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Cosmic ray variations and space weather

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1. Introduction

In my report at the Scientific Session of the Russian Academy of Sciences on 25 November 2009 at the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN), the following issues were considered:

1. *Short history of cosmic ray* (*CR*) *variation investigations at the Research Institute of Terrestrial Magnetism* (*IZMIR*) *and at IZMIRAN*: the role of N V Pushkov; E S Glokova's counter telescope; the government project of S N Vernov, N V Pushkov, and Yu G Shafer (1950–1951) on the development and production of a series of big ionization chambers, and involvement of students who graduated with nuclear specialities (but without the permission from the KGB to work at nuclear sites) into the organization of the first Soviet network of CR stations; development of the theory of CR meteorological effects and the method of coupling functions; the publication in 1957 of the world's first monograph on CR variations in Moscow and its English translation in the USA; the mistake made ten times by government officials regarding financing the new government project in 1960–1961 and the great development of the experimental basis for CR variations and all other areas of solar–terrestrial physics in the USSR; and the importance of the CR variation research for fundamental science and practical applications.

2. *CR variations as an element of space weather*: the influence of Earth's atmosphere on CR and the reverse influence of CR variations on processes in Earth's atmosphere and on global climate change; radiation hazards from galactic CRs, from solar CRs, and from energetic particles precipitated from radiation belts.

3. *CR variations as a tool for space weather monitoring and forecasting*: forecasting the part of global climate change caused by galactic CR intensity variations; forecasting the radiation hazard for people and electronics on aircraft, satellites, and spacecraft caused by variations of the galactic CR intensity; forecasting the radiation hazard from solar CR events by using an online one-minute ground neutron monitor network and satellite data; forecasting great magnetic storm hazards by using an online one-hour CR intensity data from a ground-based worldwide network of neutron monitors and muon telescopes

Below, I consider the principles of the science of CR variations and the connection with space weather issues.

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2. Principles of the science of cosmic ray variations

The main causes of the observed space–time variations of CR density and anisotropy can have the atmospheric origin, magnetospheric origin, or extraterrestrial or space origin (solar, interplanetary, galactic, and extragalactic origin) (see the extensive review in [1 – 4]).

At each CR station k for some component i (e.g., the muon component at different zenith and azimuthal angles, the neutron component for the total intensity and different multiplicities, measurements on the ground, on ships, aircraft, balloons, or spacecraft), the intensity $I_{ki}(t)$ at an instant t can be represented as

$$I_{ki}(t) = \int_{R_k(t)}^{\infty} m_i(R,t)\, D(R,t)\, \mathrm{d}R\,, \tag{1}$$

where $R_k(t)$ is the magnetospheric cutoff rigidity (in the case of CR measurements outside the magnetosphere, $R_k(t) = 0$), $m_i(R,t)$ is the integral multiplicity (the total number of secondary particles of type i generated in cascade processes from one primary particle of the rigidity R; for CR measurements in space, $m_i(R,t) = 1$), and $D(R,t)$ is the differential rigidity spectrum of primary CRs (outside the magnetosphere). It follows from Eqn (1) that, in principle, three types of CR variations are possible,

$$\begin{aligned} \delta I_{ki}(t) &= -m_i(R_k,t)\, D(R_k,t)\, \delta R_k(t) \\ &+ \int_{R_k(t)}^{\infty} \delta m_i(R,t)\, D(R,t)\, \mathrm{d}R \\ &+ \int_{R_k(t)}^{\infty} m_i(R,t)\, \delta D(R,t)\, \mathrm{d}R\,, \end{aligned} \tag{2}$$

which have magnetospheric, atmospheric, and extraterrestrial origins. The observed relative variation of the CR intensity is obtained by dividing Eqn (2) by $I_{ki}(t)$:

$$\begin{aligned} \frac{\delta I_{ki}(t)}{I_{ki}(t)} &= -W_{ik}(R_k,t)\, \delta R_k(t) \\ &+ \int_{R_k(t)}^{\infty} \frac{\delta m_i(R,t)}{m_i(R,t)}\, W_{ik}(R,t)\, \mathrm{d}R \\ &+ \int_{R_k(t)}^{\infty} \frac{\delta D(R,t)}{D(R,t)}\, W_{ik}(R,t)\, \mathrm{d}R\,, \end{aligned} \tag{3}$$

where

$$W_{ik}(R,t) = \frac{m_i(R,t)\, D(R,t)}{I_{ki}(t)} \tag{4}$$

are the coupling functions, which may be calculated from a detailed analysis of CR cascade processes and absorption in the atmosphere. This was done for the coupling (or response) functions $W_{ik}(R,t)$ and integral multiplicities (or yield functions) $m_i(R,t)$ in [5 – 7] (see the extended review in Chapter 3 of [2]).

