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Great SEP events and space weather: 4. Checking on the basis of historical event data, expanding the spectrum by using NM and satellite data simultaneously, and modernization of the model; 5. Principles of on-line radiation hazard monitoring and forecasting in space, in the magnetosphere, and in the atmosphere

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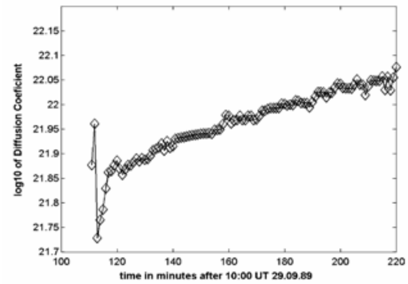
We apply programs "SEP-Research/Time of Ejection", "SEP-Research /Source" and "SEP-Research /Diffusion", developed in [1], to an SEP event in September 1989, using only NM data. In this case, we determine all three unknown parameters: time of ejection; diffusion coefficient in the interplanetary space; and energy spectrum at the source of SEP. We show that the model with a constant diffusion coefficient does not work appropriately. We extend this model in two aspects: we suppose that the diffusion coefficient depends upon the distance to the Sun by the power law, and we suppose a more complicated form for the spectrum in the source to describe simultaneously low and high energy regions according to satellite and NM data. We show that on the basis of about 30 min of data it is possible to estimate the main parameters of SEP acceleration and propagation and predict the SEP space-time-energy distribution up to about 2000 minutes with good accuracy. Then, we show how, on the basis of these results, forecasts of expected radiation hazard for computers, electronics, solar batteries, and technology in space at different distances from the Sun may be made. We show that the same forecasts can be made for satellites in different orbits in the magnetosphere, taking into account the change in cut-off rigidities along the orbits. By method of coupling functions for different altitudes in the atmosphere we describe principles of radiation hazard forecasting on-line for aircraft on regular and non-regular lines, as well as for human health and technology on the ground, depending on air pressure and cut-off rigidities, and values of shielding. If for some cases the calculated radiation hazard is expected to be higher than some definite level of danger, special alerts can be sent on-line.

1. Checking the model by on-line determination of expected diffusion coefficient



In order to check the model of SEP propagation in the interplanetary space, developed in [1], we determined first the diffusion coefficient $K(R)$. These calculations have been done according to the procedure described in [1], by supposing that $K(R)$ does not depend on the distance to the Sun. Results are shown in Figure 1.

Figure 1. The time behavior of $K(R)$ for R~10 GV.

It can be seen that at the beginning of the event the obtained results are not stable, due to large relative statistical errors. After few minutes the amplitude of SEP intensity increases, becoming many times bigger than σ, and we can see a systematical increase of the diffusion coefficient with time. This reflects the increasing of $K(R)$ with distance from the Sun.

2. The case when the diffusion coefficient depends upon distance to the Sun

Let us suppose, according to [2] that the diffusion coefficient

$$K(R,r) = K_1(R) \times (r/r_1)^{\beta}, \tag{1}$$

where r_1 = 1 AU. In this case, for SEP source function

$$Q(R,r,t) = N_o(R)\delta(r)\delta(t) \tag{2}$$

the differential density of SEP at a distance *r* from the Sun will be

$$n(R,r,t) = \frac{N_o(R) \times r_1^{3\beta/(2-\beta)}(K_1(R)t)^{-3/(2-\beta)}}{(2-\beta)^{(4+\beta)/(2-\beta)}\Gamma(3/(2-\beta))} \times \exp\left(-\frac{r_1^{\beta} r^{2-\beta}}{(2-\beta)^2 K_1(R)t}\right). \tag{3}$$

If we determined by method of coupling functions n_1, n_2, n_3 on the basis of ground based measurements (*r* = 1 AU) at times t_1, t_2, t_3 (as it was described in [1, 3]), the final solutions for β, $K_1(R)$, $N_o(R)$ will be

$$\beta = 2 - 3\left[\ln(t_2/t_1) - \frac{t_3(t_2-t_1)}{t_2(t_3-t_1)}\ln(t_3/t_1)\right] \times \left[\ln(n_1/n_2) - \frac{t_3(t_2-t_1)}{t_2(t_3-t_1)}\ln(n_1/n_3)\right]^{-1}, \tag{4}$$

$$K_1(R) = \frac{r_1^2\left(t_1^{-1} - t_2^{-1}\right)}{3(2-\beta)\ln(t_2/t_1) - (2-\beta)^2\ln(n_1/n_2)} = \frac{r_1^2\left(t_1^{-1} - t_3^{-1}\right)}{3(2-\beta)\ln(t_3/t_1) - (2-\beta)^2\ln(n_1/n_3)}, \tag{5}$$

$$N_o(R) = n_1(2-\beta)^{(4+\beta)/(2-\beta)}\Gamma(3/(2-\beta))r_1^{-3\beta/(2-\beta)}(K_1(R)t_k)^{3/(2-\beta)} \times \exp\left(\frac{r_1^2}{(2-\beta)^2 K_1(R)t_k}\right). \tag{6}$$

In the last Eq. (6) index *k* = 1, 2 or 3. To check the model let us again determine the diffusion coefficient.

