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RADIATION ENVIRONMENT INDUCED BY COSMIC RAY PARTICLE FLUXES IN THE INTERNATIONAL SPACE STATION ORBIT ACCORDING TO RECENT GALACTIC AND SOLAR COSMIC RAY MODELS

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ABSTRACT

Radiation characteristics (particle fluxes, doses, and LET spectra) are calculated for spacecraft in the International Space Station orbit. The calculations are made in terms of the dynamic model for galactic cosmic rays and the probabilistic model for solar cosmic rays developed at the Institute of Nuclear Physics of Moscow State University.

INTRODUCTION

The International Space Station (ISS) orbit radiation environment is defined by the trapped radiation and by the galactic, solar, and anomalous cosmic ray fluxes incoming to the orbit from the interplanetary space beyond the Earth's magnetic field. The galactic and solar cosmic ray fluxes carry high-energy particles and will be analyzed in this work.

The cosmic ray-defined radiation environment in satellite orbits is simulated by successive application of models from the following main groups:

1. cosmic ray particle flux models for the Earth's orbit (beyond the Earth's magnetosphere),
2. models that describe the particle flux attenuation as the particles penetrate through the Earth's magnetic field to spacecraft orbits,
3. models that describe the particle flux deformation due to particle penetration through spacecraft shielding and formation of peculiar radiation field features, namely, radiation-induced doses and LET of particles.

This work deals mainly with the models for cosmic ray particle fluxes. The particle flux penetration to the Mir station orbit is treated solely for convenience, while the particle penetration through spacecraft shielding is discussed in simple terms necessary for the estimations of radiation characteristics (e.g. absorbed dose and LET spectrum) of cosmic ray particle fields.

GALACTIC COSMIC RAY MODEL

The galactic cosmic ray model developed at INP MSU has been described in detail elsewhere (Nymmik, et al. 1992,1995) and is based on the following:

1. the model proceeds from the energy spectra of particles (protons, electrons, and Z = 2-28 nuclei) in the local interstellar space;

2. the particle fluxes at the Earth orbit are described in terms of the semiempirical solar modulation model unified for all particles. Solar activity (sunspot number) and dynamics of the general heliospheric magnetic field are the input parameters in the model;
3. the model allows for the well-known phenomenon of particle flux variation lag relative to solar activity variations for the features of the phenomenon observed during odd and even solar cycles, and for the dependence of the lag on magnetic rigidity of the particles;
4. the model describes the difference in the modulation depth of positively- and negatively-charged particles during odd and even solar cycles.

SOLAR COSMIC RAY MODEL

In its basic characteristics, the solar cosmic ray model developed at INP MSU in 1995-1996 (the SCR-96 model) is completely different from other present-day models of solar cosmic ray particle flux. The model proceeds from the probabilistic nature of the occurrence of solar cosmic ray events, from the dependence of the occurrence frequency of these events on solar activity (on sunspot number), from the power-law function of particle fluence distribution of solar cosmic ray events, and from the characteristics of the ($1 \leq z \leq 28$; E>1 MeV/nucleon) particle energy spectra found by the statistical and functional analysis of a set of solar cosmic ray events.

Dependence of Solar Cosmic Ray Occurrence Frequency on Solar Activity.

Most of the present-day solar cosmic ray models (Feynman *et al.*, 1992) define solar cosmic ray fluxes only during active phases of the solar cycle (i.e., 7 years of 11-year cycle) and disregard the dependence of the occurrence frequency of the solar cosmic ray events on any particular solar activity level. So, all solar cycles prove to be as if levelled as regards their activity and duration. Besides, the particle fluxes that occur during low solar activity are neglected. This approach is accounted for by the absence of any evident correlations between a particular solar activity level within 11-year solar cycles and the number of detected events, or the particle fluence throughout a solar cycle. Our analysis has shown that the absence of any marked correlations is camouflaged by poor statistics and by random occurrence frequency of large events. Figure 1 is the plot of the occurrence frequency of the $\Phi_{30} \geq 10^6$ proton / cm^2 solar cosmic ray events observed in 1955-1985 versus ranges of sunspot numbers W. Within the statistical accuracy, the distribution displayed can be described as (Nymmik, 1997)

$$N = 0.18 \cdot W^{0.75} \quad \text{event/year} \tag{1}$$

Correlation coefficient for this fit of the SCR events versus sunspot number is equal to 0.88.