It follows from Eqn (1) that the coupling functions are normalized:

$$\int_{R_k(t)}^{\infty} W_{ik}(R,t)\, \mathrm{d}R = 1\,. \tag{5}$$

It also follows from Eqn (1) that these very important functions may be assessed experimentally by using Earth as a giant magnetic spectrometer (using exact measurements of geomagnetic effects):

$$\begin{aligned} W_{ik}(R,t) &= -\left.\frac{\partial I_{ki}(t)/\partial R_k}{I_{ki}(t)}\right|_{R_k \to R}, \\ m_i(R,t) &= -\left.\frac{\partial I_{ki}(t)/\partial R_k}{D(R,t)}\right|_{R_k \to R}. \end{aligned} \tag{6}$$

This can be done according to Eqn (6) in the vertical direction up to rigidities ≈ 17 GV and for inclined directions up to ≈ 69 GV (see [8 – 10] and the extended review in [4]).

According to [11], the coupling function for any secondary component can be approximated by a special function (called the Dorman function in the scientific literature)

$$\begin{aligned} &W_{ik}(R,t) \\ &= \begin{cases} 0, & R < R_k, \\ \alpha_i \beta_i R^{-(\beta_i+1)} \left(1 - \alpha_i R_k^{-\beta_i}\right)^{-1} \exp\left(-\alpha_i R^{-\beta_i}\right), & R \geqslant R_k. \end{cases} \end{aligned} \tag{7}$$

It is easy to see that the normalization condition (5) is satisfied for any values of α_i and β_i. The parameters α_i and β_i for neutron monitors for different multiplicities m (parameters α_m and β_m with $m = 1, 2, 3, \ldots$) and the total neutron component (parameters α_n and β_n) were determined from latitude surveys [8 – 10] and are in good agreement with the theoretical calculations in [5 – 7]. The dependence of these coefficients on the average station pressure h (in atm $= 1000$ g cm^{-2}) and the solar activity level characterized by the logarithm of the CR intensity (for which we used the monthly average of Climax NM, $\ln(N_{\mathrm{Cl}})$, available starting from 1953) can be approximated by the functions

$$\begin{aligned} \alpha_{\mathrm{n}} &= (-2.915h^2 - 2.237h - 8.654) \ln N_{\mathrm{Cl}} \\ &\quad + (24.584h^2 + 19.460h + 81.230)\,, \end{aligned} \tag{8}$$

$$\begin{aligned} \beta_{\mathrm{n}} &= (0.180h^2 - 0.849h + 0.750) \ln N_{\mathrm{Cl}} \\ &\quad + (-1.440h^2 + 6.403h - 3.698)\,, \end{aligned} \tag{9}$$

$$\begin{aligned} \alpha_m &= \big[(-2.915h^2 - 2.237h - 8.638) \ln N_{\mathrm{Cl}} \\ &\quad + (24.584h^2 + 19.46h + 81.23)\big] \\ &\quad \times \frac{0.987m^2 + 0.225m + 6.913}{9.781}\,, \end{aligned} \tag{10}$$

$$\begin{aligned} \beta_m &= \big[(0.180h^2 - 0.849h + 0.750) \ln N_{\mathrm{Cl}} \\ &\quad + (-1.440h^2 + 6.403h - 3.698)\big]\, \frac{0.081m + 1.819}{1.940}\,, \end{aligned} \tag{11}$$

where $m = 1, 2, 3, \ldots$. Instead of Climax NM, monthly averages of any other CR observatory can also be used with an appropriate recalculation of the parameters determined by the correlation between monthly data N_{Cl} of Climax NM and a given observatory for several years. For example, the recalculated parameters for the Emilio Segrè Observatory in Israel on Mt. Hermon (ESOI, neutron monitor 6NM-64) are determined by the same Eqns (8) – (11) by using the relation

$$\ln N_{\mathrm{Cl}} = 2.161 \ln N_{\mathrm{ESOI}} - 9.665\,. \tag{12}$$

For Rome 17NM-64, the following relation must be used in Eqns (8) – (11):

$$\ln N_{\mathrm{Cl}} = 1.767 \ln N_{\mathrm{Rome}} - 3.57 \,. \tag{13}$$

According to [12, 13], for the coupling functions for some other different CR secondary components, the parameters α_i and β_i in Eqn (7) are as follows: 1) for the neutron component at $h_{\mathrm{o}} = 312$ mb, $\alpha_n = 8.30$ and $\beta_n = 1.45$; 2) for the neutron component at $h_{\mathrm{o}} = 680$ mb, $\alpha_{\mathrm{n}} = 13.62$ and $\beta_{\mathrm{n}} = 1.26$; 3) for the muon component at sea level $h_{\mathrm{o}} = 1030$ mb, $\alpha_\mu = 35.3$ and $\beta_\mu = 0.95$; and 4) for the muon component underground at a depth of 7 m w.e., $\alpha_\mu = 58.5$ and $\beta_\mu = 0.94$.