In Figure 2 are shown values of parameter $K_1(R)$ in Eq. (1). It can be seen that at the very beginning of event (the first point) the result is unstable- in this period, the amplitude of increase is relatively small, so the relative accuracy is too low, and we obtain a very big diffusion coefficient. Let us note that for very early steps of the event the diffusion model can be applied very rarely (it is more natural to apply the kinetic model of SEP propagation). After the first point we have a stable result with accuracy ± 20 %.

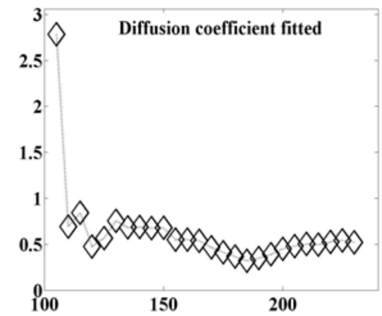


Figure 2. Diffusion coefficient $K_1(R)$ near Earth's orbit (in units $10^{23}\ cm^2\ sec^{-1}$) depending on time (in minutes after 10.00 UT of September 29, 1989).

3. SEP forecasting using only neutron monitor data

By using the first few minutes of the SEP event in NM data we can determine by Eq. (4) – (6) the effective parameters β, $K_1(R)$, and $N_o(R)$, corresponding to rigidities 7 – 10 GV. Then, by Eq. (3), we determine the forecasting curve of expected SEP flux variation for total neutron intensity. We compare this curve with the time variation of observed total neutron intensity. In reality, we use data for more than three moments of time by fitting the obtained results in comparison with experimental data to reach the minimal residual (see Figure 3, which contains 8 panels for times *t* = 110 min up to *t* = 220 min after 10.00 UT of 29 September, 1989).

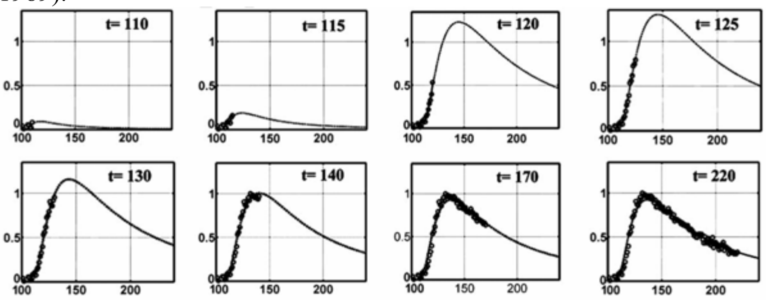


Figure 3. Calculation of line parameters β, $K_1(R)$, $N_o(R)$ according to Eq. (4)-(6) and forecasting of total neutron intensity by Eq. (3). Abscissa axes shows the time in minutes after 10.00 UT of September 29, 1989. Curves – forecasting, circles – observed total neutron intensity.

From Fig. 3 it can be seen that it is not enough to use only the first few minutes of NM data (*t* = 110 min); the obtained curve forecasts an intensity that is too low. For *t* = 115 min the forecast shows some bigger intensity, but also not enough. Only for *t* = 120 min (15 minutes of increase after beginning) and later (up to *t* = 140 min) we obtain about stable forecast with good agreement with observed CR intensity.

