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Monitoring and Forecasting of Great Solar Proton Events Using the Neutron Monitor Network in Real Time

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***Abstract*. Obtaining on-line information on the onset of great solar energetic particle (SEP) events from real-time data of the neutron monitor network (NMN) is considered and the corresponding algorithm and program are proposed. Determination of the particle energy spectrum outside the atmosphere at different moments of the flare is considered on the basis of coupling functions method. The spectra defined in diffusion and kinetic approaches are compared. Using this information the time of the SEP ejection into solar wind, the energy spectrum of a SEP event in the source inside the solar corona and the SEP diffusion coefficient in the interplanetary space during the flare can be estimated. In this work the significant possibility of the expected SEP fluxes and the energy spectrum forecasting on the early part of the increasing SEP intensity (about 20 – 30 minutes after the onset) is considered. Available satellite data in real-time scale combined with real time data from NMs are used for extrapolation of this forecast to the region of very small energy particles. The method is checked on the SEP event of September 1989. It is important to note that the accuracy of the developed method sufficiently increases with the increasing dangerous level of the SEP event. The method is not CPU damaging and can run in real time, providing inexpensive means of SEP prediction.**

I. INTRODUCTION

Great solar energetic particle (SEP) events or solar radiation storms stronger than S3 according to NOAA classification are dangerous for communication and operation systems, for computer memories, for astronauts in space stations, for passengers and crew in commercial jets and even for technology and people on the ground. The possible damage from powerful flares and the probable frequency of these flares are demonstrated in Table I. We extended a little the NOAA classification [1] up to S7 and we used "fluencies" instead of "flux" since they are more close to the accumulated radiation dose. Although "fluxes" are more suitable for a fast analysis, the "fluency" is more characteristic for a powerful event and it would be reasonable to use together with NOAA classification those based on the "fluencies". The frequency of the events in Table I is averaged over the solar cycle, although in reality the frequency of them is higher during the periods of high solar activity.

The problem is, if prediction of these dangerous phenomena is possible. We discuss here a possibility of the SEP event onset monitoring and finding particle spectra and fluxes at different altitudes in the atmosphere using real-time observations of high -energy cosmic rays (GeV/nucleon and higher) from the neutron monitor network (NMN). In this area several approaches are possible, based on the essential property of high energy particles to bring information on solar and interplanetary conditions much earlier than low and mid energy solar particles. Due to their big diffusion coefficient high energy particles come from the Sun in 8-20 minutes after acceleration and escaping into solar wind, whereas the main part of lower energy particles, which cause dangerous situation for electronics, usually come later in more than 30-60 minutes. Proton events registered at Earth (Ground Level Enhancements –GLEs) have a complete profile well before the enhancement evolving in the lower energies. This fact can be used for the calculations of spectra and fluxes for lower energies at different levels that might be useful for prediction possible radiation doses. The attempt was undertaken in [2, 3, 4], where the evolution of solar cosmic ray spectrum was analyzed on the basis of the kinetic equation solution by the ground level observations.

The way to search for the SEP event onset may be developed also from on line analysis of the longitudinal distribution of hourly or 5-minute data from NMN and separation of the 1-st and 2-nd harmonics of the cosmic ray anisotropy in real time.

TABLE I.
EXTENDED NOAA SPACE WEATHER SCALE FOR SOLAR RADIATION STORMS

SEP Events Radiation Hazard			Fluence ≥30MeV protons	Frequ-ency
S7	Ultra extreme	**Biological:** Lethal doze for astronauts, for passengers and crew on commercial jets; great influence on people health and gene mutations on the ground **Satellite operations:** very big damages of satellites electronics and computers memory, damage to solar panels, loosing of many satellites **Other systems**: complete blackout of HF (high frequency) communications through polar and middle-latitude regions, big position errors make navigation operations extremely difficult.	10^{11}	One in few thousand years
S6	Very extreme	**Biological:** About lethal doze for astronauts, serious influence on passengers and crew health on commercial jets; possible influence on people health and genes mutations on the ground **Satellite operations:** a big damages of satellites electronics and computers memory, damage to solar panels, loosing of several satellites **Other systems**: complete blackout of HF communications through polar regions, some position errors make navigation operations very difficult.	10^{10}	One in few hundred years
S5	Extreme	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest X-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^{9}	One in 20-50 years
S4	Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest X-rays) is possible. **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^{8}	One in 3-4 years
S3	Strong	**Biological**: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest X-ray). **Satellite operations**: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems**: degraded HF radio propagation through the polar	10^{7}	One per year

		regions and navigation position errors likely.		

The methods for such calculations are substantially improved (GSM, ring station method, pitch angle distribution) and are successfully used in the retrospective analysis searching for predictors of Forbush effects and geomagnetic disturbances [5, 6, 7, 30, 31]. Usual longitudinal distribution of cosmic ray variations is well described by the two first spherical harmonics, although sometimes the real behavior deflects significantly from this presentation. In these cases the "non-harmonic" longitudinal distribution of cosmic rays has some specific distinctive features [8, 29] that gives the opportunity to predict well in advance the approaching disturbance. This property of longitudinal distribution of CR variations to change abruptly its shape, being derived from the on line NM network data may be also used for the SEP event forecast.