Above, we considered the direct problem, which answers the question of how changes in the magnetosphere, the atmosphere, and space (outside the magnetosphere) are reflected in CR observation data. But is it possible to solve inverse problem? And if yes, how can it be solved, i.e., how can data on CR variations be used to determine changes in conditions in the magnetosphere, in the atmosphere, and in space? These changes are respectively determined by $\delta R_k(t)$, $\delta m_i(R,t)/m_i(R,t)$, and $\delta D(R,t)/D(R,t) = a(t)\, R^{-b(t)}$, where $a(t)$ and $b(t)$ are functions that can be determined by comparison with observation data of CR variations. With this aim, in the case where it is possible to correct CR variation data on meteorological effects ahead of time (i.e., to determine the term in Eqn (3) with $\delta m_i(R,t)/m_i(R,t)$ by using meteorological data and the theory of CR meteorological effects [14]), a special spectrographic method was developed (when observational data is available, a minimum of three CR secondary components with different coupling functions) that allows solving the system of equations like Eqn (3) for the functions $\delta R_k(t)$, $a(t)$, and $b(t)$ at each instant of time.

In some cases, it is not possible to correct the introduction of CR variation data on meteorological effects, especially in periods of high winds (when the barometer readings jump due to the Bernoulli effect), large snowfalls, and/or when data on vertical air temperature probing are absent. In these cases, the number of unknown values significantly increases, and it is necessary to add the change in air pressure δh_{o}, the depth of snow δS (in g cm^{-2}), and changes in the air temperature distribution $\delta T(h,t)$, air humidity distribution $\delta e(h,t)$, and atmospheric electric field distribution $\delta E(h,t)$. To solve the inverse problem in these cases, the general spectrographic method was developed, using a system of a large number of equations of the same type as Eqn (3) describing CR intensity variations of many different secondary components (see the detailed description in Chapter 3 in [2]). The real-time data of the worldwide network of neutron monitors and muon telescopes now give the possibility, through spherical analysis or the so-called global spectrographic method (see the detailed description in [13] and in Chapter 3 in [2]) with the help of meteorological data and coupling functions, of determining the CR distribution function for any instant of time outside Earth's magnetosphere.

3. Cosmic rays and Earth's atmosphere

This issue has two aspects. The first is how Earth's atmosphere influenced the CRs of galactic and solar origin:

1. CR cascade processes in the atmosphere (which determine the coupling functions and integral multiplicities); see [5 – 7] and the review in Chapter 3 of [2];

2. Meteorological effects (atmospheric electric field [14], barometer, wind, snow, temperature, humidity, and gravity); see a review in [1, 15] and Chapters 5 – 9 of [2].

The second aspect is how CRs of galactic and solar origin influence Earth's atmosphere:

1. Through nuclear reactions of primary and secondary CRs with air and aerosol matter accompanied by the formation of many unstable and stable cosmogenic nuclides, especially ^{14}C (radiocarbon) and ^{10}Be (see [16 – 24] and the extended review in Chapters 10 and 17 in [2]);

2. Through the generation of secondary relativistic electrons by CRs in the atmosphere and EASs (extensive atmospheric showers) playing a crucial role in atmospheric electric field phenomena: thunderstorms, discharges, Earth's electric charge balance (see [25 – 32] and the extended review in Chapter 11 in [2]);

3. Through air ionization influences on the low ionosphere and radio wave propagation, as well as on the formation of clouds and through their influence on long-term global climate change and wheat production (see the extended review in [33, 34] and in Chapters 12 and 14 in [2]). We emphasize that because it is now known how to forecast the galactic CR intensity several years (up to 11 years) ahead, it has become possible to forecast the expected part of climate change caused by long-term CR variations [35 – 39];

4. Through chemical reactions induced by interactions of galactic and solar CRs with air atoms, including the production of nitrates and the effect on the ozone layer (see the extended review in Chapter 13 in [2]).

