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Forecasting of radiation hazard and the inverse problem for SEP propagation and generation in the frame of anisotropic diffusion and in kinetic approach

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Abstract: It is well known that energy spectrum of solar energetic particles (SEP), observed by ground based neutron monitors and muon telescopes (in high energy region; the transfer to the space from the ground observations is made by the method of coupling functions, see in Chapter 3 of [1]), and by detectors on satellites and space-probes (in small energy region) changed with time very much (usually from very hard at the beginning of event to very soft at the end of event). The observed spectrum of SEP and its change with time are determined by three main parameters: energy spectrum in source, time of ejection, and propagation mode. In the past we considered the first step for forecasting of radiation hazard: the simple isotropic mode of SEP propagation in the interplanetary space (see Chapter 2 in [2]). It was shown that on the basis of observation data at several moments of time could be solved the inverse problem and determined energy spectrum in source, time of ejection, and diffusion coefficient in dependence of energy and distance from the Sun. Here we consider the inverse problem for the complicated case: mode of anisotropic diffusion and kinetic approach. We show that in this case also the inverse problem can be solved, but it needs NM data at least at several locations on the Earth. We show that in this case the solution of inverse problem starts to work well sufficiently earlier than solution for isotropic diffusion, but after 20-25 minutes both solutions give about the same results. It is important that obtained results and reality of used model can be controlled by independent data on SEP energy spectrum in other moments of time (does not used at solving of inverse problem). On the basis of obtained results can be estimate the total release energy in the SEP event and radiation environment in the inner Heliosphere, in the magnetosphere, and atmosphere of the Earth during SEP event.

The method of automatically search of the start of great SEP events

In the first we need to solve the problem of automatically searching for the start of great SEP event. The determination of increasing flux is made by comparison with intensity averaged from 120 to 61 minutes before the present Z-th one-minute data. For each Z minute data the program *SEP-Search* starts to work simultaneously for each independent channels. Let us suppose that there are two channels, A and B. In this case the *SEP-Search* program for each Z-th minute determines the values

$$D_{AZ} = \left[\ln(I_{AZ}) - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Ak})/60 \right] \Big/ \sigma, \quad (1)$$

$$D_{BZ} = \left[\ln(I_{BZ}) - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Bk})/60 \right] \Big/ \sigma, \quad (2)$$

where I_{Ak} and I_{Bk} are one-minute intensities in channels A and B of NM. If simultaneously

$$D_{AZ} \geq 2.5,\ D_{BZ} \geq 2.5, \quad (3)$$

SEP-Search repeat the calculation for the next Z+1-th minute and if Eq. 3 is satisfied again, the onset of great SEP is established and the program *SEP -Research* starts to work.

The probability of false alarms

Because the probability function $\Phi(2.5) = 0.9876$, that the probability of an accidental increase with amplitude more than 2.5σ in one channel will be $(1-\Phi(2.5))/2 = 0.0062\,\mathrm{min}^{-1}$, that means one in 161.3 minutes. The probability of accidental increases simultaneously in both channels will be $((1-\Phi(2.5))/2)^2 = 3.845\times10^{-5}\,\mathrm{min}^{-1}$ that means one in 26007 minutes ≈ 18 days. The probability that the increases of 2.5σ will be accidental in both channels in two successive minutes is equal to $((1-\Phi(2.5))/2)^4 = 1.478\times10^{-9}\,\mathrm{min}^{-1}$ that means one in 6.76×10^8 minutes ≈1286 years.

The probability of missed triggers

The probability of missed triggers depends very strong on the amplitude of the increase. Let us suppose for example that we have a real increase of 7σ (that for NM in Israel corresponds to an small increase of 9.8%). The trigger will be missed if in any of both channels and in any of both successive minutes as a result of statistical fluctuations the increase of intensity instead of 7σ will be less than 2.5σ. For this the statistical fluctuation must be negative with amplitude more than 4.5σ. The probability of this negative fluctuation in one channel in one minute is equal $(1-\Phi(4.5))/2 = 3.39\times10^{-6}\,\mathrm{min}^{-1}$, and the probability of missed trigger for any of two successive minutes in any of two channels is 4 times larger: 1.36×10^{-5}. It means that missed trigger is expected only one per about 70000 events.