4. SEP forecasting by the on-line use of both neutron monitor and satellite data

The results described above, based on on-line NM data, reflect the situation in SEP behavior in the high rigidity range (more than a few GV). For extrapolation of these results to the low energy interval (dangerous for space-probes and satellites), we use on-line satellite data available through the Internet. The problem is how to extrapolate the SEP energy spectrum from high NM energies to very low energies detected by the GOES satellite. The main idea of this extrapolation is the following: the source functions, times of ejection, and diffusion coefficients in both energy ranges are the same. The problem is that the power rigidity spectrum of SEP out of the Earth's atmosphere (in the form $\propto R^{-\gamma}$, which we determined in [1] from NM data by method of coupling functions) is not appropriate for the small rigidity ranges measured by satellites. By analyzing many SEP events, we came to conclusion that the rigidity spectrum which will be appropriate simultaneously to high and low rigidity ranges measured by NM and satellites is again a power function $\propto R^{-\gamma}$, but with a rigidity-dependent index $\gamma = \gamma_o + \alpha \ln(R/R_o)$. This spectrum has a maximum at $R_{\max} = R_o \exp(-\gamma_o/\alpha)$, and with increasing rigidity γ slowly increases. Figure 4 shows results based on the NM and satellite data of forecasting of expected SEP fluxes also in the small energy range, and a comparison with observed satellite data.

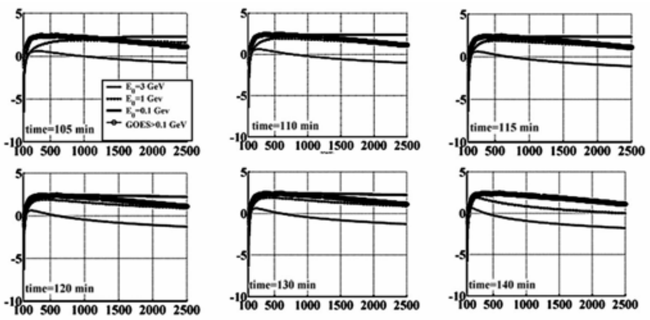
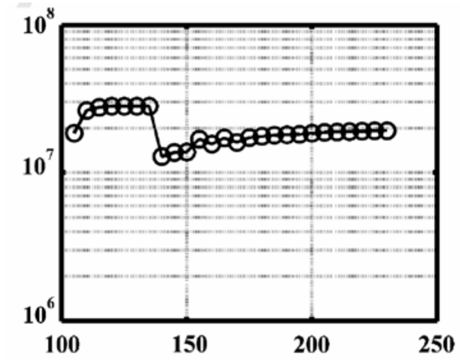


Figure 4. Predicted SEP integral fluxes for $E_k \geq E_o = 0.1\,GeV$, $E_k \geq E_o = 1\,GeV$, and $E_k \geq E_o = 3\,GeV$. The forecasted integral flux for $E_k \geq E_o = 0.1\,GeV$ is compared with the observed fluxes for $E_k \geq 100\,MeV$ on GOES satellite. The ordinate is $\log_{10}$ of SEP integral flux (in $cm^{-2}sec^{-1}sr^{-1}$), and the abscissa is time in minutes from 10.00 UT of September 29, 1989.



From Figure 4 it can be seen that the agreement between the predicted and observed FEP integral flux for $E_k \geq E_o = 0.1 GeV$ is excellent after 30-40 minutes from the onset of the event. The agreement continues to more than 2500 minutes (about two days). In Figure 5 we show the results of calculations for the expected total (event-integrated) SEP fluency for $E_k \geq E_o = 0.1 GeV$.

Figure 5. Predictions of the expected total (event-integrated) SEP fluency for $E_k \geq E_o = 0.1 GeV$. The ordinate axis is the $\log_{10}$ of the total FEP fluence (in $cm^{-2}sr^{-1}$), and the abscissa is time when the prediction was made, in minutes from 10.00 UT of September 29, 1989.

5. Alerts in cases of expected dangerous fluxes and fluency.

If the predicted fluxes are expected to be dangerous, preliminary "SEP-Alert_1/Space", "SEP-Alert_1/ Magnetosphere", and "SEP-Alert_1/ Atmosphere" will be sent in the first few minutes after the event. As more data become available, better predictions of the expected fluxes will be made. On the basis of these predictions, more definitive Alert_2, Alert_3 and so on will automatically be issued. These Alerts will give information on the expected time and level of dangerous situations for different objects in space, in the magnetosphere, in the atmosphere at different altitudes, and at different cut-off rigidities. Experts must decide what to do operationally. For example, for space-probes in space and satellites in the magnetosphere, to switch-off the electric power for 1-2 hours to save the memory of computers and high level electronics; for jets, to decrease their altitudes from 10-20 km to 4-5 km to protect crew and passengers from great radiation hazard, and so on.

6. Conclusion.

We show that by using on-line data from ground NM in the high energy range and from satellites in the low energy range during the first 30-40 minutes after the start of the SEP event, it is possible to predict the expected SEP integral fluxes for different energies up to a few days ahead. The total (event-integrated) fluency of the event, and the expected radiation hazards, can also be estimated, and corresponding Alerts can be sent.

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