4. CR variations and Earth's magnetosphere

In Earth's magnetosphere, we now have many satellites that play a very important role in our modern life: TV, communications, navigation, and many others. Especially important is GPS (Global Positioning System, including car navigation systems), which works through a worldwide network of satellites. Satellites usually spend several years in space, and are therefore exposed to the short- and long-term effects of solar and galactic CRs and many other factors of space weather. Certainly, all satellites are insured and because of anomalies (especially large anomalies that can lead to the full destruction of satellite work), insurance companies pay many hundreds of millions of dollars per year. There is a body of evidence on the existence of spacecraft anomalies caused by the space environment. A comparative analysis of the distribution of each of these parameters relative to the satellite malfunction was carried out for the total number of malfunctions (about 6000 events), and separately for high-altitude ($\sim$ 5000 events) and low-altitude (about 800 events) orbit satellites. No relation has been found between low and high-altitude satellite malfunctions. The majority of malfunctions of Kosmos satellites occurred at the same time as failures on other low-altitude orbit spacecraft, and they seemed to be related to space weather parameters. About 50% of the total number of anomalies was identified as unrelated to human or technological factors. It was supposed that the data free from these technological malfunctions might be related to space weather and were taken for correlation analysis. Is it possible to reliably predict those periods when satellite anomalies are expected, and what must be done to avoid satellite anomalies? To investigate this problem, an international team of researches from Italy, Russia, Kazakhstan, Ukraine, and Israel analyzed a large collection of known satellite anomalies (about 6000), depending on satellite orbits (altitude and inclination to the equatorial plane) and different space weather conditions. The following parameters were used for correlation analysis ([39 – 48], see the short review in Section 18.17 in [2]):

1) solar and galactic cosmic ray intensities, determined by neutron monitor data;

2) proton (> 10 MeV and > 60 MeV) and electron (> 2 MeV) fluxes according to measurements on satellites;

3) parameters of solar activity (sunspot number, solar radiation at 2800 MHz (10.7 cm), index F10.7);

4) parameters of geomagnetic activity (Ap, AE, and Dst indices).

As an example, we show in Figs 1 and 2 how the frequency of anomalies in different orbits increases as the flux of energetic protons increases. If there is a high probability of an anomaly destroying the normal work of a satellite, experts must decide what to do: for example, when high ionization is expected (at very large fluxes of energetic protons; see Figs 1 and 2), electric power may for a short time be switched off to especially important parts of electronics to exclude discharges along the treks of energetic particles.

Earth's magnetosphere shapes the trajectories of primary CRs, acceptance cones, and cutoff rigidities (see the extensive review in Chapter 4 in [4]). Changes in Earth's magnetosphere are caused by long-term variations of the main geomagnetic field and by electric currents in the magnetosphere and ionosphere. It is important that the planetary distribution of $(\delta R_k)_{\text{obs}}$ at any instant of time (especially during magnetic storms) can be determined by the above spectrographic method (see Section 1) by observations of the CR intensity via a worldwide network of stations. This information, together with data on geomagnetic field variations, can be used for determining how the parameters of ring current (main cause of Dst variation) and magnetopause currents change with time. This was done in [49 – 68] (see the extended review in Chapter 6 of [4]). On the other hand, the trajectory can be calculated for the same time instants in the framework of any theoretical model of the magnetosphere (including the main geomagnetic field): $(\delta R_k)_{\text{theor}}$. By comparing $(\delta R_k)_{\text{obs}}$ with $(\delta R_k)_{\text{theor}}$, it can be estimated what model is more suited to the reality. This can be done with galactic and solar CRs ([69 – 89]; see the extended review in Chapter 7 of [4]).

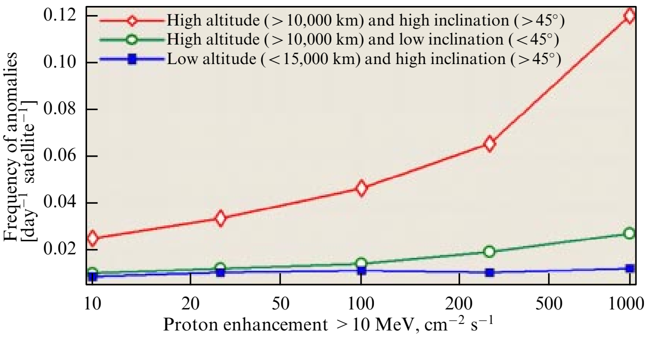

Figure 1. Mean satellite anomaly frequencies in the first two days of proton enhancements > 10 MeV depending on the maximum flux.

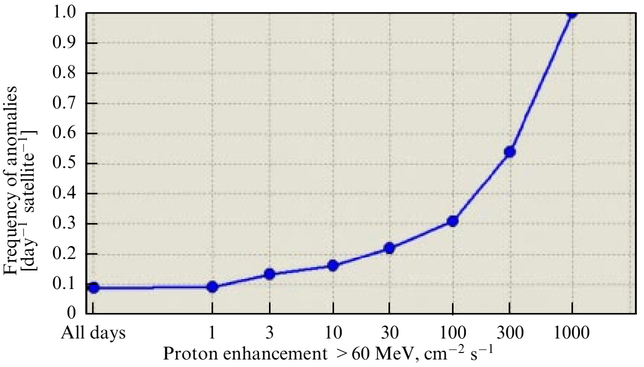

Figure 2. Frequency of satellite anomaly (high-altitude high-inclination group) depending on the maximum proton flux > 60 MeV.

