Expected Radiation Hazard at Different Phases of Solar Cycle Based on Statistical Properties of Solar Energetic Particle Fluencies

L.I. Dorman [1, 2], L. Pustil'nik [1]

[1] Israel Cosmic Ray and Space Weather Center and Emilio Segre' Observatory, Tel Aviv University, Technion and Israel Space Agency, Israel

[2] Cosmic Ray Department, Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Russia

e-mail: lid@physics.technion.ac.il

Received: 26 November 2008 ; Accepted: 28 December 2008

Abstract. Expected radiation hazard from SEP (Solar Energetic Particle) events for space probes in interplanetary space at different distances from the Sun, for satellites in magnetosphere of the Earth on different orbits, for planes on different airlines, and on people and technology on the ground on different altitudes and cutoff rigidities is determined mostly by expected fluency (total flux of SEP during solar flare event) in different energy ranges at different phases of solar cycle. Information on expected total radiation hazard from SEP events (as well as from galactic cosmic ray (CR)) in different phases of solar cycle is necessary for estimation of optimal shielding of electronics and/or people both in space (on satellites at different orbits, on interplanetary missions, and on ISS – International Space Station) as well as in atmosphere (for aircrafts at different altitudes and technology objects and people on the ground level). We estimated probabilities of fluencies on the basis of long time observation of proton flux (both direct measurements on the space detectors and on the base of recalculation from ground stations). Restored amplitude spectrum (distribution of events with given interval of amplitudes of the fluency or for fluencies more than given) enables us estimate probability of dangerous states and extrapolate this distribution for rare events of extremely high amplitudes. Main sources of data for this analysis are: 1) data from the Catalog “A Summary of Major Solar Proton Events” (Shea and Smart, Solar Phys., 1990) for 31 years observations fluencies on the ground and in space, 2) for detailed analysis – data from satellites GOES during 1994–2004, available through Internet.

Keywords: radiation hazard; solar activity; SEP events; fluency; GOES satellites

Introduction

Observational data on solar cosmic ray (CR) fluencies in the space near the Earth accumulated by ground and space CR observations during about four solar cycles present unique possibility to estimate statistical properties real of the space radiation and its sensitivity to solar activity. This information on fluency distribution is necessary for estimation of radiation hazard both in the space (satellites, interplanetary missions, space stations) and in atmosphere (aircraft level).

For these aims we study the probability of difference fluency levels of SEP events in different phases of solar activity. We estimated probabilities of fluencies on the base of long time observation of proton flux (both direct measurements on the space detectors and on the base of recalculation from ground stations). Restored amplitude-frequency spectrum (distribution of events with given interval of amplitudes of the fluency or for fluencies more than given) enables to estimate probability of dangerous states and extrapolate this distribution to rare events of extremely high amplitudes. These results allow estimating radiation dangerous level both for long-term missions in far space and for short-time expeditions in near space for different states of solar activity.

Main source of data for this analysis is data from the Catalog [1] of Shea and Smart for 31 year observations fluencies in space (1990) and for detailed analysis – data from satellites GOES during the last 11 years (1994–2004) for different energies of CR protons: >1 MeV, >10 MeV, and >100 MeV separately (source of these data: http://www.sec.noaa.gov/ftpmenu/indices/old_indices.html).

In our previous works [2 - 4] it was found that the frequencies *P* (in *event/year*) of events of solar CR fluencies with level of fluency *F* (*particle/cm*^{2}) more than given were in dependence on fluency value *F*. For these works we used fluencies of events, averaged for solar cycle. We performed our analysis of fluency distribution for different levels of solar activity (W - sunspot number intervals: 0–40, 40–80, 80–120, 120–160, 160–200, and more than 200).

Three-dimensional distribution of *Probability (as events per year) – Fluency (as lgF) – Solar Activity (as sunspot number)*

In Figs. 1 and 2 are shown 3-D distributions of Probability (as events per year) – Fluency (as lgF) – Solar Activity (as sunspot number) for SEP with energy ≥ 10 MeV and ≥ 30 MeV, correspondingly. These results were obtained on the basis of three solar cycles data collected in Catalog [1].