On-line determining of SEP spectrum

The observed relative CR variation $\delta I_m(R_c,t) \equiv \Delta I_m(R_c,t)/I_{mo}(R_c)$ of some component m can be described in the first approximation by function $F_m(R_c,\gamma)$:

$$\delta I_m(R_c,t) = b(t)F_m(R_c,\gamma(t)) \qquad (4)$$

where m = tot, 1, 2, 3, 4, 5, 6, 7, ≥8 for NM data (but can denote also the data obtained by muon telescopes at different zenith angles and data from satellites), and

$$F_m(R_c,\gamma) = a_m k_m \left(1-\exp\left(-a_m R_c^{-k_m}\right)\right)^{-1} \times \int_{R_c}^{\infty} R^{-(k_m+1+\gamma)} \exp\left(-a_m R^{-k_m}\right) dR \qquad (5)$$

is a known function. Let us compare data for two components m and n. According to Eq. 4 we obtain

$$\delta I_m(R_c,t)/\delta I_n(R_c,t) = \Psi_{mn}(R_c,\gamma) \qquad (6)$$

where

$$\Psi_{mn}(R_c,\gamma) = F_m(R_c,\gamma)/F_n(R_c,\gamma) \qquad (7)$$

are calculated by using Eq. 5. Comparison of experimental results with function $\Psi_{mn}(R_c,\gamma)$ according to Eq. 6 gives the value of $\gamma(t)$, and then from Eq. 4 the value of the parameter $b(t)$.

Inverse problem for isotropic diffusion

The solution of this problem was described in detail in Sections 2.42-2.43 in [2]. It was shown that the forecasting model, developed on the basis of this solution, starts to work well only after 20-30 min after automatically search the start of SEP. The direct solution for the diffusion coefficient $\kappa(R,r) = \kappa_1(R)\times(r/r_1)^{\beta}$ is well known [3]:

$$n(R,r,t) = \frac{N_o(R)\times r_1^{3\beta/(2-\beta)}(\kappa_1(R)t)^{-3/(2-\beta)}}{(2-\beta)^{(4+\beta)/(2-\beta)}\Gamma(3/(2-\beta))} \times \exp\left(-\frac{r_1^{\beta} r^{2-\beta}}{(2-\beta)^2\kappa_1(R)t}\right), \qquad (8)$$

where r_1 = 1 AU, and $N_o(R)$ is the source function of SEP. If we know $n(R,r,t)$ at moments t_1,t_2,t_3 after SEP injection into interplanetary space (see the previous Section), the final solutions for β, $\kappa_1(R)$, and $N_o(R)$ will be

$$\beta = 2-3\left[(\ln(t_2/t_1)) - \frac{t_3(t_2-t_1)}{t_2(t_3-t_1)}\ln(t_3/t_1)\right] \times\left[(\ln(n_1/n_2)) - \frac{t_3(t_2-t_1)}{t_2(t_3-t_1)}\ln(n_1/n_3)\right]^{-1}, \qquad (9)$$

$$\kappa_1(R) = \frac{r_1^2\left(t_1^{-1}-t_2^{-1}\right)}{3(2-\beta)\ln(t_2/t_1)-(2-\beta)^2\ln(n_1/n_2)} = \frac{r_1^2\left(t_1^{-1}-t_3^{-1}\right)}{3(2-\beta)\ln(t_3/t_1)-(2-\beta)^2\ln(n_1/n_3)}, \qquad (10)$$

where $n_i \equiv n(R,r,t_i)$, i = 1, 2, 3.

$$N_o(R) = A(r_1, \beta) n_i(R, r_1, t_i)(\kappa_1(R) t_i)^{3/(2-\beta)} \times \exp\left(\frac{r_1^2}{(2-\beta)^2 \kappa_1(R) t_i}\right). \quad (11)$$

In Eq. 11 index i = 1, 2 or 3, and $A(r_1, \beta) = (2-\beta)^{(4+\beta)/(2-\beta)} \Gamma(3/(2-\beta)) r_1^{-3\beta/(2-\beta)}$

