29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

Great SEP events and space weather: 4. Checking on the basis of historical events data, expending spectrum by using simultaneously NM and satellite data, and modernizing of the model; 5. Principles of on-line radiation hazard monitoring and forecasting in space, in 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 SEP event in September 1989 by 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 constant diffusion coefficient does not work appropriate. We extend this model in two aspects: we suppose that the diffusion coefficient depends from the distance to the Sun by the power low, and we suppose for the spectrum in the source more complicated form to describe simultaneously low and high energy regions according to satellite and NM data. We show that on the basis of about 30 min data it is possible to estimate main parameters of SEP acceleration and propagation and predict the SEP space-time-energy distribution up to about 2000 minutes with a good accuracy. Then we show how on the basis of these results may be made forecasting of expected radiation hazard for computers, electronics, solar batteries, technology in space on different distances from the Sun. We show that the same can be made for satellites on different orbits in the magnetosphere with taking into account the change of cut-off rigidities along the orbits. By the method of coupling functions for different altitudes in the atmosphere we describe principles of radiation hazard forecasting on-line for air-planes on regular and non-regular lines as well as for people health and technology on the ground in dependence of air pressure and cut-off rigidities, and values of shielding. If for some cases the calculated radiation hazard will be expected higher than some definite level of dangerous, can be on-line send special Alerts.

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

For checking the used model of SEP propagation in the interplanetary space, developed in [1], we determined at the 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 increasing becomes many times bigger than σ, and we can see a systematical increase of the diffusion coefficient with time: it reflects the increasing of $K(R)$ with the distance from the Sun.

2. The case when the diffusion coefficient depends from the 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 on the distance r from the Sun will be

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

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

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

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

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

In the last Eq. (6) index k = 1, 2 or 3. For checking 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 very big diffusion coefficient. Let us note, that for very beginning step of event the diffusion model can be very hardly applied (more natural is applying of kinetic model of SEP propagation). After the first point we have about stable result with accuracy ± 20 %.

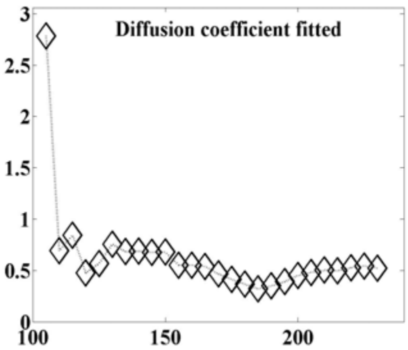

Figure 2. Diffusion coefficient $K_1(R)$ near Earth's orbit (in units $10^{23}\ cm^2\ \sec^{-1}$) in dependence of time (in minutes after 10.00 UT of September 29, 1989).

3. SEP forecasting by 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, and then by Eq. (3) we determine the forecasting curve of expected SEP flux variation for total neutron intensity. We compare this curve with 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 on 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 too low intensity. 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 using of both neutron monitor and satellite data

The results described above, based on NM on-line data, reflect the situation in SEP behavior in the high rigidity range (more than few GV). For extrapolation of these results to the low energy interval (dangerous for space-probes and satellites), we use satellite on-line 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 GOES satellite. The main idea of this extrapolation is the following: the source function, time of ejection and diffusion coefficient 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, does not appropriate for small rigidity range measured by satellites. By analyzing of 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 an rigidity-dependent index $\gamma = \gamma_o + \alpha \ln(R/R_o)$. This spectrum has 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 small energy range and comparison with observation 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 situation for different objects in space, in magnetosphere, in atmosphere on 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 send.

7. Acknowledgements

Our great thanks to Prof. Yuval Ne'eman for constant interest and support of the work of Israel Cosmic Ray and Space Weather Center and Emilio Segre' Observatory. and J. Allen, A.V. Belov, E.A. Eroshenko, K.G. McCracken, M.A. Shea, D.F. Smart, M. Storini, and V.G. Yanke for interesting discussions. The work of neutron monitor on Mt. Hermon is supported by the Collaboration of Tel Aviv University (Israel) and UNIRoma-Tre and IFSI-CNR (Italy). This research was partly supported by COST-724 (European Space Weather).

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