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The balance between fluxes of galactic cosmic rays and solar energetic particles, depending on solar activity.

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Abstract. The results are presented of analyzing the relative role of the fluxes of galactic cosmic rays and solar energetic particles (SEP) in interplanetary space as dependent on solar activity. The analysis is based on experimental data and is made in terms of the galactic cosmic ray and SEP models developed at Moscow State University. It has been concluded that the SEP event proton fluences count much under any solar activity. This means that the SEP models, which neglect the SEP events in the "quiet Sun" periods, cannot be used because such type models lead to an inaccuracy of up-to a few orders in determining the <100 MeV particle fluxes.

1 Introduction

Most of the present-day SEP analyses have concluded that the 11-year solar cycle ‘‘divided itself into two clearly defined phases" (Feynman et al., 1990) called “active” and “quiet” Sun periods. The "active" Sun years are proposed to occur when “the hazardous period for enhanced proton fluences is seven yeas long and extends from two years before sunspot maximum to four years after maximum when the sunspot maximum epoch is defined to 0.1 years’’ (Feynman et al., 1990, 1993). The rest years are defined to be the 4-year “quiet” Sun period.

The consequences of the above definition were developed in the SEP models (Feynman et al., 1993, Barth et al., 1999) that disregarded the SEPs for the “quiet” Sun periods and proposed the SEP event occurrence frequency and fluences to be constant during the “active” Sun (solar maximum) periods.

At the same time, having analyzed the dependence of SEP event occurrence frequency on solar activity (Nymmik, 1999a) and the distribution function properties of SEP event occurrence frequency (Nymmik, 1999b), the author concluded that there were neither qualitative nor quantitative reasons for such a division.

Another key point in our understanding of SEPs is the form of their energy spectra. Most of the SEP models follow Freier and Webber (1963) and describe the SEP energy spectra by the particle rigidity exponent:

$$\frac{dF}{dR} = C\exp\left(-\frac{R}{R_o}\right) \qquad (1)$$

However, the ≥30 MeV SEP energy spectra have been demonstrated (Nymmik, 1993) to be power-law functions of particle rigidity (momentum):

$$\frac{dF}{dE} = C\left(\frac{R}{239}\right)^{-\gamma}\frac{dE}{\beta}. \qquad (2)$$

This is also shown quite clearly in the report (Mottl et al., this conference).

The energy spectrum representations (1) and (2) are fundamentally different, namely, formula (1) disregards the actual high-energy proton fluxes.

The present work is aimed at detailed analyzing the relative role of the SEP phenomenon in the interplanetary radiation environment during, first of all, the so-called “quiet” Sun periods. In our analysis we use the latest version of our probabilistic SEP model, in which the base model (Nymmik, 1999c) is corrected to conform to the results of the works (Nymmik 1999a,b).

We describe the galactic particle fluxes in terms of the model (Nymmik et al., 1996). The model describes the particle fluxes as dependent on solar activity (Wolf number) and on the 22-year solar magnetic field cycle and allows for the effect of particle flux time-lag relative to solar activity. Later, the model was incorporated into the CREME-96 (Tylka et al, 1997) and SPENVIS (Heynderickx et al, 1999) information systems.

Our galactic cosmic ray and SEP models make use of one and the same input parameter, namely, the solar activity level defined to be sunspot (Wolf) number, thereby permitting quite a reliable comparison between the fluences of SEPs and galactic particles at any solar activity level.

2 Proton fluences during years of "quiet" Sun and solar maximum

Following Feynman et al. (1990,1993), the "quiet" Sun periods are defined to be 4-year periods of the 11-year cycle. Considering that the solar cycle duration is variable (around 11 years), we take the “quiet” Sun period to be 4/11 of the total period of the lowest solar activity of the last three or four solar cycles, when the SEP event protons were actually measured. The 4/11 (0.364) Wolf number

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integral distribution level corresponds to sunspot numbers 40.1 and 39.4 for the last three and four solar cycles, respectively (the mean is 39.8). The mean is very close to W=40, which was first mentioned in (Feyman et al., 1990a) among some other quiet-Sun sunspot numbers. Figure 1 shows the 12-month smoothed sunspot number distribution in the years of SEP event measurements.

