SH.1.5.16

Relationships among Solar Activity, SEP Occurrence Frequency, and Solar Energetic Particle Event Distribution Function

R.A.Nymmik

Institute of Nuclear Physics, Moscow State University, Moscow 119899, Russia

Abstract

The solar cycle 20-22 direct spacecraft measurement results are used to analyze the occurrence frequency and distribution function of solar energetic particle (SEP) events as dependent on solar activity. The analysis has shown that

- the mean occurrence frequency of the SEP events with ≥30 MeV proton fluence sizes exceeding 10^6 is proportional to sunspot number,
- the SEP event proton distribution functions for periods of different solar activity levels can be described to be power-law functions whose spectral form (spectral indices and cutoff values) are the same.

The above results permit the following conclusions:

a) to within statistical deviations, the total number of SEP events observed during any given time interval is proportional to the sum of mean-yearly sunspot numbers;

b) large SEP events can occur to within quite a definite probability even during solar minima.

1 Introduction

The SEP events occurrence frequency and distribution function are the main characteristics of the SEP fluxes. It is commonly recognized that the SEP event occurrence frequency is high during solar maximum and is very low during quiet Sun. In terms of the widely-used SEP presentations (King ,1974; Feynman et al., 1985,1993), however, the solar activity dependence of SEP occurrence frequency is represented by selecting so-called active 7-years of the 11-year cycle, rather than to be a quantitative property of an actual solar activity level. According to the cited papers, the mean SEP event occurrence frequency inferred from the >30 MeV, $\geq 10^6$ cm^{-2} proton fluence data for active Sun is from 7 to 7.5 events per year, irrespectively of solar cycle. On the other hand, some researchers study the dependence of the SEP event occurrence frequency on sunspot number (solar activity level). Neugebauer et al. (1978) found that the averaged occurrence frequency of the >20 MeV SEP event proton peak fluxes of >0.5 proton/(cm^2s.sr) was a linear function of sunspot number. Nymmik (1997) used the 1956-1985 SEP database and found the averaged occurrence frequency to be the power-law function with spectral index γ=0.7.

The SEP event distribution function was analyzed earlier mainly as inferred from the database of the full set of events, irrespective of solar activity level. Nymmik (1997) claimed that the distribution function power-law spectral index is the same for the SEP events that occur under both high and low solar activity levels.

This work is aimed at analyzing the dependence of the SEP event occurrence frequency and distribution function on solar activity defined to be a smoothed mean-monthly sunspot number. The analysis will be repeated here using the homogenous direct spacecraft-measured particle flux database only.

2 Database and Methods

In the present analysis we used the SEP event proton fluence data for the events recorded during solar cycles 20-22 measured on the IMP-7 and IMP-8 time-continuous records of mean-daily proton fluxes above thresholds of ≥30 MeV. The SEP events with ≥30 MeV proton fluences $\Phi_{30} \geq 10^6$ proton/cm^2 were selected to analyze. In the case of long-term SEP fluxes, separate events were stand out if after the daily lowering the detected daily E ≥ 30 MeV proton fluence increased again more than 1.3 times.

The solar activity level for every SEP event was determined to be the mean-monthly sunspot number for the day of SEP event flux occurrence near the Earth. These data were fixed by interpolation on the smoothened mean-monthly sunspot curve.

3 The SEP occurrence frequency

The SEP events were divided into 5 logarithmic smoothened sunspot intervals, namely W≤25.1; 25.1≤W≤39.8; 39.8≤W≤63.1; 63.1≤W≤100, and 100≤W≤158.5. The number of events and the time of solar activity interval during cycles 20-22 were found for each of the intervals. The SEP occurrence frequencies and the mean solar activity levels were calculated for given solar activity intervals. The resultant data are presented in Table 1.

Table 1

The SEP event measurement data of cycles 20-22

Intervals of solar activity (sunspot number)	Averaged sunspot number	Numbers of SEP events	Time interval of the given solar activity (years)	SEP event occurrence frequency
< 25.1	13.5	7	7.00	1.00 ± 0.38
25.1<W≤39.8	34.2	9	3.92	2.30 ± 0.77
39.8<W≤63.1	51.6	13	3.00	4.33 ± 1.20
63.1<W≤100	80.7	38	6.33	6.00 ± 0.97
100<W≤158.4	132.7	88	10.33	8.52 ± 0.91
All		155	30.58	5.07 ± 0.41

The Table I data are displayed in Fig. 1. The dashed line is the best weighted power-law approximation, which allows for statistical errors in the SEP occurrence frequency of each solar activity interval. The best approximation of the experimental data is the power law function

$$<n> = C \cdot <W>^{g} \text{ event/year} \qquad (1)$$

where C=0.083 and γ=0.996. The regression coefficient for the experimental data set and for function (1) is as high as 0.985. The equation (1) is very close to the linear function, for which the best approximation of experimental data is reached when C=0.0694. This linear function in Fig. 1 has been extrapolated also to the range of high solar activity (W>158.4) observed during cycle 19. According to the SEP event data presented by Feynman et al. (1990), the averaged SEP occurrence frequency for the W>158.4 period is $<\nu>=13.2$ and is in excellent agreement with function (2). Fig. 1 also demonstrates the mean SEP occurrence frequency $<\nu>=7.4$ event/year used in the JPL-91 and Soviet Standard SEP models. If the critical level of solar activity for 7 “active” years of 11-year cycle is close to W=40, the SEP event occurrence frequency proves to be 7.1±0.4 when averaged over 7 “active” years of cycles 20-22 and 5.1±0.4 when averaged over the total period, the “passive” 4-year periods included. It should be mentioned that the experimental data set for SEP events at $\Phi_{30} \leq 2 \cdot 10^7$ is distorted by the threshold effects of small SEP events detection and selection (Kurt and Nymmik, 1997). If the data are corrected for this effect, the true C value for the $\Phi_{30} \geq 10^6$ SEP event set is 0.106.