The principles and the experience of automatically working program, which determines the onset of great SEP events on the basis of one-minute data at a single point of observations were described in detail in many reports and papers [9, 10, 11, 12]. In this approach the probability of false and missed alerts was considered and was found negligible. The on-line determination of the SEP energy spectrum outside of the atmosphere and then determination of the time of SEP ejection into solar wind, the energy spectrum in the source inside of the solar corona, and the SEP diffusion coefficient in the interplanetary space are also included in this program. A calculation of these parameters is based on the method of coupling coefficients, improved successfully in the last years in [13, 14]. This approach of monitoring SEP onset from observations at a unique point uses data of at least three different components at this point or from the multiplicity registration that it is not carried usually at the cosmic ray stations or it has not enough statistical accuracy of measurements.

In this paper we consider a feasible possibility to search the SEP onset and some characteristics of SPE fluxes using real time data from neutron monitor network (NMN). For extrapolation of this forecast to the region of very small energies we combine NM and available satellite data in real-time scale.

II. Automatically Search for the SEP Event Onset by Ground level Data

The high-energy particles in solar proton events are a small part of the total flux and satellite detectors can't record it with sufficient statistical accuracy, as it needs very large effective surfaces of detectors and very large weight. On the other side, high-energy particles of galactic or solar origin are measured continuously by ground-based neutron monitors of very large effective surface (from 6 to 24 m^2), that provides very small statistical error (about 0.1% for hourly data and nearly 1% for 1-minute data). At present the neutron monitor network (NMN) consists of about 45 continuously operating detectors and about 20 NMs present their data in real time in the Internet [15, 32]. The method of coupling (response) functions [16, 17, 14] allows the expected SEP flux above the atmosphere and out of the Earth's magnetosphere to be calculated from ground level data. The principles and on-line operation of programs determining the onset of proton events are based on comparison current CR intensity with those averaged from 120 to 61 minutes before the present Z-th minute data. The program "FEP-Search-1 min" for each Z-th minute determines the values:

$$D_{A1Z} = \left[\ln\left(I_{AZ}\right) - \sum_{k=Z-120}^{k=Z-60} \ln\left(I_{Ak}\right)/60 \right] \Big/ \sigma_1 \quad (1)$$

$$D_{B1Z} = \left[\ln\left(I_{BZ}\right) - \sum_{k=Z-120}^{k=Z-60} \ln\left(I_{Bk}\right)/60 \right] \Big/ \sigma_1 , \quad (2)$$

where I_{Ak} and I_{Bk} are one-minute total intensities in the sections of neutron monitor A and B (or, on the NMs from different stations A and B). If the differences at each detector A and B fit simultaneously to condition

$$D_{A1Z} \geq 2.5\ \sigma,\ D_{B1Z} \geq 2.5\ \sigma \quad (3)$$

then the program "FEP-Search-1 min" repeats the calculation for the next Z+1-th minute. If equation 3 is satisfied again, the onset of a great SEP event is determined and the programs "FEP-Collect" and "FEP-Research" described in the next section, are started.

If (3) is not satisfied, the program "FEP-Search-2 min" searches for the start of an increase by using two-min data characterized by the $\sigma_2 = \sigma_1/\sqrt{2}$. In this case, the program "FEP-Search-2 min" will calculate the values

$$D_{A2Z} = \left[\left(\ln\left(I_{AZ}\right) + \ln\left(I_{AZ-1}\right)\right) \Big/ 2 - \sum_{Z-120}^{Z-60} \ln\left(I_{Ak}\right) \Big/ 60 \right] \Big/ \sigma_2 , \quad (4)$$

$$D_{B2Z} = \left[\left(\ln\left(I_{BZ}\right) + \ln\left(I_{BZ-1}\right)\right) \Big/ 2 - \sum_{Z-120}^{Z-60} \ln\left(I_{Bk}\right) \Big/ 60 \right] \Big/ \sigma_2 , \quad (5)$$

If the result is negative that means that there is not simultaneous increase in both channels of total intensity ≥ 2.5σ_2, i.e. the condition $D_{A2Z} \geq 2.5\sigma$, $D_{B2Z} \geq 2.5\ \sigma$ fails, then "FEP-Search-3 min" uses the average of three minutes Z-2, Z-1 and Z with $\sigma_3 = \sigma_1/\sqrt{3}$. If this program also gives a negative result, then the program "FEP-Search-5 min" uses the average of five minutes Z-4, Z-3, Z-2, Z-1 and Z with $\sigma_5 = \sigma_1/\sqrt{5}$.

If this program also gives negative result, i.e. all programs "FEP-Search-*K* min"(where *K*=1, 2, 3, 5) give negative result for the Z-th minute, it means that in the next 30-60 minutes there will be no radiation hazard (this information is also very useful). After negative result, such a procedure repeats for the next Z+1-th minute and so on. If any positive result is obtained for some Z-minute, the "FEP-Search" programs check the next Z+1- minute data. If the obtained result is again positive, then the program "FEP-Spectrum" determines the FEP spectrum (see below, Section VI).

