Proceedings of ICRC 2001: 3197 © Copernicus Gesellschaft 2001

ICRC 2001

The main characteristics of the solar energetic particle events relevant to solar activity

R. A. Nymmik

Skobeltsyn Institute of Nuclear Physics, Moscow State University

Abstract. The results are presented of analyzing the solar energetic particle (SEP) event number and proton fluence as dependent on solar activity. The analysis allows for the random character of the SEP event occurrences, for the threshold effect in determining the small-size events, for the coincidence (overlap) effects of event determination during high solar activity, and for the statistical and methodological errors in experimental data. It is shown, that the main experimental SEP event data (SEP event number, occurrence frequency, and proton fluences) can be explained fully by two mean regular features of SEP events, namely, (1) the mean SEP event occurrence frequency is proportional to sunspot number and (2) the SEP event distribution function normalized to a unified solar activity is independent of (invariant to) solar activity.

1 Introduction

The relationships between solar activity and the SEP event characteristics are sought for in a few works. However, all the efforts that disregarded the probabilistic nature of the SEP event occurrences and were not subjected to any adequate statistical analysis did not (and could not) yield any definite results.

Having analyzed the solar proton flux measurements of cycles 19 and 20, for instance, Lingenfelter and Hudson *(1980)* claim that "there is no detailed correlation between the fluence and suspot numbers on an annual basis". The analysis of the three-cycle (19-21) solar proton measurements has led Goswami et al. (1988) to conclude that "no definitive correlation exists between cycle-averaged solar flare proton fluxes and peak sunspot numbers".

Besides, Goswami et al. (1988) have come to the conclusion that was not supported statistically: "major flare events are relative rare near the sunspot maximum and occur mostly in the ascending or descending phase of sunspot occurrence".

Correspondence to: Nymmik R.A., nymmik@sinp.msu.ru

Feynman et al. (1990), claimed that

(1) there is almost no relation between the maximum sunspot number in a solar cycle and the solar cycle integrated flux and

(2) for annual sunspot number greater than 35 (i.e., non "quiet" Sun conditions) there is no relation whatsoever between the annual sunspot numbers and annual integrated flux (fluence).

They also claimed: "the cycle divides itself into two clearly defined phases". Seven active years extending from 2 years before sunspot maximum through 4 years after maximum are defined to be the "active" Sun period, and the rest four years to be the "quiet" Sun period.

In terms of the present work, the key point is the distribution function of the SEP event fluence sizes. In the numerous relevant works, the distribution is described to be the power-law function of peak flux (Van Hollebeke et al., 1975) and fluence (Gabriel and Feynman, 1996. The interpretation of the deviation of the adopted approximations from the power-law function in the ranges of high and low fluences is the essence of the subject. As shown by Vict. Kurt and Nymmik (1997) in the case of the ≥30 MeV proton distribution function, the deviation of the SEP events recorded in the proton fluence range $\Phi_{30}<10^7$ protons/cm^2 from the power-law function is due to the SEP event selection and detection threshold effects against the galactic particle flux background. Therefore, any comparison among the numbers of the detected SEP events cannot be made in terms of the occurrence frequency of the $\Phi_{30}<10^7$ events because the SEP events set in the $\Phi_{30}<10^7$ range is distorted by the SEP detection threshold effects, which depend on solar activity, similar to the solar activity dependence of the galactic particle flux.

The present work is aimed at analyzing the relationships between the SEP event characteristics (the occurrence frequencies of the different-size events; the total fluences) and solar activity with due allowance for the probabilistic nature of the SEP event occurrences.

2 Basic principles

The analysis is based on the following two basic features of SEP events.

1. The mean SEP event occurrence frequency is proportional to solar activity level (Nymmik, 1999a). In terms of this feature, the mean number $<n_\Phi>$ of the SEP events, whose fluence exceeds Φ over a given period (for example m months), can be calculated as

$$\langle n_\Phi \rangle = \frac{C(\Phi)}{12}\sum_{i=1}^{m}\langle W_m^* \rangle, \qquad (1)$$

where $\langle W_m^* \rangle$ is the smoothed monthly sunspot numbers, *C(Φ)* is the factor dependent on the event size Φ and on proton energy.

2. The distribution function of the Φ_{30} (fluence of E≥30 MeV protons) SEP event occurrence frequency normalized to solar activity W is a power-law function of proton fluence with spectral index –1.41 and with the gradual steeping, which is described by the exponent with the characteristic fluence $\Phi_c=4\cdot10^9$ protons/cm^2 (Nymmik, 1999b):

$$\frac{dN}{d\Phi_{30}\cdot dT\cdot W} = Const\frac{\Phi_{30}^{-1.41}}{\exp\left(\frac{\Phi_{30}}{\Phi_c}\right)} \qquad (2)$$

The most important fact here is that function (2) is invariant with respect to solar activity. This means that the probability for the extremely large SEP events to occur at any solar activity level is quite definite.

