JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. A1, PAGES 9-17, JANUARY 1, 2000

Long-term negative trend in cosmic ray flux

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Abstract. The cosmic ray fluxes in four consecutive solar activity minima (1964-1965, 1976-1977, 1987, and 1996-1997) are considered. The data obtained in long-term stratospheric measurements and at ground level (neutron monitor and ionization chamber data) are used. The long-term negative trend is derived from these experimental data. The value of the effect is $\delta \approx -(0.01\text{-}0.09)\%$ per year. The data on cosmogenic radioactive isotopes of ^{10}Be and ^{14}C which are produced by cosmic rays in the atmosphere also show the gradual decrease of their concentrations on the timescale of more than $\sim 10^4$ years. The stratospheric measurements also propose that the cosmic ray spectrum becomes softer in the energy range E=0.1-1.5 GeV with the passage of time. The consideration of solar and interplanetary parameter changes, which could be responsible for the observed negative trend in cosmic ray flux, does not show any increase. The effect could be explained if supernova explosion had taken place in the nearby interstellar space. Such an explosion could occur about $10^4\text{-}5\times10^5$ years ago at the distance 30-150 pc from the solar system.

1. Introduction

The long-term observations of cosmic ray fluxes in the atmosphere and on the ground performed with standard instruments during several 11-year solar activity cycles make it possible to obtain the information on cosmic rays in the nearby interstellar space. When studying the processes of cosmic ray modulation in the heliomagnetosphere, the flux of cosmic rays falling on the modulation region boundary from the nearby interstellar space is assumed to be constant. This assumption requires to be verified. A space probe can not be put outside the heliomagnetosphere at the distance of about 100 AU to measure the galactic cosmic ray flux. However, the comparison of fluxes obtained on the Earth during several solar activity minimum periods allows to do such verification.

If any trend in these fluxes (increase or decrease from one solar minimum to another) is observed, then it could arise from the respective changes in solar activity level during periods under consideration or from the changes in cosmic ray flux falling on the boundary of the modulation region from the nearby interstellar space. Now the homogeneous sets of long-term cosmic ray observations are available to make such an analysis possible.

Long-term measurements of cosmic ray flux (charged particles) have been performed in the atmosphere at several latitudes since 1957, at ground level by ionization chambers since 1937, and by neutron monitors since 1953 to the present time. These observations cover several solar activity minimum periods and span a wide energy range of primary particles from several hundreds of MeV (stratospheric measurements) to several tens of GeV (ionization chamber data). This paper analyzes galactic cosmic ray fluxes measured in the atmosphere and at ground level during the periods of several successive solar activity minima.

2. Long-Term Negative Trend in the Cosmic Rays Flux

Since 1957 until the present time, cosmic ray fluxes in the atmosphere have been measured at the polar, middle, and low latitudes with the standard radiosondes [*Charakhchyan et al.*, 1976; *Bazilevskaya et al.*, 1991]. In this long-term experiment, Geiger tubes are used as charged particles detectors.

Figure 1 shows the monthly values of maximal fluxes of charged particles in the atmosphere (Pfotzer maximum) N_m obtained at the northern polar latitude with the geomagnetic cutoff rigidity R_c=0.6 GV and at the middle one with R_c=2.4 GV during the period from 1957 until the present time. The circles in Figure 1 mark the periods of cosmic ray flux maxima, analyzed below. These periods correspond to low solar activity levels (minima of solar activity).

To avoid a possible biasing, we consider the data obtained at polar latitude where R_c is low and its possible changes will not disturb the cosmic ray flux. We also compare cosmic ray fluxes measured at Pfotzer maximum to ensure against possible errors that could be due to the atmospheric pressure sensors.

Figure 2 presents the monthly values of N_m smoothed with the period T=3 months in the four successive solar activity minima: 1964-1966, 1975-1978, 1986-1987, and 1994-1998. The maximum values of cosmic ray fluxes have been observed in April-June 1965, in September-October 1976, in January-March 1987, and in April-June 1997. The straight line in Figure 2 passes through the maximum values of N_m. The straight lines on Figure 2 and others were calculated by the least squares method and the values of N_m in January 1965 were taken as 100%. It can be seen that the value of cosmic ray flux decreases gradually from 1965 to 1997 with the rate $\delta=-(0.08\pm0.01)\%$/yr. Over the 30-year period of observations the total decrease equals ~2.5%.