Similar program will be applied in the case of three or more sections or stations A, B, C…N: instead of Eq. 3 the necessary conditions for determining the start of a great SEP will be

$$D_{AIZ} \ge 2.5\ \sigma,\ D_{BIZ} \ge 2.5\ \sigma,\ D_{CIZ} \ge 2.5\ \sigma,\ \ldots\ D_{NIZ} \ge 2.5\ \sigma \quad (6)$$

The probability of false alarms or missed triggers is very low for several channels, as it was shown in [9, 11, 12].

III. Principles of SEP Radiation Hazard Forecasting

Time-profiles of solar CR increases are very different for different great SEP events. It depends on the situation in the

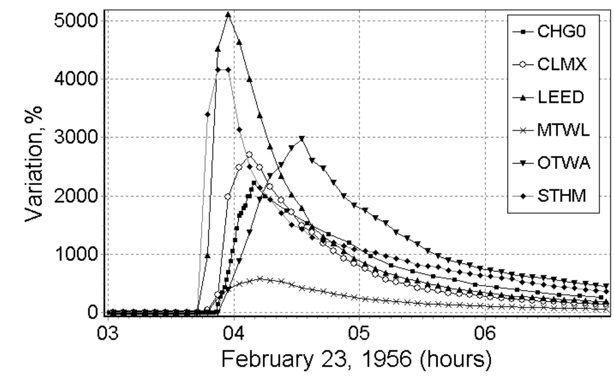


Figure 1. Time profiles of CR intensity recorded by different neutron monitors during the great SEP event on 23.02.1956. On the right side the names of NM stations are given: CHGO- Chicago, CLMX-Climax, LEED-Leeds, MTWL- Mount Wellington, OTWA- Ottawa, STHM-Stockholm.

interplanetary space. If the mean free path of high-energy particles is large enough, the increase will be sharp, very short lasting (only a few minutes), and in this case one or two-minute data will be suitable. When the mean free path of high-energy particles is much smaller (perturbed interplanetary medium prior to the event), the increase will be gradual, possibly prolonged (30-60 minutes), and in this case data of 2-, 3- or 5-minute will be useful. Moreover, for some very anisotropic events, as for example for the event of February 23, 1956, the character of increase at different stations can be very different (sharp or gradual depending on the station location relatively to impact zone), as it is shown in Fig. 1.

If any of the "FEP Search-*K* min" (described above) programs gives a positive result at any CR Observatory, the on-line program "FEP Collect" is run and collects all available data on this SEP event from CR Observatories and satellites. The programs "FEP Research" then analyze these data. The real-time research is described as following:

1. Determination of the energy spectrum above the atmosphere from the start of SEP-event (programs "FEP Research-Spectrum");
2. Determination of anisotropy and its energy dependence (program "FEP Research-Anisotropy");
3. Determination of the propagation parameters, time of SEP injection into the solar wind and total source flux of SEP as a function of energy (programs "FEP Research-Propagation", "FEP Research-Time Ejection", "FEP Research-Source");
4. Based on the obtained results, forecast of the expected fluxes and spectrum in space, magnetosphere and atmosphere is made (programs "FEP Research-Forecast in Space", "FEP Research-Forecast in Magnetosphere", "FEP Research-Forecast in Atmosphere";
5. If the forecast fluxes are found to be at dangerous levels (space radiation storms S5, S4 or S3 according to the NOAA classification), then preliminary programs "FEP Research-Alert 1 for Space", "FEP Research-Alert 1 for Magnetosphere", "FEP Research-Alert 1 for Atmosphere" are running. Then, based on further on-line data collection, more accurate programs Alert 2, Alert 3 and so on predict more accurate information.

These programs may be used with data from a single or two stations with continuous measurements of two or three at least CR components with different coupling functions, that was discussed in series of previous reports [9, 11, 12, 18]. Here we explain how these models could be applied to real-time data from the worldwide network of CR observatories (especially important for anisotropic SEP events). The illustration of this ideology is presented in Fig. 2.

IV. Using On-line CR Data From Many Observatories

In the first approximation the spectrum of primary variation of SEP events can be described by function

$$\Delta D(R)/D_o(R) = bR^{-\gamma}, \quad (7)$$

where $\Delta D(R) = D(R,t) - D_o(R)$ is the change of the spectrum

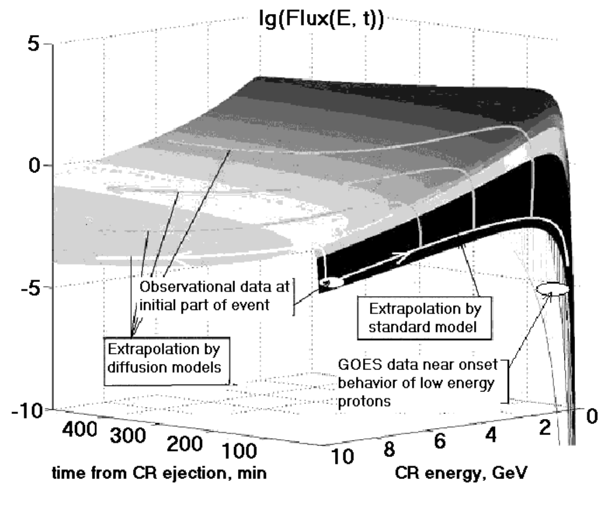


Figure 2 Illustration of the ideology of the SEP forecasting method

and $D_o(R)$ is the differential spectrum of galactic CR before the SEP event and D(R, t) is the spectrum at a later time *t*. Parameters *b* and γ depend on *t* and parameter γ also depends on particle rigidity *R* (usually γ increases with increasing *R*); these dependencies vary from one event to another. The expected variation in total counting rate at NM (or in multiplicity) *k* in the common case will be