5. CR variations and radiation hazards from solar-flare energetic particles

It is well known that solar energetic particle (SEP) events are very anisotropic at the beginning stage, especially during great events as in February 1956, July 1959, August 1972, September–October 1989, July 2000, January 2005, and many others [1, 90 – 95]. In these cases, determining the properties of primary solar CRs outside the magnetosphere on the basis of experimental data (by the above spectrographic method and coupling functions) and then determining the source function of solar CRs and the parameters of propagation in interplanetary space based on experimental data, i.e., solving the inverse problem, is very difficult both theoretically (in the framework of the kinetic Boltzmann equation or in the framework of the Fokker–Planck equation of anisotropic diffusion; see possible ways of approximately solving this problem in Chapter 2 of [3]) and experimentally, because it is necessary to organize an International Service of CR Variations (similar to the International Meteorological Service) on the basis of the existing worldwide CR stations and some satellites with data collection on a real-time scale through the Internet. An important step was taken in this direction in 2008 – 2009, when the Neutron Monitor Data Base (NMDB) was founded; it now operates continuously. The extended European part of this international service includes not only West European countries but also Russia, Kazakhstan, Armenia, and Israel.

By the procedure developed in [96 – 100] for each CR station, the starting moment of a solar CR event can be determined automatically, and then the energy spectrum of solar CR outside the atmosphere can be determined above the individual CR station for different instants of time by the spectrographic method and coupling functions. As result, the planetary distribution of solar CR intensity outside the atmosphere can be obtained, and then, by taking the influence of the geomagnetic field on particle trajectories into account, the solar CR angle distribution outside Earth's magnetosphere can be determined. On the basis of this great experimental material, the inverse problem can be solved automatically in the near future in the framework of the Fokker–Planck equation of anisotropic diffusion and/or in the framework of the kinetic Boltzmann equation [101].

However, we must recall that after one or two scatterings in interplanetary space (i.e., 10 – 15 min after the beginning of an event), the distribution of solar CRs in interplanetary space becomes practically isotropic, and hence the differences in time evolution of the solar CR intensity on CR stations is determined only by differences in coupling functions and cutoff rigidities. This implies that if we use data not from the very beginning of an event, we can solve the inverse problem, as the first step, in the framework of the much simpler theory of isotropic diffusion. This allows proceeding based on two well-established facts:

(i) the time of particle acceleration on the Sun and injection into the solar wind is very short in comparison with the time of propagation to Earth, and therefore the solar CR source function can be considered a δ-function of time;

(ii) a very anisotropic distribution of solar CRs developed after a few scatterings of energetic particles becomes nearly isotropic (well-known examples of February 1956, September 1989, and many others).

Therefore, presently, before the International Service of CR Variations mentioned above (collecting one-minute data from nearly all CR stations of the worldwide network on a real-time scale) is organized, we operate on the basis of solving the inverse problem in the framework of simple isotropic diffusion of solar CRs in interplanetary space (in this case, it is enough to use the observation data of several different CR components on one station or only a few stations). We therefore consider isotropic diffusion with a point-like instantaneous source function

$$Q(R,r,t) = N_{\mathrm{o}}(R)\,\delta(r)\,\delta(t)\,, \tag{14}$$

where r is the distance to the Sun, t is the time after the solar CR ejection into interplanetary space, and $N_{\mathrm{o}}(R)$ is an unknown function to be determined from comparison with experimental data. We suppose that the diffusion coefficient depends on the rigidity R of energetic particles and on the distance r to the Sun as

$$\kappa(R,r) = \kappa_1(R)\left(\frac{r}{r_1}\right)^{\beta}\,, \tag{15}$$

where $\kappa_1(R)$ and $\beta(t)$ are unknown functions to be determined from comparison with experimental data, and $r_1 = 1$ a.u. is the radius of Earth's orbit. In this case, the solution of the diffusion equation is given by

$$N(R,r,t) = \frac{N_{\mathrm{o}}(R)\, r_1^{3\beta/(2-\beta)}\big(\kappa_1(R)\,t\big)^{-3/(2-\beta)}}{(2-\beta)^{(4+\beta)/(2-\beta)}\,\Gamma\big(3/(2-\beta)\big)} \times \exp\left(-\frac{r_1^{\beta} r^{2-\beta}}{(2-\beta)^2 \kappa_1(R)\,t}\right), \tag{16}$$

where t is the time after solar CR ejection into the solar wind.