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Paper number 1999JA900385.
0148-0227/00/1999JA900385$09.00

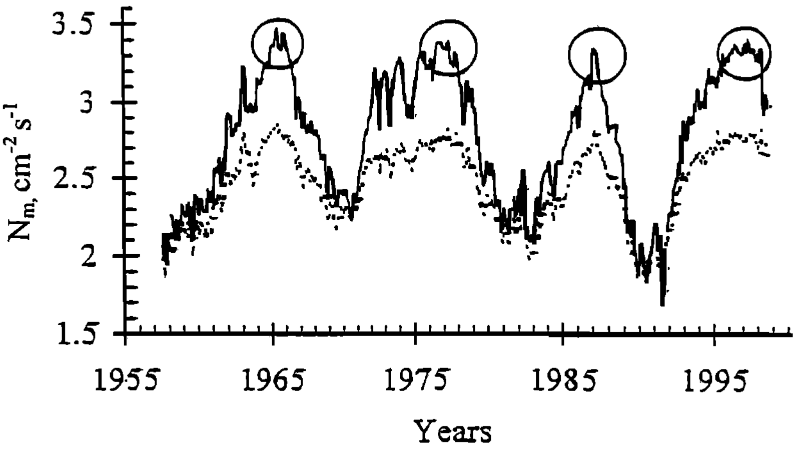

Figure 1. The time dependence of cosmic ray fluxes measured in the northern polar atmosphere (R_c=0.6 GV, solid curve) and at the midlatitude (R_c=2.4 GV, dotted curve). The values of fluxes are given for Pfotzer maximum. The circles show the periods when maximum values of cosmic ray fluxes were observed.

The same effect is observed if we analyze the data obtained at other altitudes in the polar region and at the latitudes with R_c=2.4 GV (Moscow) and 6.7 GV (Alma-Ata). The negative trend is seen distinctly if we consider the cosmic rays in the lower atmosphere where the amplitude of 11-year solar cycle is small. To avoid the influence of the temperature effect on the cosmic ray flux we need to take the yearly averaged data. As an example, the cosmic ray fluxes measured at R_c=0.6 GV at the atmospheric pressure level X=180-200 g/cm^2 are depicted in Figure 3. The negative trend value is δ=–(0.09±0.01)%/yr.

If the long-term negative trend takes place in the stratospheric measurement data, the same effect has to be also seen in other data. When making the analysis of long-term data, the sets of data have to be homogeneous and the values of R_c have to be the same during the period under consideration. We have analyzed the long-term sets of 32 neutron monitor data. Some data sets do not cover four solar activity minimum periods (e.g., Chicago, Deep River, and Potchefstroom). Others do not yield a homogeneous row of data (e.g., Alma-Ata, Calgary, and Kiev). These data sets were excluded from the analysis. The 12 neutron monitors have homogeneous long-term sets of data spanning four solar activity minima. The minor changes of R_c only were observed at these stations [*Shea and Smart*, 1997]. All of them show the negative trend. Table 1 gives the values of δ calculated from 3-monthly averaged data.

As an example, the recordings of Moscow neutron monitor (3-month smoothed values, R_c=2.4 GV) for the four successive solar activity minimum periods are given in Figure 4. The negative trend with the value of δ=–(0.08±0.01)%/yr is evident. It is well known that cosmic rays fluxes are different in minima of positive and negative phases of the 22-year solar magnetic cycle. The negative phase corresponds to the periods when the polarity of solar magnetic field lines is inward in the northern polar regions of the Sun and outward in the southern ones (1959-

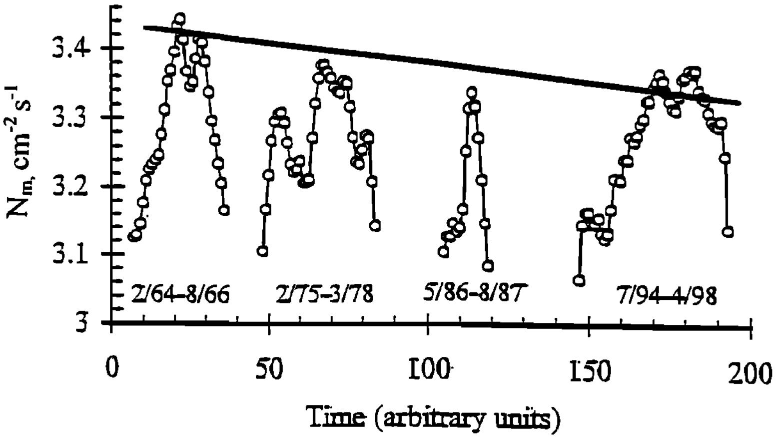

Figure 2. The four periods of maximum cosmic ray fluxes are depicted on an enlarged scale (see circles in Figure 1). The 3- month running values of N_m correspond to Pfotzer maximum. N_m were measured in the northern polar atmosphere (R_c=0.6 GV). The beginning and the end of each period are given under the curves. The straight line calculated from the four maximum values on N_m by the least squares method shows the decrease of N_m with the rate δ=–(0.08±0.01)%/yr.