$$\Delta I_k(R_c)/I_{ko}(R_c) = -\Delta R_c W_k(R_c, R_c) + bF_k(R_c, \gamma), \quad (8)$$

where ΔR_c , is the change of cut-off rigidity due to change of the Earth's magnetic field and $W_k(R_c, R_c)$ is coupling function for detector at the point with rigidity $R = R_c$. Now we have unknown variables γ, *b*, ΔR_c. Solution of the system of equations (8) for many detectors allows the parameters γ, *b*, ΔR_c to be derived from the calculation matrix of the spectral slope $\gamma_{mn}(i)$, matrix of amplitude *bmn(i)* and minimization of correspondent standard deviations $\sigma(\gamma_{mn}(i))$ and $\sigma(b_{mn}(i))$ for different energetic channels at a moment T [11]. Function $F_k(R_o, \gamma)$ includes also the coupling function $W_k(R_c, R_c)$, which are necessary to transfer the observed intensity (at ground level detectors) to the primary cosmic rays spectrum. Improved coefficients for the coupling functions were taken from theoretical calculations in [14] and from latitude survey in [13, 17].

Using the neutron monitor network and the above technique, the accurate information on the distribution of the increased CR flux near the Earth can be found. As a first step, we can separate all stations of the NMN on pairs with almost the same asymptotic longitudes (to exclude effects of SEP anisotropy), but with different cut-off rigidities and determine automatically parameters of SEP spectrum in the interplanetary space according to the procedure described above. The anisotropy of SEP flux in dependence on particle rigidity may be determined by the comparison of results obtained for different pairs of NMs.

If we obtain SEP spectrum at least in three moments T_1, T_2, and T_3, we can determine the time of energetic particles ejection T_e, diffusion coefficient *K(R)* and SEP spectrum in source $N_0(R)$. The calculations of K(R) were carried according to the procedure described in [11, 12] in the assumption of diffusion coefficient does not depend upon the distance to the Sun. Results are shown in Fig. 3. It can be seen that the results obtained at the beginning of the event are not stable due to large statistical errors. After few minutes the amplitude of the CR intensity increase become many times bigger than σ, and we see systematical increase of the diffusion coefficient with the time: really it reflects the increasing *K(R)* with the distance to the Sun.

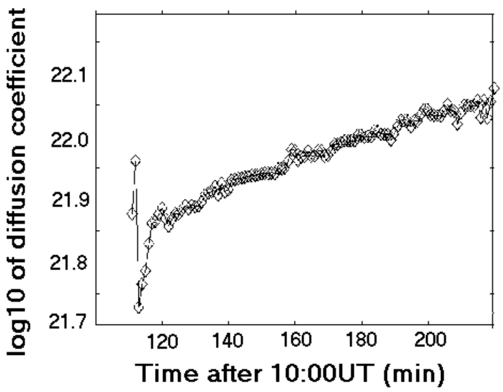


Figure 3. Behavior of diffusion coefficient *K* during SEP event on September 29, 1989 calculated for R ~ 10 GV in units cm^2/ s assuming $K(R)$ independent on the solar distance.

We suppose for very large SEP events, the use of global-spectrographic method (see review of this method in [19]) will enable us to determine in real-time the SEP distribution function outside the Earth magnetosphere as a function of particle rigidity, and temporal changes of the spherical harmonics of the SEP distribution function. If there is a big enough number of NMs with real time data, it seems to be more