Kinetic and anisotropic diffusion cases

In this approach we will be based mainly on theoretical works [4, 5], according to which the evolution of the particle distribution function $f(y,\tau,\mu)$ follows from the kinetic equation written in the drift approximation:

$$\frac{\partial f}{\partial \tau} + \frac{\mu \partial f}{\partial y} + f - \frac{1}{2}\int_{-1}^{1} f d\mu = \frac{\nu_s}{v}\delta(y)\delta(\tau)\varphi(\mu), \quad (12)$$

where y is coordinate along regular IMF and τ is time in dimensionless units ($y = z\nu_s/v$, $\tau = \nu_s t$); $\nu_s = v/\Lambda$ is the collision frequency of SEP with magnetic inhomogeneities; $\mu = \cos\theta$, and θ is the particle pitch-angle. The right-hand side of Eq. 12 describes an instantaneous injection of SEP with an initial angular distribution

$$\varphi(\mu) = \frac{a_\mu \Delta_\mu}{2\left(\Delta_\mu^2 + (\mu - \mu_o)^2\right)}. \quad (13)$$

For the finite time injection in the right-hand side of Eq. 12 instead of $\delta(\tau)$ will be

$$\chi(\tau) = \nu_o^2 \tau \exp(-\nu_o \tau), \quad (14)$$

where ν_o^{-1} characterizes the mean duration of the injection. In this case the solution of Eq. 12, obtained by the method of direct and inverse Fourier–Laplace transform, will be

$$G(y,\tau) = \int_0^\tau d\xi \int_{-1}^{1} d\mu \chi(\tau - \xi) f(y,\xi,\mu)\psi(\mu). \quad (15)$$

This solution consists from three terms

$$G(y,\tau) = G_{us}(y,\tau) + G_s^o(y,\tau) + G_s^d(y,\tau). \quad (16)$$

The first component describes a contribution of the un-scattered particles which exponentially decreases with time τ:

$$G_{us}(y,\tau) = \frac{\nu_s \nu_o^2 \exp(-\nu_o \tau)}{v} \times \int_0^\tau \frac{d\xi}{\xi}(\tau - \xi)\varphi\left(\frac{y}{\xi}\right)\psi\left(\frac{y}{\xi}\right)\exp(\xi(\nu_o - 1)). \quad (17)$$

A contribution of the scattered particles can be divided into two parts. One, the non-diffusive term $G_s^o(y,\tau)$, also exponentially decreases with time, and another term, $G_s^d(y,\tau)$, has a leading meaning in the diffusive limit of $\tau >> 1$. Namely, the non-diffusive term reads

$$G_s^o(y,\tau) = \frac{\nu_s \nu_o^2 \exp(-\nu_o \tau)}{8\pi v}\left\{\int_0^{y/\tau} d\eta \Psi(y,\tau,\eta)[S(\tau) - S(y)] + \int_{y/\tau}^{1} d\eta \Psi(y,\tau,\eta)[S(y/\eta) - S(y)]\right\}. \quad (18)$$

where

$$\Psi(y,\tau,\eta) = \frac{\exp(y\Lambda(\eta)/2)}{\left((\mu_o - \eta)^2 + \Delta_\mu^2\right)\left((\lambda_o - \eta)^2 + \Delta_\lambda^2\right)}. \quad (19)$$

The last (diffusive non-vanishing) term in Eq. 16 has a sense only for $|y| < \tau$ and reads as

$$G_s^d(y,\tau) = \frac{\nu_s \nu_o^2}{4\pi v}\int_{-\pi/2}^{\pi/2}\frac{dk}{k^2}\Phi(y,k) \times \left\{e^{\tau\kappa} - e^{(y-\tau)\nu_o + y\kappa}\left[1 + (\tau - y)(\nu_o + \kappa)\right]\right\}. \quad (20)$$

where $\kappa \equiv k\cot k - 1$, and

$$\Phi(y,k) = \frac{\left(B_\mu B_\lambda - \Gamma_\mu \Gamma_\lambda\right)\cos(ky) + \left(B_\mu \Gamma_\lambda + \Gamma_\mu B_\lambda\right)\sin(ky)}{D_\mu D_\lambda \cos^2 k}.$$

Expected temporal profiles for NM and comparison with observations

For example, some selected NM data for the 24 May 1990 are demonstrated in Fig. 1.