We have four unknown parameters: the time of solar CR ejection into the solar wind T_{e}, β, $\kappa_1(R)$, and $N_{\mathrm{o}}(R)$. We assume that according to ground and satellite measurements at the distance $r = r_1 = 1$ a.u. from the Sun, we know $N_1(R)$, $N_2(R)$, $N_3(R)$, and $N_4(R)$ at UT times T_1, T_2, T_3, and T_4. In this case, the times after ejection of solar CRs into the solar wind are

$$\begin{aligned} &t_1 = T_1 - T_{\mathrm{e}} = x\,, \quad t_2 = T_2 - T_1 + x\,, \\ &t_3 = T_3 - T_1 + x\,, \quad t_4 = T_4 - T_1 + x\,. \end{aligned} \tag{17}$$

For each $N_i(R, r = r_1, T_i)$, we use Eqns (16) and (17) to obtain

$$\begin{aligned} &N_i(R, r = r_1, T_i) \\ &= \frac{N_{\mathrm{o}}(R)\, r_1^{3\beta/(2-\beta)}\big(\kappa_1(R)(T_i - T_1 + x)\big)^{-3/(2-\beta)}}{(2-\beta)^{(4+\beta)/(2-\beta)}\,\Gamma\big(3/(2-\beta)\big)} \\ &\times \exp\left(-\frac{r_1^2(2-\beta)^{-2}}{\kappa_1(R)(T_i - T_1 + x)}\right), \end{aligned} \tag{18}$$

where $i = 1, 2, 3, 4$. To determine x, we consecutively eliminate the unknown parameters $N_{\mathrm{o}}(T)$, $\kappa_1(R)$, and β. We first eliminate $N_{\mathrm{o}}(R)$ by using four equations like (18) to write the three equations

$$\frac{N_1(R, r = r_1, T_1)}{N_i(R, r = r_1, T_i)} = \left(\frac{x}{T_i - T_1 + x}\right)^{-3/(2-\beta)} \times \exp\left[-\frac{r_1^2}{(2-\beta)^2\kappa_1(R)}\left(\frac{1}{x} - \frac{1}{T_i - T_1 + x}\right)\right], \tag{19}$$

where $i = 2, 3, 4$. To eliminate $\kappa_1(R)$, we take the natural logarithm of both parts of Eqns (19) and then divide one equation by another; as result, we obtain the two equations

$$\frac{\ln(N_1/N_2) + \big[3/(2-\beta)\big]\ln\big[x/(T_2 - T_1 + x)\big]}{\ln(N_1/N_3) + \big[3/(2-\beta)\big]\ln\big[x/(T_3 - T_1 + x)\big]} = \frac{1/x - 1/(T_2 - T_1 + x)}{1/x - 1/(T_3 - T_1 + x)}\,, \tag{20}$$

$$\frac{\ln(N_1/N_2) + \big[3/(2-\beta)\big]\ln\big[x/(T_2 - T_1 + x)\big]}{\ln(N_1/N_4) + \big[3/(2-\beta)\big]\ln\big[x/(T_4 - T_1 + x)\big]} = \frac{1/x - 1/(T_2 - T_1 + x)}{1/x - 1/(T_4 - T_1 + x)}\,. \tag{21}$$

After eliminating the unknown parameter β from Eqns (20) and Eqn (21), we obtain an equation for x:

$$x^2(a_1a_2 - a_3a_4) + xd(a_1b_2 + b_1a_2 - a_3b_4 - b_3a_4) + d^2(b_1b_2 - b_3b_4) = 0\,, \tag{22}$$

where

$$d = (T_2 - T_1)(T_3 - T_1)(T_4 - T_1)\,, \tag{23}$$

$$a_1 = (T_2 - T_1)(T_4 - T_1)\ln\frac{N_1}{N_3} - (T_3 - T_1)(T_4 - T_1)\ln\frac{N_1}{N_2}\,, \tag{24}$$

$$a_2 = (T_3 - T_1)(T_4 - T_1)\ln\frac{x}{T_2 - T_1 + x} - (T_2 - T_1)(T_3 - T_1)\ln\frac{x}{T_4 - T_1 + x}\,, \tag{25}$$

$$a_3 = (T_2 - T_1)(T_3 - T_1)\ln\frac{N_1}{N_4} - (T_3 - T_1)(T_4 - T_1)\ln\frac{N_1}{N_2}\,, \tag{26}$$

$$a_4 = (T_3 - T_1)(T_4 - T_1)\ln\frac{x}{T_2 - T_1 + x} - (T_2 - T_1)(T_4 - T_1)\ln\frac{x}{T_3 - T_1 + x}\,, \tag{27}$$

$$\begin{aligned} &b_1 = \ln\frac{N_1}{N_3} - \ln\frac{N_1}{N_2}\,, \\ &b_2 = \ln\frac{x}{T_2 - T_1 + x} - \ln\frac{x}{T_4 - T_1 + x}\,, \end{aligned} \tag{28}$$