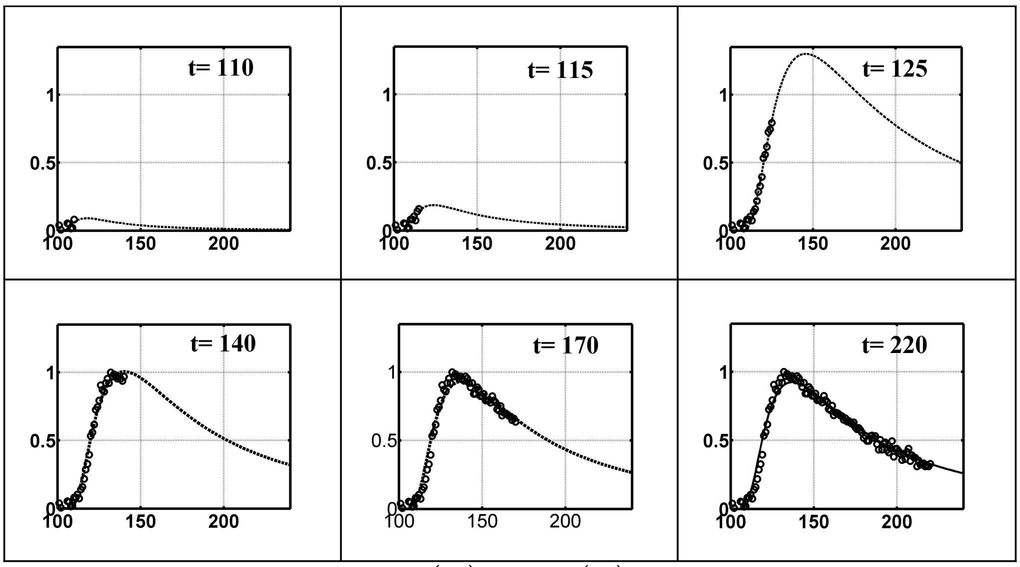


Figure 4. On-line calculation of the parameters β , $K_1(R)$ and $N_o(R)$ by fitting to real time data at different moments of the SEP event of September 29, 1989. Time *t* is shown after 10.00 UT in minutes. Along the ordinate the CR intensity as log10 is plotted, the abscissa indicate current time of event in min after 10:00UT. Curves mean the forecasted and circles indicate the observed total neutron intensity. The onset of event was at 11:45 UT.

effectively to apply more global methods as it was used in retrospective analysis by Shea and Smart in [20], or in [21, 22]. It will allow a better determination of SEP propagation parameters in interplanetary space, and of the total flux and energy spectrum of particles accelerated in the solar flare, in turn improving detailed forecasts of dangerous large SEP events.

V. SEP Forecasting Using Only Neutron Monitor Data

During the first few minutes of SEP event recorded by NM data we can determine effective parameters β, $K_1(R)$, and $N_0(R)$, corresponded to the rigidity about 7 – 10 GV, and then we calculate the curve of expected SEP flux behavior for total neutron intensity by using NM coupling function. This curve is compared with the observed time variation of total neutron intensity. Really we use data for more than three moments to fit the obtained results by the minimal residual. See Figure 4, which contains 6 panels for time moments from t = 110 min up to t = 220 min after 10.00 UT of 29 September 1989 (the onset time was at 11:43UT). Figure 4 demonstrates that during the first few minutes the accuracy of NM data (t = 110 min) is not sufficient to obtain good forecast curve, because of too low intensity. For t = 115 min the forecast shows little 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 almost stable forecast in a good agreement with observed CR intensity (with accuracy about ± 10 %). A diffusion coefficient $K_1(R)$ on this period is plotted in Figure 5. From this figure is also evident 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

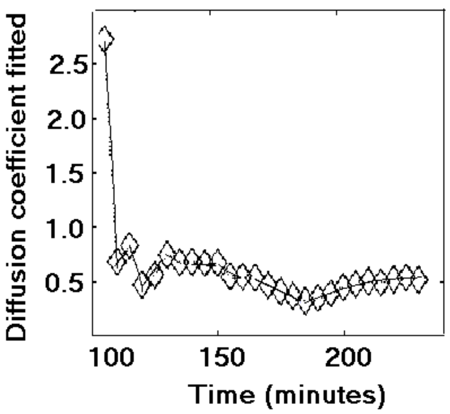


Figure 5. Diffusion coefficient $K_1(R)$ near the Earth's orbit (in units 10^{23} cm^2 s^{-1}) obtained by fitting model to experimental data with dependence of the $K_1(R)$ on the distance upon the Sun. Time is after 10.00 UT of September 29, 1989 in minutes.

accuracy is too low, and we obtain very big diffusion coefficient. After the first point we have almost stable result with accuracy ± 20 %, what is comparable with Figure 3, where

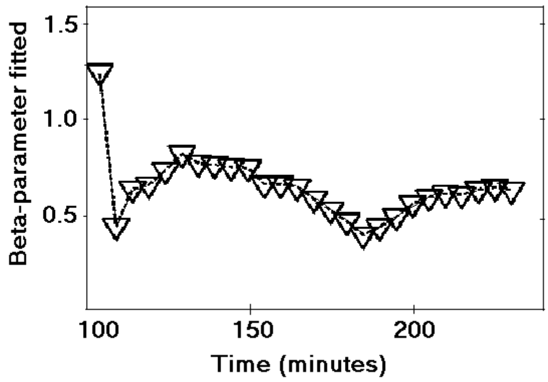
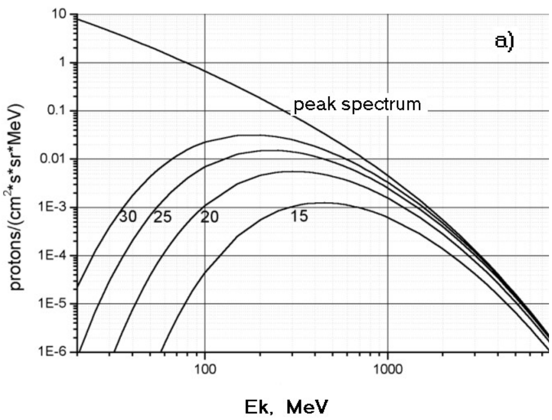


Figure 6. Dependence of parameter β on time after 10.00 UT on September 29, 1989 derived from the model fitting to experimental data. The onset time was at 11:43 UT.