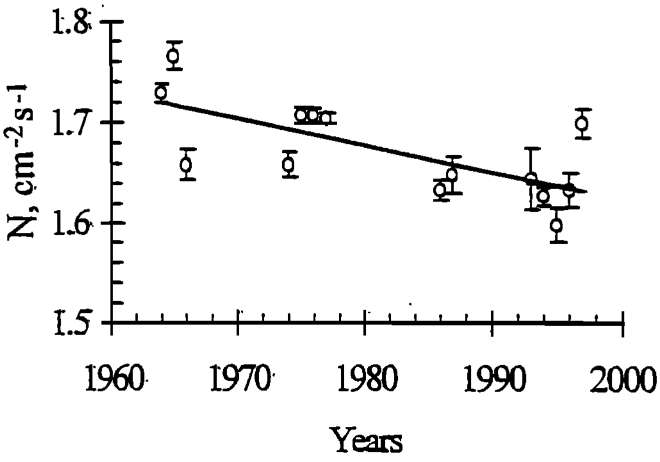

Figure 3. The yearly averaged cosmic ray fluxes measured in four successive solar activity minimum periods in the northern polar atmosphere at atmospheric pressure X=180-200 g/cm^2. The negative trend is shown by the straight line and its value is $\delta=-(0.09\pm0.02)$%/yr. The vertical bars of experimental points give the standard errors.

1968 and 1982-1989). During the positive phases (1972-1979 and 1991-present), magnetic field lines are outward in the Northern Hemisphere and inward in the Southern Hemisphere. The different behavior of cosmic rays in negative and positive phases of 22-year solar magnetic cycle is clearly defined in Figure 4. In the negative phases the cosmic ray fluxes recorded by neutron monitors at ground level are higher than in the next positive ones: $N^{65}>N^{77}$ and $N^{87}>N^{97}$. Strictly speaking, it should be better to compare the maximum cosmic ray fluxes in subsequent positive and negative phases of 22 solar magnetic cycles separately. In case of the Moscow neutron monitor, comparison of the periods of April-June 1965 and January-March 1987 (negative phases), September-October 1976, and April-June 1997 (positive phases) also gives the negative values of trend $\delta=-(0.02\pm0.01)$%/yr and $\delta=-(0.05\pm0.01)$%/yr respectively. To have more experimental points (minimum four), we calculated the trends without separation of data obtained in the positive and negative phases of solar magnetic cycles.

Table 1. The Value of Trend in Cosmic Ray Flux (δ) According to Neutron Monitor Data, Ionization Chamber Data, and Stratospheric Measurements in Pfotzer Maximum

Site	R_c, GV	δ, %/year
Thule	0.0	-0.08±0.01
Goose Bay	0.6	-0.06±0.01
Apatity	0.6	-0.08±0.01
Ouly	0.8	-0.05±0.01
Washington+	1.5	-0.02±0.01
Yakutsk	1.6	-0.09±0.01
Kiel	2.3	-0.08±0.01
Moscow	2.4	-0.08±0.01
Climax*+	3.0	-0.04±0.01
Jungfraujoch	4.6	-0.08±0.01
Hermanus	4.6	-0.05±0.01
Huancayo	12.8	-0.03±0.01
Ionization chamber+	1.6-2.2	-0.010±0.003
Murmansk, stratosphere	0.6	-0.08±0.01
Moscow, stratosphere	2.4	-0.08±0.01

*The Climax neutron monitor data have been adjusted after 1980-1981 because of a normalization problem. These data are used here without correction coefficient 1.0121 for the period after August 1981 [*Pyle*, 1997]. We consider there is no need to introduce the correction without strong argument. The trend equals $\delta=-(0.002\pm0.004)$%/yr if the correction coefficient is applied.

+The data of these stations cover five periods of solar activity minima.

The observations of high-energy cosmic rays using ionization chambers have been started in 1935 and cover five periods of solar activity minima. The averaged data from these instruments obtained in Cheltenham, Christchurch, Fredericksburg, Tixie, and Yakutsk [*Charakhchyan and Stozhkov*, 1981; *Ahluwalia*, 1997] also give the long-term negative trend. Figure 5 (adopted from *Ahluwalia* [1997]) shows the decrease in ionization chamber count rate from the solar activity minimum of 1944 to 1987.

Table 1 gives the values of δ obtained based on neutron monitor and ionization chamber data and stratospheric measurements of cosmic ray fluxes. The values of δ were calculated the following way: monthly averaged cosmic ray fluxes were smoothed with the 3-monthly period. After that the maximum smoothed values were selected for each solar activity minimum. Least squares method was used to calculate negative trend for these values. The calculations of δ were made for four maximum cosmic ray flux values in the four successive minimum solar activity periods except Climax and Washington neutron monitor and ionization chamber data where the five minimum solar activity periods were used. The cosmic ray fluxes in January 1965 were taken as 100%. One can see that maximum cosmic ray fluxes gradually decrease over the period under consideration (for the first time the long-term negative trend in cosmic rays was discussed by *Stozhkov et al.* [1997]).