From Fig. 1 can be seen that probability of fluency (*P*) increases with solar activity (W) only for *F* = 10^7–10^8, 10^8–10^9, and 10^9–10^{10} *particle/cm²*. For low fluency side of distribution F = 10^{10}–10^{11} *particle/cm²* the frequency P

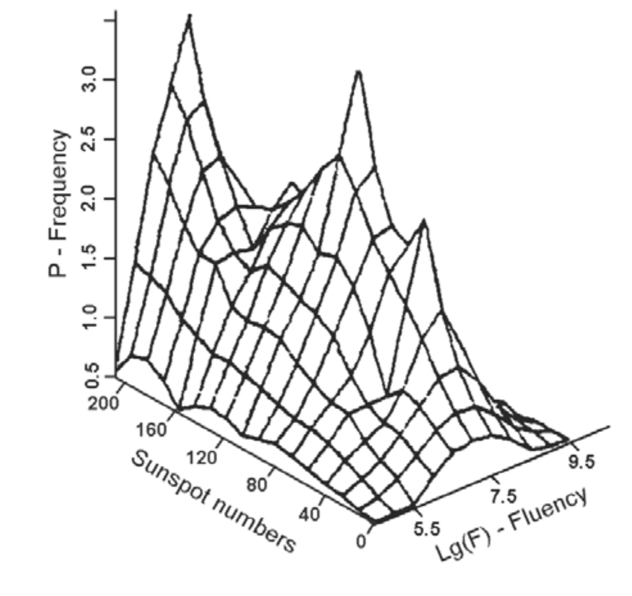

Fig. 1. Frequency P distribution in dependence on sunspot number and lg(F) for solar protons with E > 10 MeV;. Average for three solar cycles; Based on data summarized in Catalog [1].

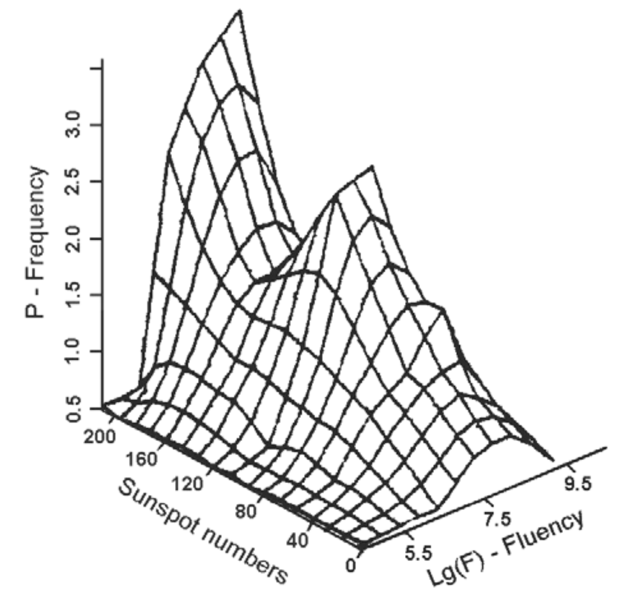

Fig.2. The same as in Fig. 1, but for solar protons with E ≥ 30 MeV; Based on data summarized in Catalog [1].

has a maximum at W = 80–120 (high solar activity) and decreases with increase of W after this sunspot maximum. For the biggest observed fluency F = 10^{10}–10^{11} *particle/cm²*, these events were observed only in the periods of intermediate solar activity levels W = 40–80 and 80–120. About the same situation can be seen from Fig. 2 for particles with energy >30 MeV.

Averaging data for solar cycle and analytical presentation of *Probability (Frequency) – Fluency* dependence

If we average all data for solar cycle, we can determine the dependence $P(F)$. This dependence can be presented in analytical form as

$$P = P_{\max}\left(F/F_m\right)^{-\gamma}\exp\left(\alpha\left(1-\left(F/F_m\right)^{-\gamma/\alpha}\right)\right), \qquad (1)$$

where $P_{\max}$ is the maximum value of probability *P*, and F_m is the corresponding value of fluency. In Eq. 1 for protons with energy E > 10 MeV

$$\gamma = 1.2, \quad \alpha = \begin{cases} 2.05 & \text{at } F \le F_m \\ 8.0 & \text{at } F > F_m \end{cases}, \qquad (2)$$

and for protons with energy E > 30 MeV

$$\gamma = 1.2, \quad \alpha = \begin{cases} 1.9 & \text{at } F \le F_m \\ 12.0 & \text{at } F > F_m \end{cases}. \qquad (2)$$