By its form, function (2) is identical to the expression used in (Lu et al., 1993) to describe the distribution of solar flares. The sought power-law distribution gets depressed in the high-fluence range (Lingenfelter and Hudson, 1980, Goswami et al. 1988), thereby indicating that the fluences approach their extreme sizes restricted by the solar power energy limit.

3 The number of SEP events

The mean number of SEP events expected within a given solar activity period is determined by formula (1), which we use primarily to find the SEP event number during different solar activity cycles. Table 1 presents the calculation input data (the sum of annual sunspot numbers $W_i=\sum_{m=1}^{12}\langle W_m\rangle$ and the coefficients $C(\Phi_{30})$) and the calculated <n> values (with their statistical deviation $\pm\sqrt{<n>}$) together with observed SEP event number. The observed SEP event data of cycles 19-21 have been borrowed from the tables (Feynman et al., 1990). The cycle 22 data are the processed daily proton flux measurement data taken from on IMP-8 Internet site.

From Table 1 it follows that, within the statistical deviation range, the numbers of different-size SEP events recorded during cycles 19-22 are defined by relations (1) and (2).

The mean SEP event numbers expected during different solar activity periods of 1965-1977 (see Fig. 1) were also calculated (Table 2).

The observation time within each of the periods was determined by summing up the numbers of the months when the smoothed sunspot numbers fell within the respective solar activity period. Each of the SEP events was attributed to one or another solar activity period by interpolating the smoothed mean-monthly SEP event numbers to the day of the event onset.

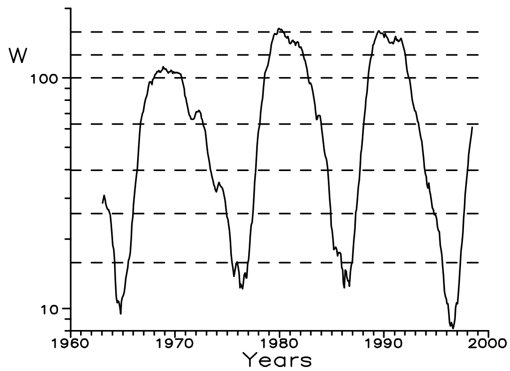

Fig. 1. The 13-month smoothed sunspot numbers and the separate solar activity periods (the horizontal lines).

Table 1. The number of SEP events calculated by equation (1) (the numerals with statistical deviation) and the recorded SEP numbers (in brackets) during cycles 19-22.

Cycle		≥10^7	≥10^8	≥10^9
	$C(\Phi_{30})$	0.0365	0.011	0.0019
19	ΣW_i=963	35.1±5.9 (43)	10.7±3.2 (13)	1.82±1.4 (4)
20	ΣW_i =707	25.8±5.1 (27)	7.9±2.8 (5)	1.33±1.2 (1)
21	ΣW_i =830	30.2±5.5 (28)	9.2±3.0 (7)	1.6±1.3 (0)
22	ΣW_i =783	28.5±5.3 (24)	8.7±3.0 (10)	1.5±1.2 (4)
All cycles	ΣW_i =3283	119.6±10.9 (122)	36.5±6.0 (35)	6.3±2.5 (9)

The comparison among the calculated data demonstrates a satisfactory-calculation-to-experiment agreement. Besides, the following two facts should be noted.

First, the number of the $\Phi_{30}\geq10^7$ protons/cm^2 SEP events expected at a low solar activity is small. Therefore, the respective statistical error is so high that we can well admit a smaller number of the SEP events recorded at <W>≤25 compared with the calculation results.

Table 2. The solar activity periods, the mean solar activity within each of the periods, the total times (T, years) of a given solar activity level within 1965-1977, and the expected mean (the numerals with their statistical deviations) and observed (n_{exp}) SEP event numbers.

ΔW	<W>	T	$n(\Phi \geq 10^7)$	n_{exp}	$n(\Phi \geq 10^6)$	n_{exp}
<15.8	12.6	4.17	2.2±1.5	1	5.5±2.8	6
15.8÷25.1	19.9	3.33	2.7±1.6	0	7.0±2.6	4
25.1÷39.8	32.2	3.92	5.2±2.3	6	13.2±3.6	12
39.8÷63.0	51.1	2.92	6.1±2.5	8	15.7±4.0	13
63.1÷100	77.0	5.0	15.7±4.0	22	40.4±6.3	36
100÷126	110.0	2.58	11.6±3.4	16	29.8±5.5	33
126÷158	145.3	5.67	33.7±5.8	31	86±9.3	56*

First, the number of the $\Phi_{30} \geq 10^7$ protons/cm^2 SEP events expected at a low solar activity is small. Therefore, the respective statistical error is so high that we can well admit a smaller number of the SEP events recorded at <W>≤25 compared with the calculation results.