Another argument in favor of the existence of the long-term negative trend in cosmic rays comes from the analysis of cosmogenic isotope ^{10}Be concentration in deep ice cores of Antarctica and Greenland and cosmogenic isotope ^{14}C concentration in tree rings (see for detail, e.g., *Kocharov* [1996]). The radioactive isotope ^{10}Be with a half-life of 1.5×10^6 years is produced in interactions of cosmic rays with nuclei of the atmosphere (mainly with nitrogen). Then it is removed from the atmosphere by precipitation. The ^{10}Be concentration depends only weakly on the weather conditions. The interactions of cosmic rays with atmospheric nuclei also yield secondary neutrons. In turn, these neutrons produce radioactive isotope ^{14}C (a half-life of 5730 years) in the nuclear reactions ^{14}N(n, p)^{14}C. After complex processes, atoms of ^{14}C fall into tree rings and accumulate there. The ^{10}Be and ^{14}C concentration data given by *Beer et al.* [1990] and *Dergachev* [1999] show the decrease in cosmic ray fluxes on the timescale about 25,000 years. As an example, the concentrations of ^{10}Be measured in the ice samples obtained in Greenland where R_c=0 GV are depicted in Figure 6 for the periods of solar activity minima from the beginning of our century till 1978 (the data were taken from *Beer et al.* [1990] and *Blinov* [1997]). The negative trend of a value of $\delta=-(0.05\pm0.01)$%/yr is present in these data. The analysis of ^{14}C concentrations in tree rings shows the gradual decrease of these values with the rate $\delta\approx-0.002$%/yr at the timescale about 25,000 years [*Dergachev*, 1999]. It must be admitted, however, that in contrast to ^{10}Be the concentration of ^{14}C depends on the Earth's magnetic dipole value and climate conditions.

With the long-term measurements of cosmic rays in the atmosphere at polar and midlatitudes (R_c=0.6 GV and R_c=2.4 GV accordingly), we can define the changes of galactic

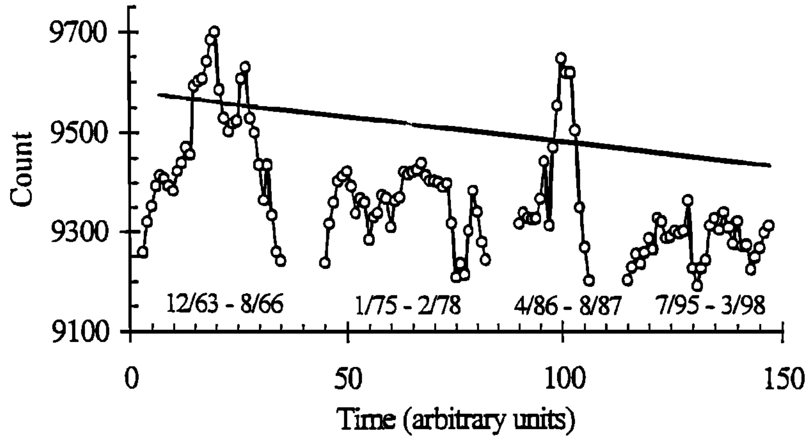

Figure 4. The 3-month running values of cosmic ray fluxes measured by neutron monitor in Moscow (R_c=2.4 GV) in four successive solar activity minima. The periods of each minimum are given under the curves. The straight line gives the negative trend δ=–(0.08±0.01)%/yr.

cosmic ray spectrum in the energy range E=0.1-1.5 GeV from one solar activity minimum to another one..Let us consider the values of $dN(x)=N_{0.6}(x)-N_{2.4}(x)$ where $N_{0.6}(x)$ and $N_{2.4}(x)$ are omnidirectional cosmic ray fluxes in the atmosphere at the atmospheric pressure level x and at the latitudes with R_c=0.6 GV and 2.4 GV [*Pereyaslova et al.*, 1981]. Figure 7 shows the yearly averaged values of $dN(x)$ for solar activity minima of 1965, 1977, 1987, and 1997. As one can see the particles are absorbed in the atmosphere according to the expression

$$dN(x) = dN(0) \times \exp(-x/L), \qquad (1)$$

where $dN(0)$ is the flux of primaries in the energy interval of E=0.1-1.5 GeV falling on the top of the atmosphere and L is the absorption length of charged particle flux. For the whole period of our measurements the yearly averaged values of L were calculated by the least squares method and the results are given in Figure 8. The periods of high solar activity with small values of $dN(x)$ are omitted. The straight line demonstrates the gradual decrease of L from 1960 to 1998. It means the softening of galactic cosmic ray spectrum in the energy range 0.1-1.5 GeV or an increase in the nuclear component in total flux of primaries falling on the top of the atmosphere. It should be noted that the changes of R_c at midlatitude (R_c=2.4 GV) from 1960 till 1998 are not sufficient to explain this result. According to calculations made by *Shea and Smart* [1997], the values of R_c were 2.36 GV in 1965, 2.43 GV in 1980, and 2.30 GV in 1990.