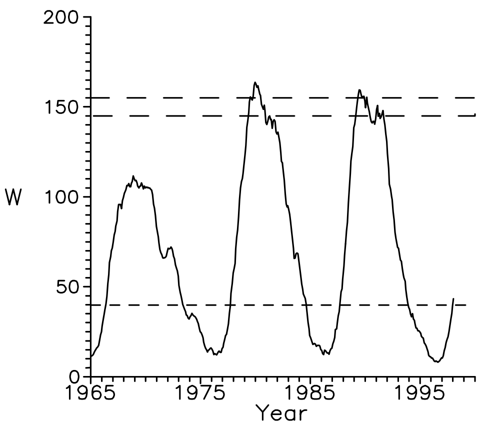

Fig.1. The mean-monthly smoothed sunspot numbers W between 1964 and 1998. The "quiet Sun" periods are below the short-dash line. The long-dash lines confine the high solar activity domain used in the present analysis.

The distribution in Figure 1 was used to determine the sunspot number W for each of the SEP event onset day. Since 1965, 22 events with ≥30 MeV proton fluences in excess of 10^6 protons/cm have been recorded for quiet sun periods. Of them, 18 events were recorded before 1985 (Feynman et al, 1990) and 4 events of 1994-1997 were found by our IMP-9 database analysis. These SEP events are as follows (the years and the days of a year of the SEP event onsets are indicated): 1965 (36), 1973 (210, 250, 307), 1974 (159, 184, 254, 309), 1975 (232), 1976 (83, 121, 235), 1977 (203, 251), 1985 (21, 114, 185, 198), 1994 (51), 1995 (293), 1997 (308, 310).

For the purposes of the analysis, the dataset must be divided into two groups

1. The years of 1965-1977, when the ≥10 and ≥30 MeV protons fluxes only were measured and
2. The years of 1985-1997, when the ≥60 MeV proton fluxes were also measured.

The total (summarized with respect to all events) particle fluence data are presented in Table I. The total periods, T (months), of proton fluence measurements are also presented. For comparison, the same data on the SEP events that occurred when the mean sunspot number was 145≤ <W> ≤155 are presented according to the for the 1965-1997 dataset.

Table 1. The total and mean-yearly proton fluences measured during time T (months) at different solar activity levels in 1965-1997.

W period	W≤40; period 1	W≤40; period 2	145≤W ≤155
$\Sigma\Phi_{E\geq10}$	$7.82{\cdot}10^8$	$1.24{\cdot}10^9$	8.610^9
$\Sigma\Phi_{E\geq30}$	$1.36{\cdot}10^8$	$4.0{\cdot}10^8$	$1.63{\cdot}10^9$
$\Sigma\Phi_{E\geq60}$	-	$1.3{\cdot}10^8$	$3.89{\cdot}10^8$
T	101	85	24
$\langle\Phi_{E\geq10}\rangle$	$8.9{\cdot}10^7$	$1.74{\cdot}10^8$	$4.3{\cdot}10^9$
$\langle\Phi_{E\geq30}\rangle$	$1.6{\cdot}10^7$	$5.68{\cdot}10^7$	$8.6{\cdot}10^8$
$\langle\Phi_{E\geq60}\rangle$	-	$1.84{\cdot}10^7$	$1.95{\cdot}10^8$

Figure 2 shows the experimental ≥10, ≥30, and ≥60 MeV integral annual fluence data from Table I. For the data of quiet Sun period 2 and for the 145≤W≤155 data, it is possible to extrapolate the energy spectrum to high energies in conformity with the proposition that the ≥30 MeV SEP energy spectra are power-law functions of proton rigidity (Nymmik, 1993). For quiet Sun period 1, we have extrapolated the energy spectrum to the high-energy range using the same index of the rigidity spectrum (γ_p=4.14) as for quiet Sun period 2.