Second, the $\Phi_{30} \geq 10^6$ SEP events do not exhibit this feature under low solar activity. In return, there occurs a marked counting loss of small-size SEP events under high solar activity (56 against 86). The counting loss is readily explainable by the fact that the small-size ($\Phi_{30} \sim 10^6$) SEP events that trail the SEP events, whose Φ_{30} are often in excess of 10^8 or 10^9, remain unidentified.

4 The SEP event proton fluence

The SEP event occurrences are probabilistic, so the single event sizes are random, and the entire set of the SEP events is governed by the distribution (2). At a certain mean SEP event number <n>, therefore, the total SEP event fluence is defined by the fluctuations in the SEP event number (which are comparatively small) and in the proton fluence (which are much larger).

The occurrence probability of all the possible total fluence sizes, which can be Monte Carlo calculated for each of the solar activity cycles, was estimated by calculating the random SEP event numbers and the random single event sizes in terms of the distribution (2). Figure 2 shows the distributed logarithms of the proton fluence sizes in the space radiation environments during cycles 19-22.

From Fig. 2 it is seen that the differential distributions of the proton fluence size logarithms of cycles 19-22 get much overlapped. For example, the probability is 0.32 for the total proton fluence over a cycle with solar activity similar to that of cycle 19 (ΣW = 963) to be below its level over the weakest cycle, which is similar to cycle 20 (ΣW=707). From the above it is clear that the data of but a few solar cycles are quite insufficient for any correlation to be found between solar activity and the proton fluence, just what was done in Feynman et al., (1990).

In addition, the total proton fluence sizes observed over a solar cycle, which are in no way in variance with the calculated distributions, are labeled above the abscissa in Figure 2. The calculations indicate that, if we wish to demonstrate that the mean total proton fluence over the solar cycles like cycle 19 would exceed those over such weak cycles as cycle 20 within probability 0.9, we have to get experimental data of about a hundred of identical cycles.

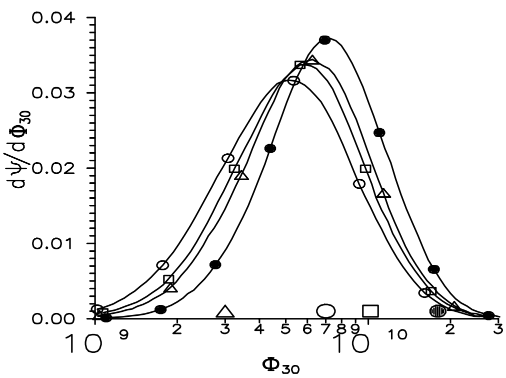

Fig. 2. Differential probability (the lines) for the total integral ≥30 MeV proton fluences to occur during cycles 19 (the dots), 20, (the circles), 21 (the triangles), and 22 (the squares). The big markers indicate the fluence sizes observed over a cycle.

Examine now the situation with the dependence of the mean-annual proton fluences on solar activity. Basing on the Table 2 data, we Monte Carlo-simulated the integral distributions of the mean-annual fluences over each of the solar activity periods. The results are displayed in Figure 3.

The horizontal lines in the figure mark the mean-yearly fluence sizes corresponding to integral probabilities of 0.9, 0.5, and 0.1 for the fluences to exceed the respective sizes. The latter are presented in Fig. 4, where they are shown as vertical lines (0.1-0.9) centered in probability 0.5

All the experimental dots (except for the 25.1<W≤39.8 activity period) fall within the 0.1÷0.9 probability range. The outstanding mean-yearly fluence during the 25.1<W≤39.8 activity period is readily explainable by the extremely poor statistics of the respective SEP events. None of the $\Phi_{30} \geq 10^7$ SEP events occurred during that period (in terms of the Poisson distribution, the respective probability is 7%), whereas a single such event occurred even at a lower solar activity W<25.1.

The fact is also worth noting that, given the total earlier measurement period, the possible fluence range gets much extended, so that the situations become realizable (and have been realized actually) in which the mean-annual fluence under a lower solar activity (63<W≤100) exceeds that under a higher solar activity (100<W≤126) Since the former activity period occurs during both the ascending or descending solar activity

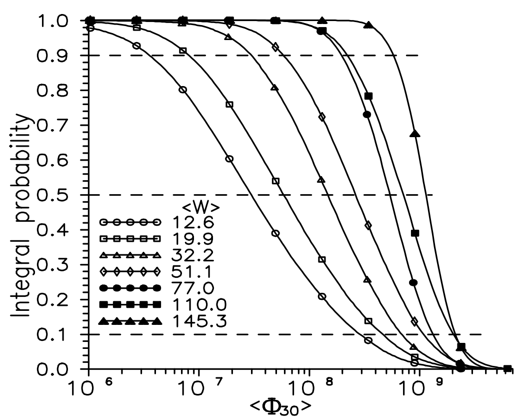

Fig. 3. Integral probability for the mean-yearly fluences of sizes above the levels indicated in the abscissa to be observed during different solar activity periods (the means over 1965-1997 are shown). The dashed lines confine probabilities 0.1, 0.5, and 0.9.

