeV) were obtained. It is remarkable that the best power-law fit is attained at a slope of 1.28-1.30 without significant difference from that of >10MeV. It is evidenced that events with energies greater than 100MeV are originated from the same sources with those of >10MeV.

4.-The longitude distributions of the parent flares of SPEs show a "preferable connecting region" at the interval 30°E-90°W. The events with energy >100MeV display their distribution maximum at 20°-90°W. Size distributions of the SPEs originated only from the west flares (>25°W) in different threshold energies slope steeper (1.72-1.85) than those obtained from the full-disk flare-related events. We speculate now that the west flare- related events size distributions reflect much better the real size distribution of the flares accelerated protons and eliminate the old existing discrepancy between the slope of the peak size distributions of the different emissions of solar flares and that of the SPEs after full disk originated flares.

A more detailed investigation of the well determined proton events in different energy channels will help us to find out the flare sources of SPEs that can produce GLEs or not and to define a more general indicator of solar activity for a better understanding of the interplanetary conditions.

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