diffusion coefficient was found as effectively increasing with time. Parameter β describes the increase of diffusion coefficient with the distance from the Sun according to the relation $K(R,r) = K_1(R) \times (r/r_1)^{\beta}$) for SEP propagation in the interplanetary space is plotted in Fig. 6. One can see that again, the first point is anomalously large, but after this the result became almost stable with average value $\beta \sim 0.6$ (with accuracy about ± 20%). We should note, that for very beginning of event the diffusion model is hardly applied, the kinetic model of SEP propagation would be more natural, as it was shown in [2, 3], and in [23]. The diffusion (a) and "kinetic" (b) approximations spectra for the event of June 15, 1991 are presented in Fig. 7. The peak spectrum for this event was obtained by NMN and satellite experimental data in [24], and it was used to calculate proton spectrum at any time after particle injection near the Sun. The results of such calculations in the diffusion approximation under instantaneous particle release are depicted in Fig. 7a. The numbers near the curves represent the time after particle injection in minutes. It was supposed that the mean free path depends on rigidity by the power law with power index 0.2. It is interesting to note that at the initial phase of the proton event the energetic spectrum has a pronounced maximum, which is shifted with time in the low energy region [25]. Energetic spectra, calculated according to kinetic approach, are given in Fig. 7b. In contrast to the diffusion approximation these spectra have sharp beginning in the low energy range. Such behavior of the spectrum shape is due to the later arrival of low energy CR under simultaneous, impulsive release of particles from the source.

Comparison of the calculated in "kinetic" approach time-intensity profiles of CR intensity and anisotropy using the observable data on NMN and satellites allow the estimation of characteristic duration of injection and transport path of injected particles. So, the approach based on the kinetic equation solution can be used for GLEs analysis and for short time prognosis of the powerful proton events [4, 26].

VI. Simulation of SEP Fluxes and Fluencies Using On-line NM and Satellite Data



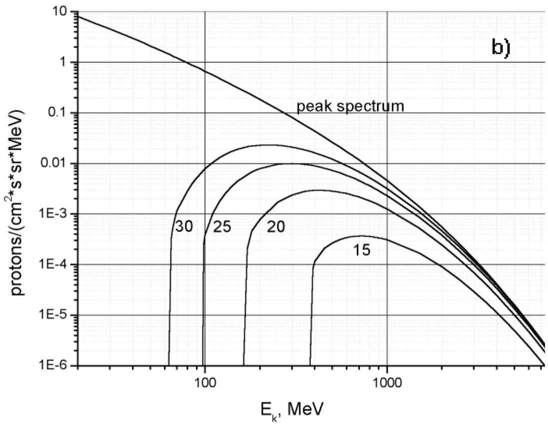


Figure 7. Energetic spectra of solar protons calculated for the SEP event of June 15, 1991 on the basis of peak spectrum derived from experimental data: a) accordingly to diffusion model; b) accordingly to the kinetic equation solution. The numbers near curves correspond to the time after particle injection (in minutes).

The simulation of SEP fluxes described in the above section may be of significantly higher accuracy if real time satellite data from the small energy range are included in this analysis. Extrapolation SEP energy spectrum from high NM energies to low satellite energies is based on the assumption that source of SEP event is the same both for high and low energy particles. The source function with time is a δ–function, and relative to energy is power function with index γ changed with energy E_k as:

$$\gamma = \gamma_o + a\ln\left(E_k / E_{kmax}\right), \qquad (9)$$

so

$$N_o(R,T) = \delta(T - T_e)\times R^{-\left(\gamma_o + a\ln\left(E_k/E_{kmax}\right)\right)}. \qquad (10)$$

We suppose that diffusion coefficient $K(R,r)$ in the interplanetary space is described by a power function upon the distance to the Sun (as $\propto \left(r/r_1\right)^{\beta}$) and a power function for the transport path, so

$$K(R,r) = K_1(R)\times\left(r/r_1\right)^{\beta}, \qquad (11)$$

where

$$K_1(R) = K_1\times(\mathrm{v}/c)\times\left(R/R_1\right)^{\beta}, \qquad (12)$$

and v is particle velocity, R_1=1 GV. Parameter β and time of ejection T_e derived from NM data suppose to be the same for small energy range. The fitting of parameters R_o, a, E_{kmax}, δ is done for each step of 5-minute measurements using more and more data. In the example on September 29, 1989 we started from t = 105 min (relatively to 10.00 UT, time of the onset was 11:43UT) and used the first five minute data; then our program made fitting for t = 110 min using the first ten minute data; for t = 115 min the program used the first 15 minute data. In Ref. [18, 27] this approach is considered in details. The results of forecasting of SEP integral fluxes for $E_k \geq E_o = 0.1\,GeV$, $E_k \geq E_o = 1\,GeV$, and $E_k \geq E_o = 3\,GeV$ are represented in Fig.8. The forecasted integral flux for $E_k \geq E_o = 0.1\,GeV$ was compared with observations on GOES satellite (>100 MeV), and it can be seen from Fig. 8, that the forecasted SEP integral flux for $E_k \geq E_o = 0.1\,GeV$ became in good agreement with GOES measurements in 30-40 minutes after the event onset. This method provides a good prediction of SEP integral flux for more than 2500 minutes (about two days).