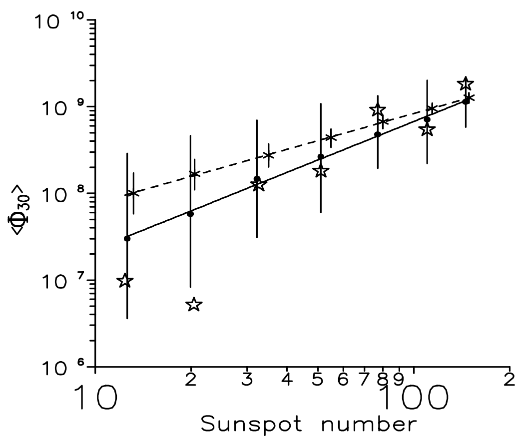

Fig. 4. Expected mean-yearly fluences versus solar activity. The dots are the fluence sizes of 1965-1997 calculated from Fig. 3 at probability 0.5. The ends of the vertical lines are the fluences at probabilities 0.9 and 0.1. The asterisks are the experimental data. The crosses with vertical bars show the same dependence in the hypothesized situation of 100-year observations for each solar activity period.

phase, a phantom of a certain effect might arise (and even has arisen and got rooted as regards cycles 19-21).

The phantom nature of such an effect was proved during cycle 22, whose solar maximum was accompanied by a number of large SEP events that made the mean-yearly proton fluence peak at W = 126-158.

So, the question arises of what is the actual duration of the measurement period for the spread of the mean-yearly fluences to form a more or less smooth dependence that would signify any notable correlation of the fluences with solar activity. Figure 4 shows the calculation result for an imaginary situation when the measurement period duration reaches 100 years for each of the solar activity periods.

From the figure 4 it follows that, even after such a long period elapses, any mean-yearly fluence measured under a high solar activity cannot be expected to exceed that measured under a lower activity. At the same time, the results of measuring the mean-yearly fluences under high and moderate solar activity will give a chance for some fine effects (like the Gnedyshev effect) to be found.

It is also of interest to examine the functional dependence of the expected fluence size on solar activity. Given a 50:50 probability, the dependence takes the form

$$<\Phi_{30}>= 7.6 \cdot 10^5 \cdot W^{1.48}$$

for the period of 1965-1997 and

$$<\Phi_{30}>= 7.0 \cdot 10^6 \cdot W^{1.04}$$

for the hypothesized 700-year period.

Our calculations have shown that, as the measurement period (the SEP event statistics) increases, the ultimate mean-yearly fluence size becomes proportional to solar activity. This particular feature of the dependences of the mean-yearly proton fluences on solar activity and on the measurement period duration arises from the distribution function form (2) and from its probabilistic nature.

5 Conclusion

From he above it follows that the present-day experimental data on the SEP event numbers and on the SEP fluence sizes as dependent on solar activity can be explained quite adequately in terms of the probabilistic nature of the events, considering that

- the SEP event occurrence frequency is proportional to solar activity and
- the SEP event occurrence frequency distribution of SEP event sizes is invariant when normalized to a solar activity level.

The above analysis has shown that the probabilistic nature of the SEP events imposes substantial restrictions on the feasibility for any SEP event-associate regularity to be found. This is also why the claimed predominant generation of large SEP events during the decay and rise phases of solar activity, just as the claimed absence of any correlation between proton fluences and solar activity, seem to be groundless, for the claims were not based on any proper quantitative and statistical analysis.

References

Feynman J. , et al., Solar Physics, 126; 385, 1990.
Gabriel S.B. and Feynman J., 1995, Solar Phys. 165,337-345.
Goswami J.N., et al, *JGR*,.93, A7, 7195 1988.
Lingenfelter R.E. and Hudson H.S., 1980, Proc. Conf. Ancient Sun. Ed. Pepin R.O. et al., p.69.
Lu E., et al. APJ 412, 841-852, 1993.
Nymmik R.A., in proceedings of the *25th ICRC*, 6, 280, 1999a
Nymmik R.A., in proceedings of the *25th ICRC*, 6, 268, 1999b.
Van Hollebeke et al., 1975, Sol. Phys. 41,189.
Kurt Vict..and Nymmik R.A., *Space Research*, 35(5), 98, 1997.