Dependencies $P(F)$ for different levels of solar activity

In Fig. 3, the dependencies of frequency *P* (*events/year*) of events from the value of logarithm of fluency *lg (F)* of solar protons with energy >10 MeV are shown for different levels of solar activity (for sunspot numbers W: 0-40, 40-80, 80-120, 120-160, and 160-200).

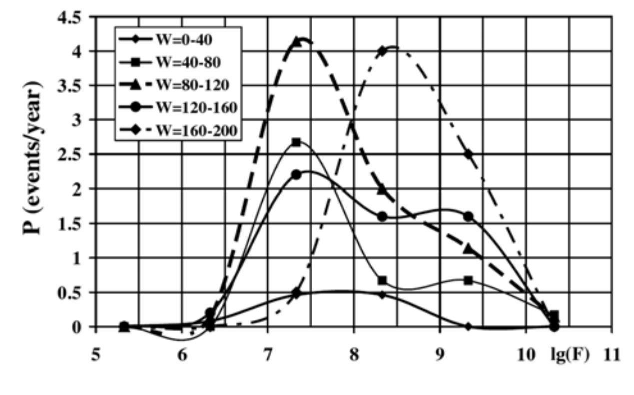

Fig.3.The dependencies of observed frequency P (events/year) of events as function from the value of logarithm of fluency lg (F) for solar protons with energy >10 MeV for different five intervals of solar activity level; Based on data summarized in Catalog [1].

It can be seen from Fig. 3 that at the lowest solar activity (W = 0–40) the events' frequency P is very small: only 0.5 *events/year* in the fluency range F = $2\cdot10^7$–$2\cdot10^8$ *particle/cm²* (but at smaller and bigger fluencies expected P ~ 0). Increase of solar activity leads to a correspondent increase of SEP events [5], but this process takes place in a very inhomogeneous manner for different intervals of fluencies. For example: if for intermediate level of solar activity (W = 40–80) in population of SEP dominate (up to 4 events per year) events with middle level of fluencies (F = 10^7–10^8 *particle/cm²*), but for a higher level of solar activity (W = 80–120, 120–160 and 160-200) input of strong flares with high or very high fluency (F = 10^8–$10^{9.5}$ *particle/cm²*), starts to increase and dominate. This redistribution of events in “fluency space” reflects the fact of relative domination of the strong and giant flares during high and maximal solar activity.

Opposite to low energy protons, behavior of population of more energetic particles (>30 MeV) is another (see Fig. 4).

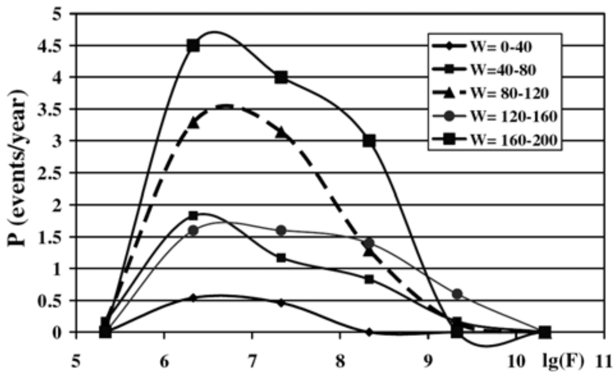

Fig. 4. The same as in Fig. 3, but for solar protons with energy E > 30 MeV. Based on data summarized in Catalog [1].

From Fig. 4 can be seen that the distribution in fluency has important peculiarity: probability *P* increases in amplitude with increasing of solar activity (from *P* ~ 0.5 *events/year* for minimal W up to *P* ~ 4 *events/year* for the maximal one). However, redistribution of events in “fluency space” does not take place – distribution of events with fluency increases self-likely on its own conservation form and position of maximum. Only for intermediate level activity (W = 80–120) some disturbance of this law takes place – input of high fluency events increases and forms flat maximum, covering range of fluencies $2\cdot10^7$–$2\cdot10^9$ *particle/cm²*. This disturbance reflects well-known fact of increase of probability for high amplitude solar flares in the transition states of solar activity from minimum to maximum and back.