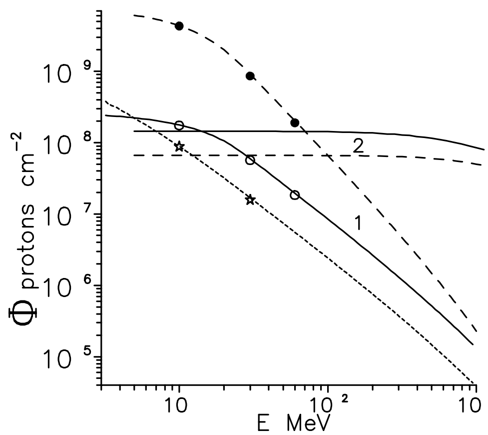

Fig. 2. The mean-yearly proton integral fluence spectra measured during the "quiet sun" (open circles for periods 1 – dotted line and 2 – solid line) and 145≤ W> ≤155 (dark circles) periods anfd their extrapolations. The solid and dashed lines (1) are the experimental data extrapolations to high energies for "quiet Sun" and high solar activity, respectively. The solid and dashed lines (2) are the annual integral galactic proton spectra at the same solar activity.

Figure 2 shows also the calculated (Nymmik et al. 1996) annual integral energy spectra of galactic cosmic ray protons during the same two solar activity periods. It is seen that, during the quiet Sun period, it is only the 10 MeV annual integral solar energetic proton fluences that exceed the annual galactic proton fluence. During high solar activity, the detected solar energetic proton fluences exceed the galactic proton fluences even at >60 MeV.

Unfortunately, it is the differential energy spectra of the particles that determine the space radiation environment. Figure 3 shows the differential energy spectra that correspond to the integral energy spectra displayed in Figure 2. Since the galactic and SEP event proton energy spectra are of different forms, the situation changes drastically. From the data of Figure 3 it follows that the mean annual SEP event proton fluences measured in the Earth orbit during the "quiet Sun" periods exceed the model-calculated galactic cosmic ray fluences before the proton energies reach 100 MeV, and the 10 MeV solar energetic proton fluences are up to 3-4 orders as high as the galactic particle fluences. During high solar activity, the measured mean-yearly SEP event proton fluences become equal to the calculated GCR proton fluences at 400 MeV.

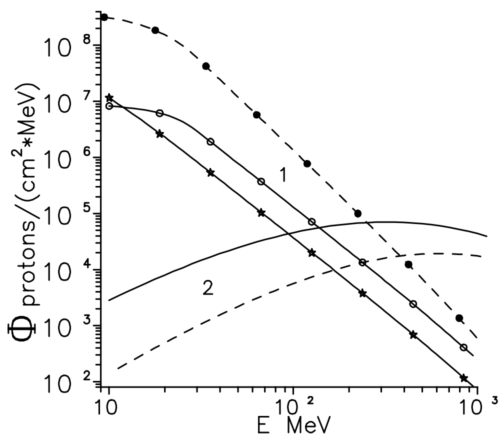

Fig 3. Differential energy spectra of annual proton fluences. The curves are the same as in Figure 2.

3 The balance between the fluences of SEPs and Galactic cosmic rays.

Because the SEP event numbers are random (given a known mean SEP event number), wile the proton fluence sizes are random within their distribution function, the above presented mean annual fluence data are also of random character and fail to fully describe the situation with the SEP fluences.

The situation with the dependence of SEP fluences on solar activity is fully described by the probabilistic SEP model (Nymmik, 1999). The model establishes the differential proton fluence energy spectra at different probabilities and indicates that the fluences determined by certain spectra should be exceeded within a given probability.

Figure 4 shows the results of calculating the annual differential proton energy spectra during quiet Sun (according the Figure 1 data, the mean sunspot number is <W>=21.5 during that period) and during solar maximum (<W>=150). The SEP fluence spectra are presented at some probabilities for the fluences to be exceeded. The energy spectra from Figure 3, which were determined by extrapolation to high energies from a very narrow energy range (30-60 MeV), are also shown. These energy spectra are very roughly compared with the model energy spectra, whose parameters are determined by analyzing a large set of experimental data in a broad energy range. Nevertheless, the mean-yearly 30 MeV proton fluences determined from the above selected experimental data are slightly above the 50% probability model curves. This is quite obvious, but it is the slopes of the model spectra that are preferred in our analysis.

Thus, the balance between the SEP event and galactic proton fluences has to be calculated in terms of the models (Nymmik, 1999c; Nymmik et al., 1995). Figure 5 shows the calculation results for the same quiet Sun (W=21.5) and solar maximum (W=150) periods as above. For quiet Sun, the calculated fluence balance is shown at 90%, 50%, and 10% probabilities for the balance to exceed given ratios. For solar maximum, the data are presented for 50% and 10% probabilities.