Distribution Function.

The SCR-96 model assumes that the function of ≥30 MeV proton fluence distribution of solar cosmic ray events is the power law throughout the range of fluences ($\Phi_{30} \geq 10^5$ protons /cm^2) observed at the Earth orbit:

$$\psi(\Phi) = \frac{1}{N}\frac{dN(\Phi)}{d\Phi} = C \cdot \Phi^{-1.40}, \tag{2}$$

where dN is the number of events with Φ within the dΦ range (Kurt and Nymmik, 1996).

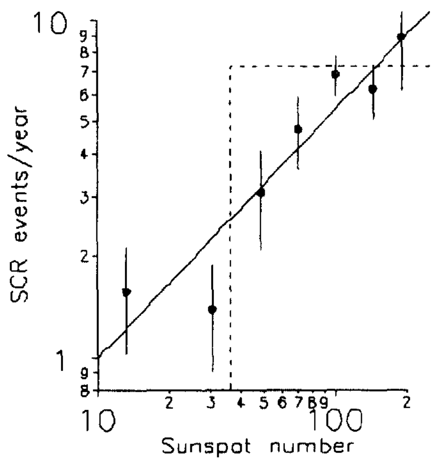

Fig. 1. Occurrence frequency of solar cosmic ray events with fluences $\Phi_{30} \geq 10^6$ proton / cm^2 versus smoothened by 12 months monthly mean sunspot number - solid line (Nymmik, 1967). Dashed line - occurrence frequency of solar cosmic ray events model Feynman *et al.* 1993.

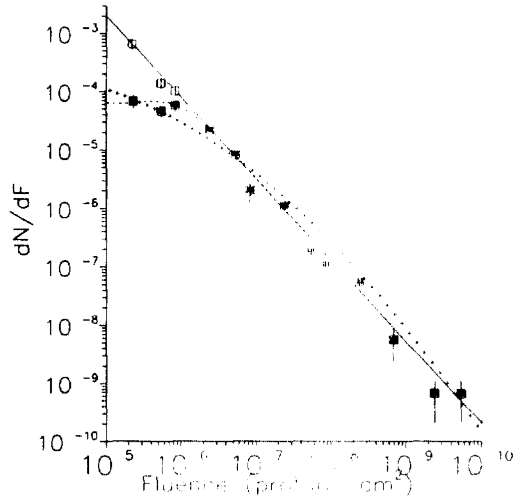

Fig. 2.
Differential distribution of the number of solar cosmic ray events for the E≥30 MeV proton fluence. The dark squares are experimental data (Gabriel and Feynman 1996). The light squares are the data corrected for the threshold effect. The solid line is the distribution by Eq.(1). The dashed line is the distribution by Eq.(1) allowing for the threshold effect (Kurt and Nymmik, 1996). Crosses marked in the lognormal distribution.

This result has been obtained by analyzing experimental data of Gabriel and Feynman (1996) and is shown in Figure 2. Kurt and Nymmik (1996) have shown that the observed "droop" of the distribution in the range of fluences $\Phi_{30} \leq 5 \cdot 10^6$ proton / cm^2 is due completely to the threshold effect of solar cosmic ray detection (selection). The effect having been allowed for, the experimental distribution proves to be a power-law function to within an accuracy a few times higher compared with the log normal function used conventionally to describe the distribution. At $\Phi_{30} \geq 10^9$ protons/cm^2, the distribution does not suffer any steepening either. This means that the present-day experimental data do not justify using log normal functions in the solar cosmic ray models because the functions lead to undue underestimation of the large solar cosmic ray events that are of importance in terms of radiation environment.

Besides, the results of calculating the distribution functions of the events broken into three groups differing in solar activity level (see Figure 3) do not contradict the power-law form of the general distribution to within the statistical error [Eq. (1)]. Therefore, the available experimental data do not contradict the proposition that the mean occurrence frequency of solar cosmic ray events is a function of solar activity, while quite a definite probability exists for even very large events to occur during the "quiet" period of solar cycles. This circumstance is disregarded by the present-day solar cosmic ray models, but has been allowed for in the SCR-96 model by using the above functions [Eqs. (1) and (2)].