3. Possible Mechanism of the Long-Term Negative Trend

When carrying out long-term measurements, the level of instrument efficiency must be kept constant. This is the main

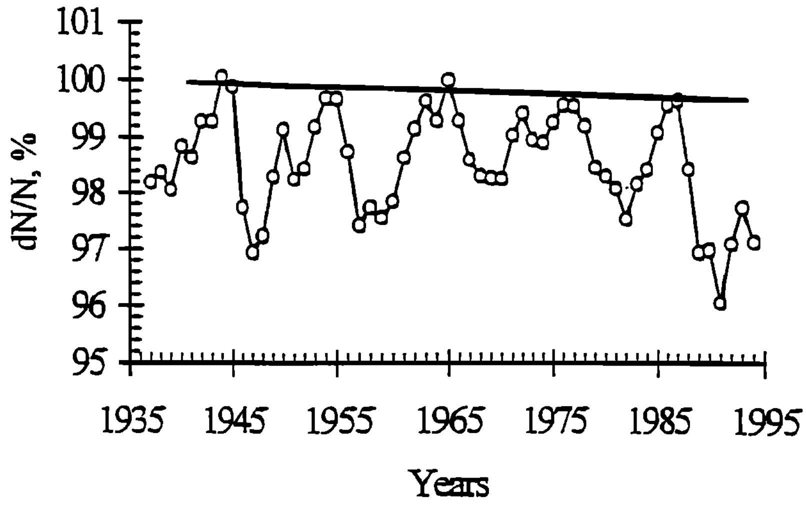

Figure 5. The changes in the ionization chamber count rate (yearly averages) relative to 1965 taken as 100% versus time (adopted from *Ahluwalia* [1997]). The straight line calculated for periods of maximum values of cosmic ray fluxes (maximum values of dN/N) gives the negative trend δ=–(0.010±0.003)%/yr.

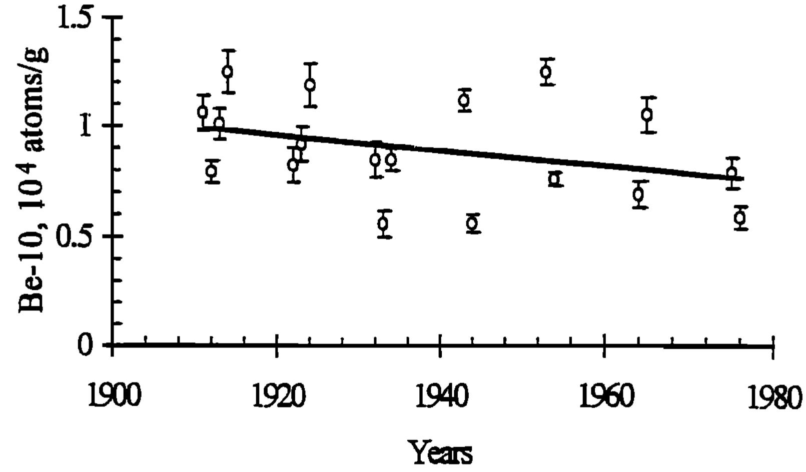

Figure 6. The concentrations of ^{10}Be in ice cores (yearly averages) in successive minima of solar activity from the beginning of this century till 1978 (the data were taken from *Blinov* [1997]). The negative trend is shown by the straight line and its value equals $\delta=-(0.05\pm0.01)\%/\mathrm{yr}$. The vertical bars show the standard errors.

task of any long-term experiment. In our case the value of negative trend in cosmic rays is very small and this effect could be associated with the efficiency drift of scientific instruments. For stratospheric measurements, special methods of detector efficiency control are used. There is special equipment for calibration of detectors. The precautions have been taken to keep relative accuracy of the data over the 40-year measurement period. The calibration of each detector has been made using special installation, and cosmic ray count rate of the detector is compared with that of the reference detectors. There are several groups of reference detectors (counters) constructed in the 60th, 70th, 80th and 90th years. The count rate of natural background particles of these reference counters is periodically compared within these groups. Correction factor is deduced from the ratio of the detector count rate to the reference detectors count rate. We estimate the accuracy of the monthly averaged stratospheric measurements to be better than 1%. The control of the efficiency of neutron monitors is provided by the comparison of count rates of the neutron monitor different sections with each other. The fact that a very small value of cosmic ray flux decrease is observed by the instruments of different types gives the confidence that this effect is not an artificial one.