$$b_3 = \ln\frac{N_1}{N_4} - \ln\frac{N_1}{N_2}\,,$$

$$b_4 = \ln\frac{x}{T_2 - T_1 + x} - \ln\frac{x}{T_3 - T_1 + x}\,. \qquad (29)$$

As can be seen from Eqns (25) and (27)–(29), the coefficients a_2, a_4, b_2, and b_4 very weakly (logarithmically) depend on x. Therefore, we solve Eqn (22) by the iteration method: as a first approximation, we use $x_1 = T_1 - T_e \approx 500$ (which is the minimum time propagation of relativistic particles from the Sun to Earth's orbit without scattering). Then, from Eqns (25) and (27)–(29), we determine $a_2(x_1)$, $a_4(x_1)$, $b_2(x_1)$, and $b_4(x_1)$, and from Eqn (22), we determine the second approximation x_2, and so on. After determining x, i.e., using Eqn (17), we determine t_1, t_2, t_3, t_4, the final solutions for β, $\kappa_1(R)$, and $N_o(R)$. We determine the unknown parameter β from Eqns (20) and (21):

$$\beta = 2 - 3\left[\ln\frac{t_2}{t_1} - \frac{t_3(t_2 - t_1)}{t_2(t_3 - t_1)}\ln\frac{t_3}{t_1}\right]$$
$$\times\left[\ln\frac{N_1}{N_2} - \frac{t_3(t_2 - t_1)}{t_2(t_3 - t_1)}\ln\frac{N_1}{N_3}\right]^{-1}. \qquad (30)$$

Then we determine unknown parameter $\kappa_1(R)$ from Eqn (19):

$$\kappa_1(R) = \frac{r_1^2(t_1^{-1} - t_2^{-1})}{3(2-\beta)\,\ln(t_2/t_1) - (2-\beta)^2\ln(N_1/N_2)}$$
$$= \frac{r_1^2(t_1^{-1} - t_3^{-1})}{3(2-\beta)\,\ln(t_3/t_1) - (2-\beta)^2\ln(N_1/N_3)}\,. \qquad (31)$$

After determining the parameters β and $\kappa_1(R)$ we can determine the last parameter $N_o(R)$ from Eqn (18):

$$N_o(R) = N_i(2-\beta)^{(4+\beta)/(2-\beta)}\,\Gamma\left(\frac{3}{2-\beta}\right) r_1^{-3\beta/(2-\beta)}$$
$$\times\left(\kappa_1(R)\,t_i\right)^{3/(2-\beta)}\exp\left(\frac{r_1^2}{(2-\beta)^2 k_1(R)\,t_i}\right), \qquad (32)$$

where $i = 1, 2, 3$.

Thus, by finding x, we find the time of ejection $T_e = T_1 - x$ and then the transfer time T of observation data from the UT after ejection $t = T - T_e$. By substituting the obtained β, $\kappa_1(R)$, and $N_o(R)$ in Eqn (16), it is easy to predict how the intensity of solar CRs changes with time at any distance from the Sun in interplanetary space or in Earth's atmosphere at any depth and any cutoff rigidity (by using Eqn (3) and the method of coupling functions).

We used the results described above in the method of great radiation hazard prediction based on online CR one-minute ground and satellite data [98, 99]. To test the method and estimate how many minutes of observation after the beginning of a solar CR event we need to predict all events with sufficient accuracy, we used one-minute data obtained during the very anisotropic solar CR event in September 1989 by a neutron monitor on the top of Gran Sasso in Italy, and one-minute satellite data on protons with the energy $\geqslant 0.1$ GeV. It is important that this neutron monitor detected one-minute data not only of the total neutron intensity but also of neutron multiplicities ($\geqslant 1$, $\geqslant 2$, $\geqslant 3$, up to $\geqslant 8$) with different coupling functions [see Eqns (7)–(11)]. Taking satellite data into account and using the spectrographic method and coupling functions, this allowed minute-by-minute determining the energy spectrum of solar CRs outside Earth's magnetosphere, i.e., the functions $N_i(R, r = r_1, T_i)$ solving the system of equations (18). Then, on the basis of the inverse problem solution described above, we determined the unknown ejection time $t_1 = T_1 - T_e = x$ from Eqn (22), the parameters β from Eqn (30), $\kappa_1(R)$ Eqn (31), and $N_o(R)$ from Eqn (32). With the obtained values of these parameters, we then used Eqn (16) and the coupling functions to determine the expected CR intensity variations in the neutron monitor and GOES (geostationary operational environmental satellite), and to compare them with real observations. The results of the comparison (see Fig. 3) show that for high-energy particles (more than several GeV, measured by a neutron monitor) about 15–20 min was needed for approximate forecasting, and about 35 min was needed for exact forecasting of all events. For forecasting in a small energy region (about 100 MeV), we need to use data for about 30–40 min to give the exact forecast for about two days. Then, from Eqn (16)