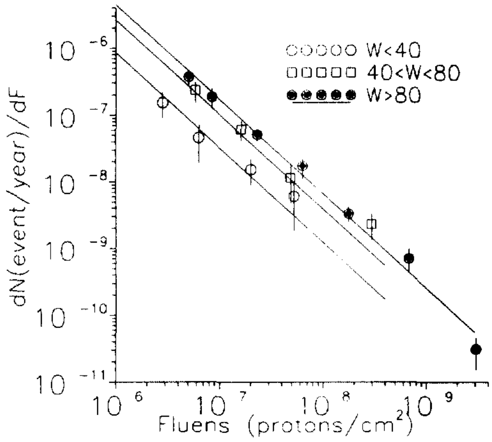

Fig. 3 Differential distribution of the number of solar cosmic ray events for the $E \geq 30$ MeV/nucleon proton fluence size at different solar activity levels, calculated for the experimental data Feynman *et al.*, (1990).

Energy Spectra of Solar Cosmic Ray Particles.

The relevant statistical and functional analysis (Nymmik, 1996b) has demonstrated that the energy spectra of all particles in all solar cosmic ray events at $E_o \geq 30$ MeV/nucleon are power-law functions of momentum (per nucleon)

$$F(E)dE = F(p)\frac{dp}{dE}dE = C\cdot\left(\frac{p}{p_o}\right)^{-g}\cdot\frac{dE}{b} \tag{3}$$

where $\beta = p\big/\sqrt{p^2+(2mc^2)^2}$ is relative particle velocity;. $p=\sqrt{E(E+2mc^2)}$;
p_o=239 MeV/c/(nucleon).
At lower energies, the spectra suffer a "droop" whose form and value are described again by Eq. (3) if the spectral index is expressed as

$$\gamma = \gamma_o\left(\frac{E}{E_o}\right)^{-\alpha} \tag{4}$$

where γ_o is the spectral index value at E≥30 MeV.
The set of the solar cosmic ray energy spectra are described by the mean spectral parameters $\overline{\gamma}_o$ and $\overline{\alpha}$ and by fluctuations of these parameters about their mean values. In the case of proton spectra, the spectral parameters are functions of the proton fluence of an event (Nymmik, 1995).

A correlation holds between the spectral parameters of protons and nuclei. On the average, however, we have

$$\overline{\gamma_o^{(z)}} = K_\gamma \cdot \gamma_o^{(p)} = (1.26\pm 0.07)\cdot\gamma_o^{(p)} \tag{5}$$

and

$$\alpha^{(z)} = K_\alpha \frac{\gamma_o^{(z)}}{\gamma_o^{(p)}}\cdot\alpha^{(p)} = \left(\frac{A}{Q}\right)^{-0.47}\cdot\frac{\gamma_o^{(Z)}}{\gamma_o^{(p)}}\cdot\alpha^{(p)}, \tag{6}$$

where A_z and Q_z are, respectively, mass number and mean charge of ion in solar cosmic rays (Figure 4.)
Eqs. (5) and (6) were found by analyzing the p, He, O, and Fe spectra of 10 solar cosmic ray events presented in Mazur *et al.* (1992). In the analysis, the particle energy spectra were approximated by formulas (3) and (4) which describe the experimental data to within a better accuracy than the stochastic acceleration formulas used in Mazur *et al.* (1992). The heavy ion flux is essentially characterized by the ion charge state distribution. The SCR-96 model assumes that the mean charge state is distributed as