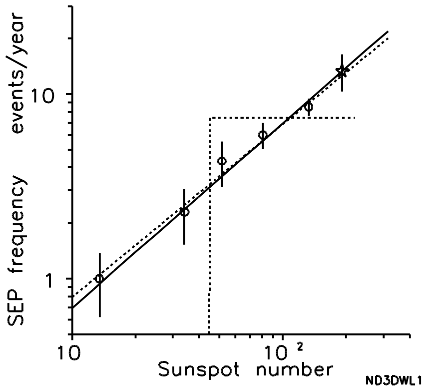

Figure 1: The mean SEP event occurrence frequency versus sunspot number .The circles are the experimental data of solar cycles 20-22. The asterisks are the mean SEP event occurrence frequency during solar cycle 19 for <W>≥158. The solid line is the linear function. The dashed line is the power-law function (Eq. 1).

Our results indicate that the SEP event occurrence frequency is proportional to sunspot number and that the SEP, which were detected on the Earth orbit, are generated during the periods of very low solar activity, with the mean occurrence frequency being proportional to the annual smoothed mean-monthly sunspot numbers.

4 The SEP Event Distribution at Different Solar Activity Levels

The present-day statistical accuracy of SEP event distribution is sufficiently good for the SEP event distribution to be studied over periods of different solar activities. Nymmik (1997) has shown that the spectral indices of power-law distribution are the same (or much alike) during the different solar activity periods. Here, we analyze the SEP event data used above and allow for the new distribution function form (Nymmik, 1999) and the dependence of the averaged SEP event occurrence frequency on solar activity. According to (Nymmik, 1999), the function of SEP event distribution by ≥30 MeV proton fluences inferred from the direct spacecraft measurements and from the proton flux data of lunar rock radionuclides may be presented as

$$\frac{dN}{d\Phi_{30}} = Const \cdot \Phi_{30}^{-1.41} \cdot \exp-\left(\frac{\Phi_{30}}{4.0 \cdot 10^{9}}\right), \tag{2}$$

On the other hand, from (1) it follows that the SEP event number N_k determined over the period T_k of a certain solar activity W_k is

$$N_k = n_k T_k = C W_k \tag{3}$$

and

$$\frac{1}{T_k W_k} \frac{dN_k}{d\Phi_{30}} d\Phi_{30} = const \tag{4}$$

Let as show that this is true.

The SEP event set used in the above analysis was divided into 2 groups for the solar activity periods $<W_1>$ <80 and $<W_2> \geq 80$. The solar activity at the moments of each of the SEP event occurrences, W_i, was calculated and, after that, averaged over the two groups:

$$< W_k >= \frac{1}{n_k} \sum_i^n W_i \tag{5}$$

where n_k is the number of SEP events during period k; W_i is the annual smoothed mean-monthly sunspot number calculated on the day of SEP occurrence.

For the above mentioned solar activity periods we found $< W_1 >= 37.6$ and $< W_2 >= 123.8$. For the full set of SEP events, the mean solar activity for SEP occurrence is $< W_{total} >= 74.4$.For the above two periods we calculated the distributions of experimental data according to Eq. (3), which result is displayed in Fig. 2. For two groups of experimental data, we have calculated also the "best" distribution functions (3) which differ from each other by the spectral coefficients and cutoff of the exponential function. The difference in the distributions functions is below 10%. Besides, Fig. 2 shows the experimental data for the very low solar activity period (<W><40) when $< W_3 >= 22.5$. These data do not differ from the rest of the data either.

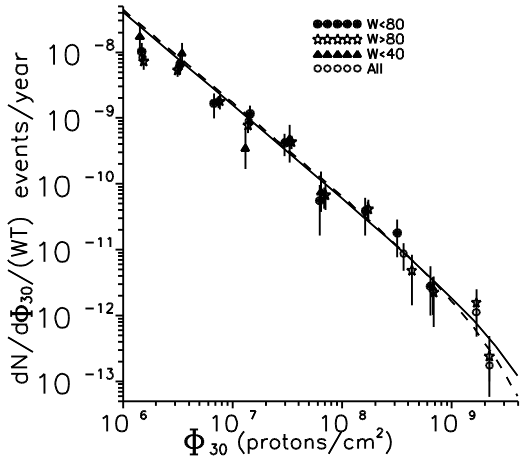

Figure 2: The differential distribution functions divided into solar activity levels (Eq. 3). The symbols are the experimental data (see the text and in the figure) The solid line is the best distribution function for the <W>≥80 period. The dashed line-the same for <W><80.

5 Conclusion

Both of the results indicate that the up-to-date experimental data do not contradict to the con cept that solar activity changes the SEP occurrence frequency only and that the set of physical processes (coronal mass ejection, particle acceleration and diffusion), which lead to the SEP event occurrences in the Earth orbit, are the same during all of the solar activity periods. Moreover, the SEP event distribution related to a solar activity level seems to be invariant with respect to solar activity. If it is the fact, the probability for large SEP events to occur in the Earth orbit depends on solar activity level only and may prove often to be actual even during low solar activity periods.

6 References

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