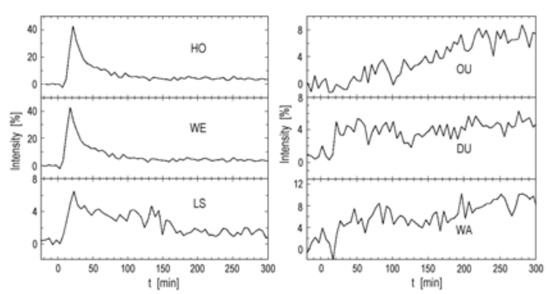

Figure 1: Two groups of NM records of the event on 24 May 1990. Left - have the narrow peak of the anisotropic stream of the first fast particles (HO – Hobart, WE– Mt.Wellington, LS – Lomnický Štít); right - show a diffusive tail with a wide maximum at a later time (OU – Oulu, DU – Durham, WA– Mt.Washington). From [4].

In Fig. 1 the time (in min) is measured from the onset of particle injection taken as 20.50 UT of May 24, 1990. The theoretically predicted temporal profiles for the selected NM in the model described above are demonstrated in Fig. 2, left and right panels, respectively, using the calculated asymptotic direction for each NM station.

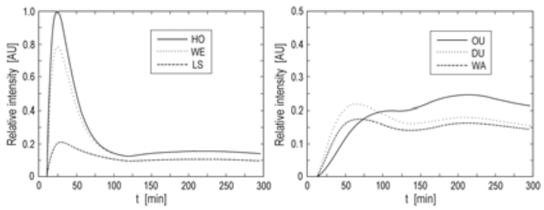

Figure 2: Theoretical prediction of temporal profiles for the selected NM using calculated parameters λ_o, $\Delta\lambda$ and mean $\overline{R}$ for each NM. On the ordinate axis are shown expected intensity relative to HO in maximum. According to [4].

This calculation shows that HO and WE have very similar characteristics, λ_o is 0.9 and 0.86, respectively, with $\Delta\lambda = -0.26$. Station LS has $\lambda_o = 0.34$, $\Delta\lambda = 0.4$. In the second group of NM, OU, DU, and WA have $\lambda_o = -0.94, -0.9, -0.85$ and $\Delta\lambda = 0.06, 0.1, 0.3$, respectively. Oulu and Apatity give absolutely the same theoretical curves resulting from their similar characteristics and very similar temporal profiles of the event. The last two NMs (DU and WA) experienced small increases at 1–2 hours after onset, as the theory predicts, see Fig. 1 (right panel), owing to smaller λ_o and larger $\Delta\lambda$ and larger mean $\overline{R}$.

Conclusion: seven steps for forecasting of radiation hazard during SEP events

For realization of the *first step* of forecasting we need one minute real-time data from about all NM of the world network. On the each NM must work automatically the program for the search of the start SEP events as it was described in Sections 1–3. This search will help to determine which NM from about 50 of total number operated in the world network show the narrow peak of the anisotropic stream of the first arrived solar CR (NM of the 1-st type) and which show a diffusive tail with a wide maximum at a later time (NM of the 2-nd type). In the *second step* we determine rigidity spectrum of arrived SEP $I_s(R)$ above each NM outside of the atmosphere, and then separately for NM of the 1-st type and 2-nd type by using method of coupling functions as it was described above in Section 4 (in more detail see Chapter 3 in [1]). In the *third step* we should try to use the model of isotropic diffusion for a rough estimation of expected radiation hazard (see Section 5). In the *fourth step* we should determine for different NM the mean $\overline{R}$, λ_o and $\Delta\lambda$ characterizing for this event. By using these parameters and experimental data on NM time profiles in the beginning time we cane determine parameters of SEP non-scattering and diffusive propagation, described in Sections 6 and 7 (the *fifth step*). On the basis of determined parameters of SEP non-scattering and diffusive propagation we then determine expected SEP fluxes and pitch-angle distribution during total event in interplanetary space in dependence of time after ejection (the *sixth step*). In the *seventh step* by using again method of coupling functions we should determine expected radiation doze which will be obtain during this event inside space probes in interplanetary space, satellites in the magnetosphere, aircrafts at different altitudes and cutoff rigidities, for people and technologies on the ground.

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