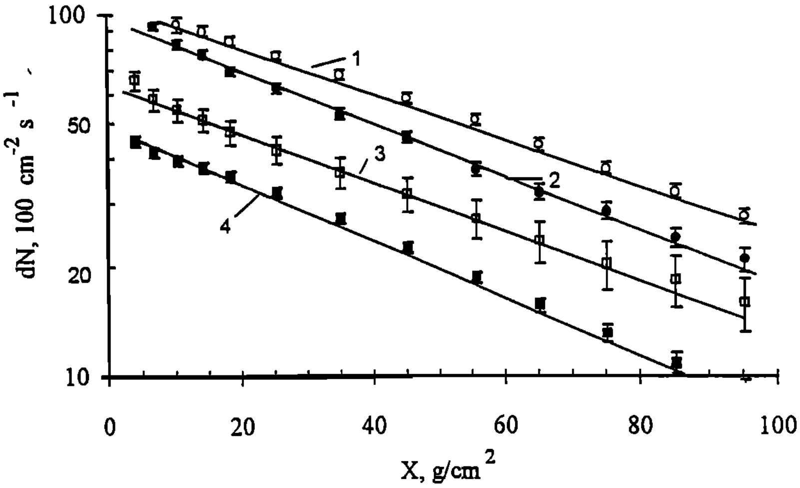

Figure 7. The charged particle fluxes in the atmosphere *dN(x)* averaged per year produced by primaries with energies E=0.1-1.5 GeV versus atmospheric pressure x in the four successive solar activity minima: 1965, 1977, 1987, and 1997. The absorption law of *dN(x)* has the form $dN(x)=dN(0)\times exp\ (-x/L)$ where *dN(0)* is the flux of primaries on the top of the atmosphere and L is the absorption length of omnidirectional charged particle flux. The vertical bars show standard deviations. Line 1, 1965 (negative phase): L=(69.1±1.7) g/cm^2; line 2, 1977 (positive phase): L=(58.2±1.4) g/cm^2; line 3, 1987 (negative phase): L=(67.3±5.8) g/cm^2; line 4, 1997 (positive phase): L= (58.0±1.6) g/cm^2.

From 1965 to 1997 the decrease of absorption length L is observed. The difference between L obtained in positive and negative phases of 22-year solar magnetic cycle is observed also.

To avoid superposition of data the values of *dN(x)* of each minimum were multiplied by constants.

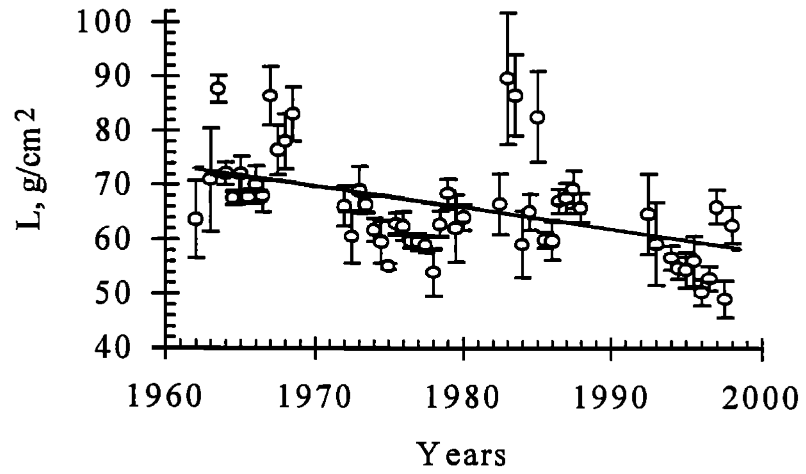

Figure 8. The time dependence of *L* calculated from the absorption curves of the half-year averages of *dN(x)*. The straight line shows the gradual decrease of *L*. The vertical bars give the values of standard errors.

There are several natural causes which could produce this trend. One of them is solar activity increase for the period under consideration. Table 2 lists the long-term changes in some solar activity indices, parameters of interplanetary space, and some indices of the Earth's magnetic field for the solar activity minimum periods of 1964-1966, 1975-1978, 1986-1987, and 1995-1997 (Solar Geophysical Data, 1964-1998). The monthly averaged values were taken for consideration. The calculations of δ were made with the same method that was used for negative trend calculations in cosmic rays.

From Table 2 it follows that the increases in solar activity level, interplanetary space parameters, or the Earth's magnetic field disturbances are not observed in solar activity minima periods from 1964 to 1997. There is also no positive trend in the number of sunspots during the periods of solar activity minima from 1900 to 1997: $\delta(R_z)=-(0.001\pm0.002)$%/yr. Thus the Sun or interplanetary space or the Earth's magnetosphere are unlikely to be responsible for the long-term negative trend observed in cosmic rays. It is quite possible that there is some "hidden" and unknown variability of our Sun or interplanetary space which could influence cosmic ray flux and be the reason for the long-term negative trend. In this case the conclusion that our Sun becomes more active with the passage of time could be very important for solar-terrestrial physics. Recently, *Lockwood et al.* [1999] found that during the past 100 years the solar coronal magnetic flux leaving the Sun was increased by a factor 2.3. The interplanetary magnetic field strength data and *aa* index data were used to calculate yearly total solar source magnetic fluxes. If this effect takes place in solar activity minimum periods (when monthly values of *aa* index and interplanetary magnetic field strength are used), it could be the cause of the observed negative trend in cosmic ray flux.