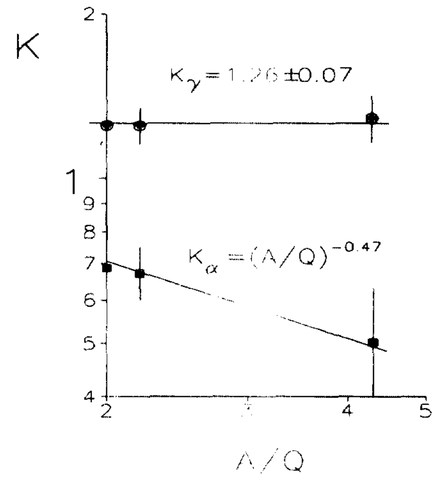

Fig. 4. Coefficients K_γ and K_α of Eqs. (5) and (6) as found from the experimental data of (Mazur *et al.*, 1992)

$$\overline{Q\left(A/z\right)} = z - 0.21 \cdot (z-5)^{1.32} \tag{7}$$

According to Gagarin *et al.* (1996) the standard deviation of the normal distribution of the charge states is taken here to be

$$\Delta Q = 1.17 \cdot (z-5)^{1.32} \cdot z^{-1} \tag{8}$$

Knowing the dependence of the mean occurrence frequency of events on solar activity, the particle fluence distribution of events, and the behavioural features of particle energy spectra make it possible to calculate the solar cosmic ray fluxes ($1 \le Z \le 28$ and $\mathbf{E} \ge 3$ MeV/nucleon) as a probabilistic quantity for any time interval with a predictable solar activity level.

Fluence Probability in Terms of the SCR-96 Model.

The above input propositions make it possible to calculate the dependencies of the occurrence probability of particles with energies above a prescribed level as functions of fluence size for different duration of observations beyond the Earth's magnetosphere. For this purpose, given a definite solar activity level, the mean occurrence frequency of solar cosmic ray events is calculated, a random number of events is simulated on the basis of the resultant mean, and a random fluence size in a Φ_{30} event is simulated [from the distribution described by Eq. (1)]. The expressions describing the energy spectra of protons (Nymmik, 1995) and ions (Eqs. (5) and (6)) are then used to simulate random parameters of the particle energy spectra. This work focus on events with $\Phi_{30} \ge 10^5$ proton/cm^2. Figure 5 are the results of calculating the integral probability of fluences of protons and iron nuclei with energies of ≥3, ≥30, and ≥300 MeV/(nucleon) during a year-long flight at solar activity levels defined by sunspot numbers W=10, W=140, and W=200. The distributions for the ≥3 and ≥30 MeV protons at W=140 were compared with results from the JPL model (Feynman *et al.*, 1993). Noticeable qualitative and quantitative differences were noted between the two models that arise from the differences in the techniques for describing the same experimental data underlying the two models. Families of integral distributions similar to those shown in Figure 5 and calculated for differentenergy particles under identical initial conditions make it possible to calculate the energy spectra that describe the particle fluence sizes expected under different probabilities.