VII. Forecasting of SEP Flux and Fluency on Different Distances from the Sun in the Space, the Atmosphere and the Magnetosphere

In the case, when diffusion coefficient $K_1(R)$ near the Earth's orbit, parameter β, time of ejection T_e and rigidity spectrum $N_0(R)$ in the source are determined from above procedures, then, according to Parker model [28], the expected SEP density at the moment T on the distance r from the Sun can be described as:

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

(13)

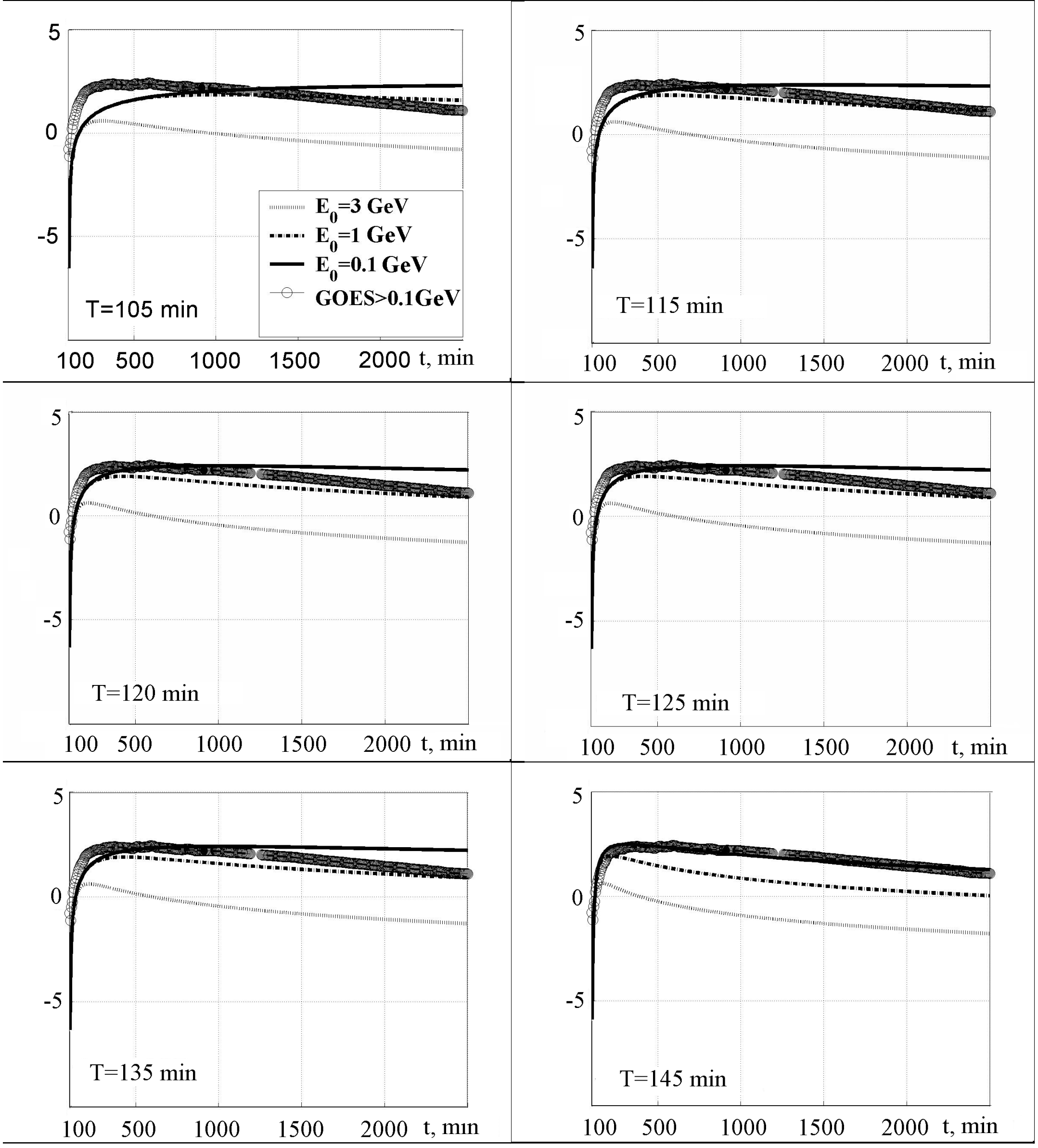


Figure 8. Combined forecasting of SEP integral fluxes for different energies $E_k \geq 0.1GeV$, $E_k \geq 1GeV$, $E_k \geq 3GeV$. The forecasted integral flux for $E_k \geq 0.1GeV$ is compared with GOES observations. Ordinates mean log10 of SEP integral flux, and abscissa indicate time of event in minutes from 10.00 UT of September 29, 1989. The onset of event is at 11:43UT.