Table 2. Indices of Solar Activity, Interplanetary Space, and Magnetic Field of the Earth in Solar Activity Minimum Periods

Characteristics	Solar Activity Minimum Periods				δ, %/yr
	1964-1966	1975-1978	1986-1987	1995-1997	
R_z	5.7±1.9 (8.1964)	6.7±1.2 (1.1976)	6.5±2.3 (1.1987)	5.6±4.4 (9.1996)	-0.04±1.65
λ=10.7 cm, 10^{-22} W/(m^2 Hz)	70.3±0.7 (6.1964)	71.0±1.0 (1.1976)	70.1±0.2 (1.1987)	69.9±0.1 (3.1996)	-0.01±0.04
Magnetic field of the Sun as a star, nT		8.0±0.6 (12.1976)	7.0±0.5 (5.1986)	6.6±0.2 (6.1996)	-0.80±0.35
Interplanetary magnetic field, nT	4.8±0.3 (11.1965)	5.0±0.2 (7.1976)	5.3±0.2 (7.1986)	4.8±0.1 (8.1996)	+0.02±0.18
Solar wind velocity, km/s	381±16 (2.1964)	388±8 (5.1978)	365±13 (11.1987)	366±3 (6.1997)	-0.15±0.10
Ap index	6.0±0.6 (12.1964)	9.3±0.3 (7.1976)	7.3±0.3 (5.1987)	6.3±0.6 (6.1996)	-0.07±0.27
aa index	12.5±1.1 (4.1965)	17.9±0.3 (7.1976)	13.6±0.6 (5.1987)	13.2±0.5 (7.1997)	-0.00±0.18

Trends of these values δ are defined relative to January 1965 taken as 100%. The periods with minimum values of indices (after 3-monthly smoothing) are given in parentheses.

The decrease of cosmic ray particles in the nearby interstellar space (the decrease of the flux on the modulation region boundary) might be the cause of the negative trend observed in cosmic ray flux. If the explosion of supernova had occurred ~(10^4-10^5) years ago not so far from the solar system (at the distance less than several hundreds of parsecs) the decrease could take place. Such a case was discussed by *Amosov et al.* [1991], *Johnson* [1993], and *Sonett et al.* [1997]. This explosion could be responsible for a large part of the cosmic rays observed in the solar system at the present time [*Johnson*, 1993]. The contributions of other distant sources to the present cosmic ray flux are not considered in our calculations below.

Two scenarios are possible for cosmic ray propagation from the supernova explosion.

The first one assumes the cosmic rays to be produced by a point-like source during a short time. The accelerated particles propagate in the interstellar space by the convection-diffusion process. If the maximum of diffusion wave of charged particle flux moved away from the solar system then a decrease of the particle flux should have to be observed, and the spectrum of particles should have to be softened. The solution of the spherical symmetric diffusion equation with convection of particles is the following:

$$n(r,t) = \frac{N}{(2\pi Dt)^{3/2}} \times \exp\left[-\frac{(r-ut)^2}{4Dt}\right], \qquad (2)$$

where n is the charged particle concentration, N is the number of particle accelerated in the supernova explosion, t is the time elapsed after supernova explosion, r is the distance to supernova, u is the average shock wave velocity, D is the diffusion coefficient [*Dorman and Miroshnichenko*, 1964]. From expression (2) the value of the trend is easily defined:

$$\delta = \frac{1}{n}\frac{dn}{dt} = -\frac{3}{2} \times \frac{1}{t} + \frac{r^2 - (ut)^2}{4Dt^2}, \qquad (3)$$

Let us consider two cases when the value of trend equals δ=−0.01%/yr and δ=−0.07%/yr. In our case the energy of detected primaries is 1-10 GeV and we can take $D=10^{27}$ cm^2/s and $u=3\times10^3$ km/s [*Berezhko and Krymsky*, 1988]. Then the following values of t and r are obtained (see Table 3). Thus the values of r and t may be found to explain the negative trend in cosmic rays via the supernova explosion in the nearby interstellar space.

In the energy range of primaries $E=10^{11}$-10^{14} eV a sidereal anisotropy was measured by several instruments [see, e.g., *Munakata et al.*, 1997]. Its experimental value is ~$(1\text{-}8)\times10^{-4}$.

Table 3. The Time and the Distance of the Possible Supernova Explosion if $D=10^{27}$ cm^2/s and $u=3\times10^3$ km/s

	δ=−0.01%/yr		δ=−0.07%/yr	
t, years	r, pc	A	r, pc	A
3×10^4	89	1.4×10^{-2}	27	4.3×10^{-3}
5×10^4	146	1.4×10^{-2}	36	3.5×10^{-3}
10^5	288	1.4×10^{-2}	57	2.8×10^{-3}
3×10^5	856	1.4×10^{-2}	131	2.1×10^{-3}