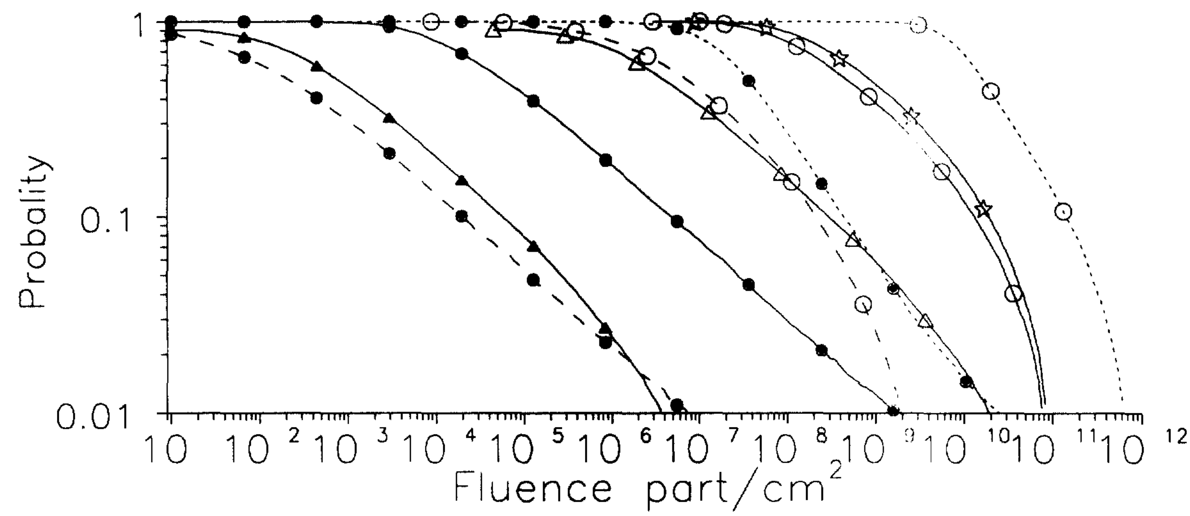

Fig. 5. Probability for the fluences of protons and Fe ions of various energies to exceed definite levels during one-year missions at different solar activity levels. The dotted, solid, and dashed lines are for the $E \geq 3$, 30, and 300 MeV/nucleon particles, respectively. The light circles are for protons at W=140, the stars are for protons at W=200, the light triangles are for protons at W=10, the black circles are for iron ions at W=140, the black triangles are for iron ions at W=10.

TRANSMISSION FUNCTION FOR THE INTERNATIONAL SPACE STATION ORBIT

Transmission functions specify the charged-particle flux fraction that penetrate to the station orbit from interplanetary space as a function of magnetic rigidity, R, of the particles.The function is calculated in terms of the Earth's magnetic field intraterrestrial source model (IGRF 1985) superimposed with magnetic fields of the currents in the magnetosphere, on the magnetospheric surface, and in the magnetospheric tail. The model for the currents has been developed by Tsyganenko (1989). The magnetic fields of the current systems make the Earth's magnetic field vertical rigidity diminish, especially during magnetospheric disturbances. Figure 6 shows the transmission functions of vertical particle flux penetration to the Alpha station orbit (a 51.6° inclination, a 470-km circular orbit altitude), calculated with an empirical model that makes use of these magnetic field sources (Nymmik, 1992; Danilova and Tyasto, 1995; Boberg *et al.*, 1993).

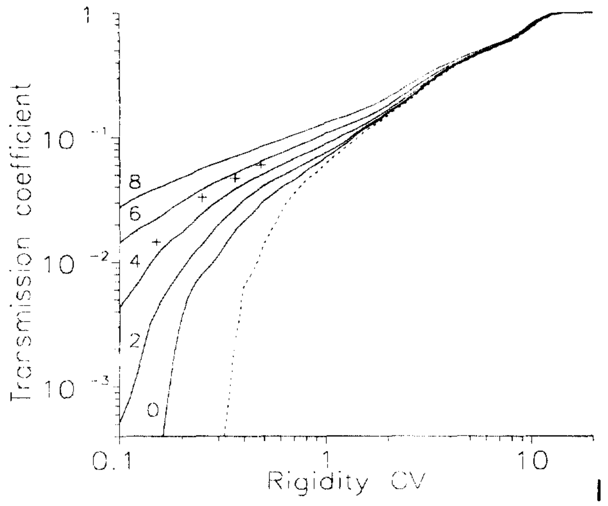

Fig. 6. Transmission functions for the 51.8° inclination, ≈500-km altitude orbit. The dotted curve is the IGRF model. The solid curves are the transmission functions for different geomagnetic disturbance levels (the numerals are the K_p indices). The crosses are transmission coefficients at $K_p = 5$ according to Boberg *et al.* (1993).

In the case of highly disturbed field $(K_p = 5$, our model uses the extrapolated values of the vertical rigidity attenuation factors Δ (Nymmik, 1991) such that

$$\Delta(R_o, K_p) = \frac{R_o}{R(R_o, K_p)} \quad , \qquad (9)$$

where R is the cut-off rigidity for disturbed field and R_0 is the cut-off rigidity from the IGRF-model. Δ are a power-law function of R_0 and the exponent of the K_p index value.

COSMIC RAY-INDUCED RADIATION ENVIRONMENT CHARACTERISTICS ON BOARD THE INTERNATIONAL SPACE STATION

The above model concepts make it possible to calculate the energy spectra of galactic and solar cosmic ray particles behind the station shielding in the orbit. The galactic cosmic ray penetration to the Alpha station orbit was calculated by the transmission function under a weak geomagnetic disturbance ($K_p =$) for moderately-disturbed solar cosmic ray fluxes ($K_p = 4$). The fluxes behind a moderate-thickness shielding were calculated including the particle energy loss for ionization and the particles lost in inelastic nuclear interactions. Figures 7 and 8 present the calculation results for protons and iron nuclei, respectively. The galactic cosmic ray energy spectra were calculated for radiation environment as of 1990 (solar maximum) and 1996 (solar minimum).