From Figure 5 it follows that the annual SEP event proton fluences exceed the annual galactic proton fluences during 90% of the quiet Sun years (W≤40) at proton energies of up to 60 MeV, during 50% of the years at the energies of up to 90 MeV, and during 10% of the years at the energies of up to even 230 MeV

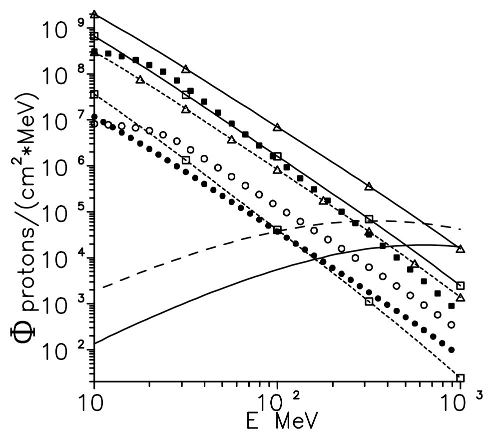

Fig. 4. The model-calculated differential proton energy spectra during quiet Sun (the dashed lines) and solar maximum (the solid lines). The solar energetic proton fluence spectra are shown at two probabilities (50%, the circles and 10%, the triangles. The dense-dotted curves are the measured fluence fits from Figure 3. The lower curves are the annual galactic proton fluence spectra during quiet Sun (the dashed curve) and solar maximum (the solid curve).

At a very low solar activity (W<20), of course, the proton balance curves of Figure 5 will run much below, so that a definite probability will appear for not a single SEP event to occur.

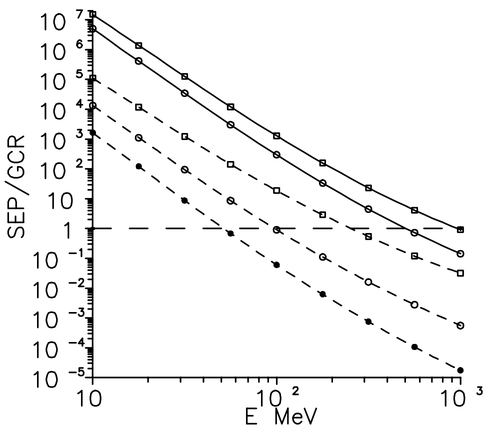

Fig 5. The annual SEP event-to-annual galactic proton fluence ratios (balance) during quiet Sun (the dashed curves) and solar maximum (the solid curves). The probabilities for the solar-to-galactic fluence ratio curves to run above the presented lines are 90% (the dots), 50% (the circles), and 10% (the squares).

During solar maximum, the annual solar proton fluences exceed the annual galactic proton fluences in 50% of the years at proton energies of up to 500 MeV and in 10 % of the years at proton energies of up to 900-1000 MeV.

4 Conclusions

Two main components of high-energy particles exist in the interplanetary space, namely, SEPs and galactic cosmic rays. Taken together, the two components give rise to radiation hazard for space missions. The hazard level depends on solar activity because both high-energy particle components are solar activity-dependent. The galactic particle fluxes constitute the permanent radiation, whose intensity varies rather slowly with solar activity. The SEP occurrences are random and should be described by probabilistic models.

From the above calculations it follows that the SEP event proton fluences count much during all the solar activity periods, the "quiet" Sun included. Therefore, the SEP models, which neglect the SEP events in the periods of low solar activity, cannot be used because such models lead to an inaccuracy of up to a few orders in determining the particle fluxes in interplanetary space.

Our analysis has demonstrated that the choice of low solar activity periods for interplanetary missions does not exclude the SEP-induced hazard. Moreover, there exists an essential probability during low solar activity for the SEP particle fluences to appear, which would be larger than $\Phi_{E\geq30} \geq 10^8$ protons/cm^2. Our analyzing the experimental data has led us to conclude that there does not exist any strict prohibition for the SEP events larger than $\Phi_{E\geq30} \geq 10^9$ to occur during quiet Sun in future.

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