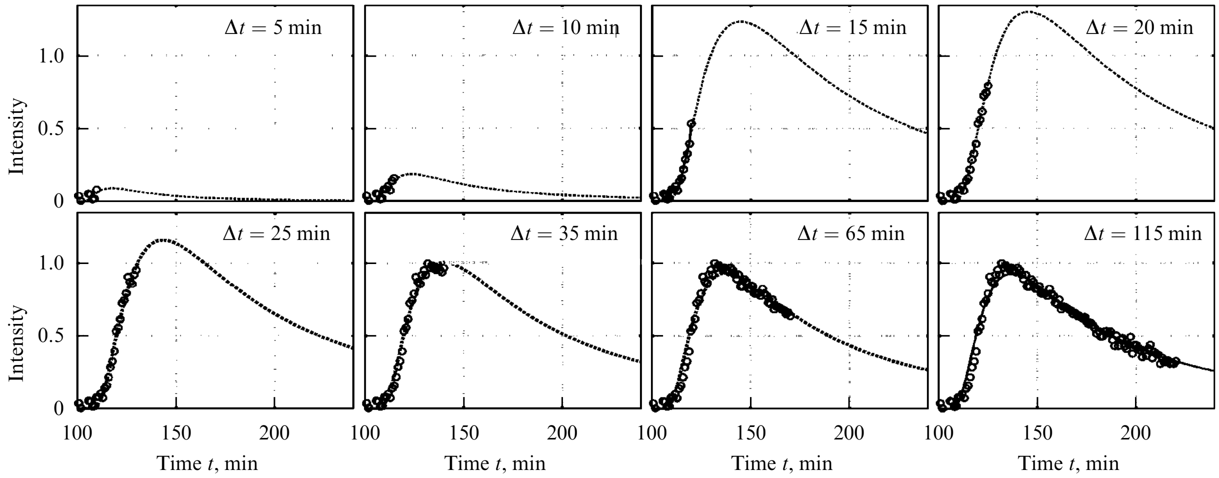

Figure 3. Results of calculating the x, β, $\kappa_1(R)$, and $N_o(R)$ parameters based on the first 5, 10, 15, ... minutes of observation with a neutron monitor ($\Delta t = 5$ min, $\Delta t = 10$ min, $\Delta t = 15$ min, ...) and using Eqn (16) to estimate the expected time dependence of the solar CR intensity, followed by a recalculation with the help of a coupling function in terms of the projected variation in the count rate in a neutron monitor. The unit along the vertical axis is the observed maximum of the increase in the solar CR flux intensity based on the neutron monitor date at Gran Sasso. The horizontal line is the time (in minutes) from10.00 UT, 29 September 1989.

and the coupling functions, we can also estimate the total expected radiation hazard during all events for spacecraft at different distances from the Sun, for satellites in the magnetosphere at different orbits, for aircraft at different altitudes, and for different objects in the atmosphere and on the ground.

6. Conclusion

The science of CR variations, which lies between nuclear physics, astrophysics, the physics of the Sun, heliosphere, and magnetosphere, geophysics, and meteorology, has long had mainly a fundamental character without any important practical applications. Only in the last 15 – 20 years, in connection with the impressive development of space research, the broad use of satellites, the founding of GPS, the extension of airlines to altitudes about 10 km, and especially the great jump in developing microelectronics (very sensitive to cosmic radiation), has the practical application of CR variations, especially for space weather monitoring and forecasting, started developing intensively. This application is promoted by the world-wide network of CR stations founded in the last 50 – 60 years and equipped with neutron monitors and muon telescopes (in the energy range of more than a few GeV) and a series of satellites launched in the last 30 years that has continuously measured CR intensity variations in much smaller energy intervals and made their one-minute data available through the Internet. The methods described above have important prospects for development using the anisotropic part, at the very beginning of a solar CR event [101]. With the founding of the International CR Variation Service in the near future (as mentioned above, the first step in this direction was made in 2008 – 2009 and with the founding of NMDB, the extended European part of this service), it will become possible to forecast the expected radiation dose for about two days, not 20 – 40 min after the beginning of a solar CR event (as was described above) but sufficiently earlier, about 5 – 15 min after the beginning of an event, as described in [101] (which can have great practical significance). Moreover, the founding of a well-functioning International CR Variation Service will allow continuously determining the change in time of the angle–energy CR distribution outside Earth's magnetosphere by one-hour CR data from the world-wide network of neutron monitors and muon telescopes (by the global spectrographic method: see Chapter 3 in [2]). This important information allows forecasting the approach of powerful interplanetary shock waves and coronal mass ejections (CMEs) for 15 – 20 hours to Earth; by interaction with Earth's magnetosphere, CMEs cause big magnetic storms that are dangerous for human health (with the frequency of myocardial infarcts, brain strokes, and auto accidents increasing) and cause some part of the anomalies (malfunctions) in the work of satellites [42 – 48] and large induction currents at high latitudes that disturb the work of electrical high-voltage power networks and large-scale pipelines [42, 102]. Unfortunately, in this short paper, we were not able to describe this important issue in more detail, but we plan in the near future to devote a special paper to this important aspect of the CR variation research.

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