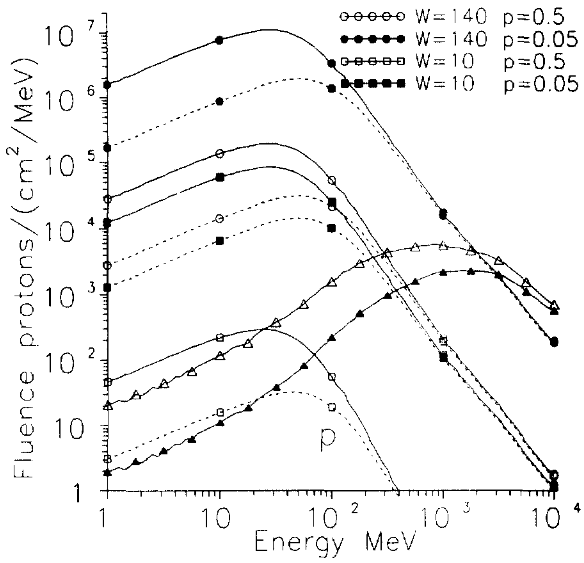

Fig. 7. Differential energy spectra of annual proton fluences in the Alpha station orbit behind shielding thickness x. The light and black triangles are galactic cosmic rays behind x = 3.2 g/cm^2 in 1996 and in 1990, respectively. The solid and dotted lines are for x = 3.2 and 10.0 g/cm^2, respectively.

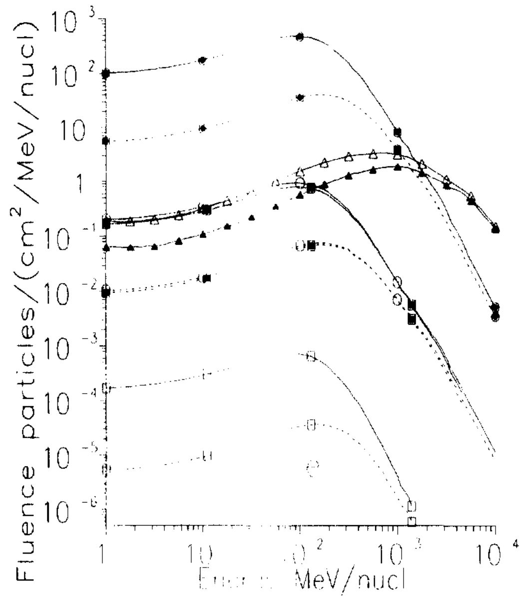

Fig. 8 Differential energy spectra of annual iron ion fluences in the Alpha station orbit behind shielding thickness x. Notation is the same as in Figure 7.

The probabilistic spectra of solar cosmic ray particles were calculated for solar activity levels W=10, W=140, and W=200 and for the probability levels p=0.5 and p.=0.05. The solar cosmic ray proton probabilities p = 0.5 and 0.05 mean that the occurrence probability of fluxes above the given level is 50% and 5%, respectively.

From the data displayed it is seen that the annual solar proton fluences behind shielding in the Alpha orbit exceed the galactic cosmic ray particle fluences. The only exception is under a low solar activity, when the solar proton fluence behind a shielding x 3.2 g/cm^2 within a 0.5 probability becomes comparable to the galactic cosmic ray proton fluence.

The situation is different with the iron ion fluences. In this case the solar particle fluence under a maximum solar activity behind a shielding $x \geq 3.2$ g/cm^2 within a 0.5 probability becomes comparable to the galactic cosmic ray iron fluence.

The above behavioural features are also reflected in the differential particle LET spectra plotted in Figure 9. In the case of solar cosmic ray particles with LET >100 MeV·cm^2/g behind a 3.2 g/cm^2 shielding, the particle fluences under a low solar activity (W=10, p $\leq$ 0.05) are below the galactic cosmic ray particle fluxes. Under a high solar activity (W=140), and probability p $\leq$ 0.5 the solar cosmic ray fluxes exceed the galactic particle fluxes.