where Γ is gamma-function, and $r_1 = 1.5 \times 10^{13}$ cm = 1AU

The expected integral flux $I_s(r, T, E_{kmin})$ inside the space-probe

with the threshold energy E_{kmin} at distance r from the Sun and at moment T will be

$$I_s(r, T, E_{kmin}) = \int_{E_{kmin}}^{\infty} n(R(E_k), r, T) \cdot dE_k, \qquad (14)$$

and the fluency $F_s(r, E_{kmin})$ that will receive a space-probe during all time of event (which determine the radiation dose) will be

$$F_s\left(r, E_{kmin}\right) = \int_{T_e}^{\infty} dT \int_{E_{kmin}}^{\infty} n\left(R\left(E_k\right), r\right) \cdot dE_k$$

(15)

The fluency for SEP on September 29, 1989 was calculated for $E_k \geq E_o = 0.1\,GeV$ by the parameters found from NM and satellite data step by step, starting from the first 10-20 minutes after the onset. This expected fluency presented in Fig. 9 is in a good agreement with GOES observable data, and this evidences of a good possibility to forecast the behavior of low energy particle fluxes even from the first step of the SEP event evolving.

On the basis of (13) the expected SEP fluxes and fluencies may be estimated inside the Earth's magnetosphere for satellites at different orbits (at $r = r_1 = 1\,AU$). For satellites at different cut-off rigidities $R_c(T)$ inside the Earth's magnetosphere the expected FEP flux will be:

$$I_s\left(T, R_c\left(T\right)\right) = \int_{R_c(T)}^{\infty} n(R(T), T) \times dR \; ,$$

(16)

where $R_c(T)$ is determined by the orbit of satellite. The expected fluency that a satellite will receive at its orbit $R_c(T)$ during all time of an event (proportional to the radiation dose) will be:

$$F_s\left(R_c\left(T\right)\right) = \int_{T_e}^{\infty} dT \int_{R_c(T)}^{\infty} n\left(R(T)\right) \times dR$$

(17)

Analogous formula can be obtained for expected intensity of secondary CR component of type i (electron-photon, nucleon, muon and others) generated by SEP in the Earth's atmosphere at different altitudes and cut-off rigidities.

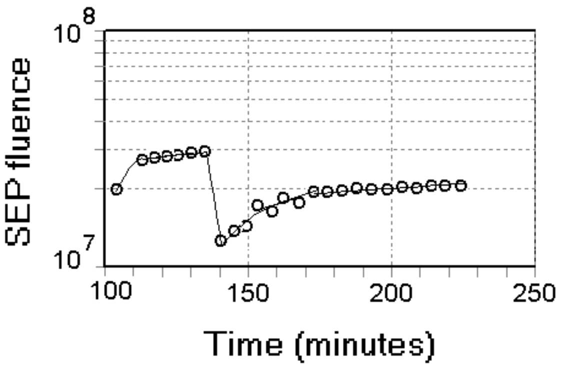


Figure 9. Forecasted SEP fluency for $E_k \geq E_o = 0.1\,GeV$ in units p/cm^2 sr. Estimation was done by the model parameters derived at every moment by fitting this model to experimental data. Abscissa indicates the time in minutes from 10.00 UT on September 29, 1989. It can be seen that the expected fluency by using NM and satellite data can be forecasted with good accuracy in the first 10-20 minutes after the start of SEP event.

At time T it will be in some point characterized by pressure level h_o and cut-off rigidity R_c as following:

$$I_{si}\left(T, R_c, h_o\right) = \int_{R_c}^{\infty} n(T, R, h_o) \times W_i\left(R, h_o\right) dR$$

(18)

where $W_i\left(R, h_o\right)$ is the coupling function. The expected total fluency (proportional to the radiation dose) will be obtained by integration of equation 18 over all the time of the event and summarizing by all secondary components:

$$Y_s\left(R_c, h_o\right) = \sum_i \int_{T_e}^{\infty} dT \int_{R_c}^{\infty} n\left(T, R, h_0\right) \times W_i\left(R, h_o\right) dR$$

(19)

This estimation is important for aircrafts and ground objects on different altitudes at different locations that means different cut-off rigidities.

VIII. Conclusion

In this paper the method of monitoring the alert situation of the great solar proton events on the basis of the on-line data from the neutron monitor network is proposed. The developed conception and the described method derive on line the SEP spectrum out of the magnetosphere on the basis of continue registration of cosmic ray intensity by the ground level neutron monitors.

The method and programs are evolved to determine on-line the diffusion coefficient, $K_1(R)$ near Earth's orbit, parameter β described the increasing of diffusion coefficient with the distance from the Sun for SEP propagation in the interplanetary space and the total SEP flux and energy spectrum $N_0(R)$ in the source as well. These parameters are checked by simulation of total neutron intensity forecasting. For the application of the method and the calculations the use of coupling functions is necessary.

The obtained on-line information can be considered as a basis for the next on-line working programs "FEP-Forecasting in Space" for different distances from the Sun, "FEP-Forecasting in Magnetosphere" for satellites with different orbits and "FEP-Forecasting in Atmosphere" for balloons and air-planes on different altitudes at different cut-off rigidities as well as for people and technology on the ground at different cut-off rigidities.

It is shown that the use of online data from ground level NMs together with satellite measurements allows the prediction of the SEP integral fluxes for different energies during the first 30-40 minutes of the event and the calculations of the fluency on the long duration events (up to few days). These results lead to the estimation of the expected radiation hazard very useful for the Space Weather studies.

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