Main results following from GOES data

As we mentioned above, in Introduction, these data were analyzed in details in [5, 6]. Here we will only summarize main obtained results.

1. On the basis of 11-year observations on GOES 7–11 for 1994–2004 of daily fluencies for particles with energies E > 1 MeV, >10 MeV, and >100 MeV it was shown that main input to the integral fluency during 1994–2004 was caused by few rare events with the highest fluencies. Several rare giant events gave a bigger input to integral fluency for 11-year cycle than thousands of lower fluency events.

2. Fluencies for different energy channels demonstrate different asymmetry relative to minimum and maximum levels of solar activity. In spite of general correlation of frequency of high fluency SEP events with sunspot number (correlation coefficients from 0.55 to 0.86), there are strong deviations between variation of sunspot numbers and frequencies of fluency.

3. Energy spectrum of particles appears in observed fluencies and in its distribution in 2-D diagrams: Fluency (low energies) – Fluency (high energies). It shows existence of two different populations of events: first population consists of events in low-energy particles without any reaction in high-energy particle fluencies; second population consists of events with simultaneous proportional reaction in all energetic channels from >1 MeV to > 100 MeV (regression coefficients about 0.9 and correlation coefficients 0.7–0.8). We suppose that the origin of the second population is solar CR generation in great solar flares with wide energy spectrum; the origin of the first low energy population may be caused by weak solar flares, CME and interplanetary shock waves without high energy particle generation.

Acknowledgements

Our thanks are going to M.A.Shea and D.F. Smart for preparing very important full Catalog [1] of solar CR events for about three solar cycles. Our thanks are due to the GOES team, which presented the observational data for 1994–2004 to open access. We express our thanks also to Dr. A. Sternlieb, Prof. I. Ben Israel, Dr. Z. Kaplan and Dr. G. Bella for useful discussions and permanent support of Israel CR and Space Weather Center.

This research is partly supported by European Projects INTAS, COST and FP-7 (NMDB).

We express our great gratitude to organizers of very high level, interesting and effective UN/ESA/NASA/JAXA Workshop on the International Heliophysical Year 2007 and Basic Space Science "First Results from the International Heliophysical Year 2007" (2-6 June 2008, Sozopol, Bulgaria).

REFERENCES

[1] M.A.Shea, D.F.Smart, “A Summary of Major Solar Proton Events”, *Solar Physics*, 1990, v.127, pp. 297–320.

[2] I.V.Dorman, L.I.Dorman, D.Venkatesan, “Solar Cosmic Ray Event Frequency Distribution in Dependence of Fluency and of Solar Activity Level”, in: Proceedings of the 23rd International Cosmic Ray Conference, Calgary, 1993, v. 3, pp. 79–82.

[3] L.I.Dorman, L.A.Pustil’nik, “Solar Cosmic Ray Events: Statistical Characteristics for the Diagnostic of Acceleration, Escaping and Propagation Processes”, in: Proceedings of the 24th International Cosmic Ray Conference, Rome, 1995, v. 4, pp. 86–89.

[4] L.I.Dorman, L.A.Pustil’nik, “Statistical Characteristics of FEP events and their connection with acceleration, escaping and propagation mechanisms”, in: Proceedings of the 26th International Cosmic Ray Conference, Salt Lake City, 1999, v. 6, pp. 407–410.

[5] P.I.Y.Velinov, G.Nestorov, L.I.Dorman, “Cosmic Ray Effects on Ionosphere and on Radiowaves Propagation”, Publishing House of the Bulgarian Academy of Sciences, Sofia, 1974, 312 pages.

[6] L.I.Dorman, L.A.Pustil’nik, “On the Probability of Solar Cosmic Ray Fluency during SEP Event in Dependence of the Level of Solar Activity”, Advances in Space Research, 2007, v. 39, pp. 1102–1108.