Figure 10 shows the absorbed doses calculated as functions of the probability for the dose to exceed the level indicated in the plots for three spherical shielding thicknesses.

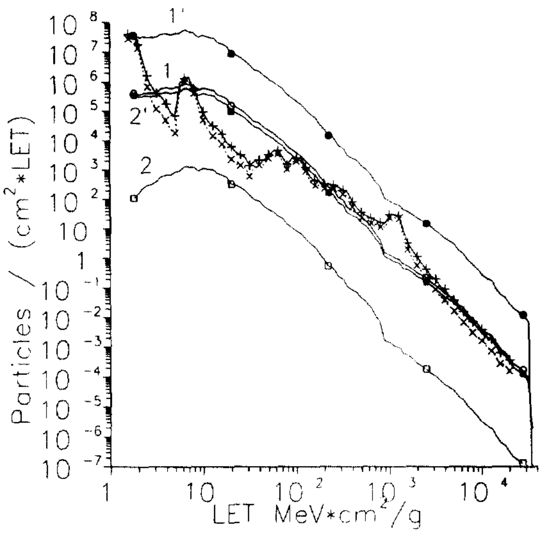

Fig. 9. Differential LET spectra of annual particle fluences behind 3.2 g/cm^2 shielding in the Alpha station orbit. The crosses are galactic cosmic rays in 1996 (+++) and in 1990 (xxx), respectively. Curves 1 and 1' are, respectively, solar cosmic ray particle fluxes for p = 0.5 and 0.05 at W = 140. Curves 2 and 2' are the same at W = 10.

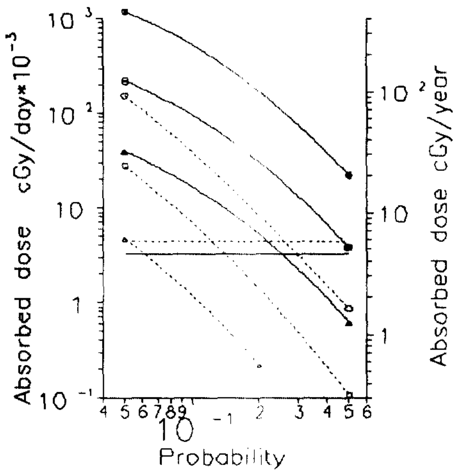

Fig. 10. Annual absorbed radiation doses versus probability, p, for solar cosmic ray fluxes to exceed the given level in the Alpha station orbit. The horizontal dotted and solid lines are the galactic cosmic ray doses in 1996 and in 1990, respectively). The solid and dotted curves are the doses at W = 140 and 10, respectively. The circles, squares, and triangles are shielding thicknesses of 1.0, 3.2, and 10.0 g/cm^2, respectively

The doses induced by galactic cosmic ray particles are presented for a 3.2 g/cm^2 shielding. Under low solar activity, the dose induced by solar cosmic rays only behind 1 g/cm^2 shielding exceeds the galactic cosmic ray dose within as low probability as ~0.1. Under high solar activity the doses induced by galactic and solar cosmic rays behind a 3.2 g/cm^2 shielding prove to be the same within a 0.5 probability. At W=140, within a 0.05 probability, the annual dose from solar cosmic rays exceeds 14 rad behind 10 g/cm^2 and 80 rad behind 3.2 g/cm^2 shielding.

CONCLUSION

The analysis of the results of calculating the particle spectra and the absorbed doses on a spacecraft in the Alpha station orbit in terms of the present-day galactic and solar cosmic ray models shows that there exists a substantial probability for solar cosmic rays to contribute to radiation environment in the orbit. This ensues from adequate estimating the present-day experimental data on the distribution function of solar cosmic ray events, from allowing for the certain dependence of solar cosmic ray event occurrence frequency, and from specifying the characteristics of solar cosmic ray energy spectra. It is also of importance to allow for the geomagnetic field depression during solar cosmic ray events, which permits the particles to penetrate more readily to the orbit. The particle charge composition is also essential in terms of penetration of heavy solar cosmic ray ions to the Alpha station orbit.

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