A is the value of sidereal anisotropy

For the spherical symmetric model of the supernova explosion discussed above one can obtain the value of sidereal anisotropy A as the ratio of the diffusion flux of particles $F_d=-D\times dn/dr$ to the isotropic flux of particles $F_i=nc/3$:

$$A = \frac{3D}{c} \times \frac{1}{n} \times \frac{dn}{dr} = \frac{3r}{2ct}, \qquad (4)$$

where c is the particle velocity [*Hayakava*, 1969; *Johnson*, 1993; *Moraal*, 1996]. Here we take into account that there are two stages of shock wave propagation. During the first stage of free propagation the shock wave has a high velocity, $u=(1\text{-}2)\times10^4$ km/s. The second stage corresponds to adiabatic propagation of the shock wave with subsonic velocity [*Berezhko and Krymsky*, 1988; *Amosov et al.*, 1991]. We suggested the convection process to be small at the second stage in comparison with that of the diffusion, and anisotropy A was defined with u=0. Table 3 shows the calculated values of A for relativistic particles and for values of r and t taken from this Table.

Thus one can find some sets of parameters (time and distance of explosion, diffusion coefficient, and average speed of shock wave) to describe satisfactorily the value of negative trend and sidereal anisotropy (see two bottom rows in each section of Table 3). It is noteworthy that the value of negative trend could be lower as the observed cosmic ray flux includes some part of particles from other distant sources.

There is an alternative scenario of cosmic ray production after supernova explosion. The nearby supernova explosion gives rise to a shock wave. The shock wave accelerates particles efficiently during the blast phase of ~10^3 years from the moment of the explosion. Weaker acceleration is also possible during the adiabatic phase [*Berezhko and Krymsky*, 1988; *Amosov et al.*, 1991; *Johnson*, 1993; *Erlykin et al.*, 1998]. In this model the contribution of distant sources is taken into account. The calculations performed by *Tzarev and Chechin* [1999] in the framework of such a model give satisfactory agreement with the experimental data.

4. Discussion

The experimental data on the long-term negative trend in cosmic rays presented above could be explained if the supernova explosion had taken place at the distance 30-150 pc from the solar system about 10^4-5×10^5 years ago. *Shklovsky* [1966], *Amosov et al.* [1991], *Bignami et al.* [1993], *Gehrels and Chen* [1993], and *Walter et al.* [1996] considered the problem of existing celestial objects near the solar system which could be remnants of supernova explosions. The possible candidates are given in Table 4.

Table 4. The Celestial Objects (Supernova Explosion Remnants (SNR)) Near the Solar System

SNR	r, pc	t, years	References
Vela	500	$(2\text{-}3)\times10^4$	*Nishimura et al.* [1997]
Monogem	300	8.6×10^4	*Nishimura et al.* [1997]
Loop 1	170	2.0×10^5	*Nishimura et al.* [1997]
Geminga	<100	3.4×10^5	*Bignami et al.* [1993], *Gehrels and Chen* [1993]
Neutron star	<100	-	*Walter et al.* [1996]
Spur	≤30	5.0×10^4	*Shklovsky* [1966]

The comparison of r and t given in Tables 3 and 4 shows that Spur, Geminga, or Loop 1 could be sources of cosmic rays observed in the solar system. Earlier, *Johnson* [1993] and *Sonett et al.* [1997] came to the same conclusion on Geminga when they analyzed the data on the ^{10}Be concentrations and the sidereal anisotropy of cosmic rays with $E=10^{11}$-10^{14} eV.

The analysis of cosmogenic isotope ^{14}C concentrations in tree rings and ^{10}Be concentrations in ice cores also demonstrates the possibility of supernova explosion in the vicinity of the solar system [*Raisbeck et al.*, 1987; *Siegenhalter and Beer*, 1988; *Amosov et al.*, 1991; *Kocharov*, 1996].

The suggestion of a possible supernova explosion near the solar system may be verified experimentally. It is known that high-energy electrons lose energy due to inverse Compton effect on the relict photons and synchrotron radiation in galactic space. The time during which an electron loses half of its energy E equals $t=(1.5\times10^5)/E$ where t is given in years and E is in TeV [*Nishimura et al.*, 1997]. Thus far only several electron-like events in the TeV energy range were detected [*Nishimura et al.*, 1997]. From the relationship between t and E one can find the distance where the source of these electrons could be located: $r^2=4Dt$. For electrons with $E=5$ TeV, $t=3.5\times10^5$ years, and $D=5\times10^{28}$ cm^2/s, the source is at $r=418$ pc. Hence only a nearby source, located at a distance less than several hundred parsecs from our solar system, could contribute to the high-energy electron flux. The detection of electrons with energy more than several TeV could confirm the supernova explosion near the solar system.

Erlykin et al. [1998} also came to the conclusion on the nearby supernova explosion on a bases of the analysis of the "knee" peculiarities in the cosmic ray spectrum at $E=3\times10^{15}$ eV. *Grigorov* [1990] reported the softening of the proton spectrum in TeV energy range (increase of the proton energy spectrum exponent from $\gamma=2.65$ for protons with $E\leq1$ TeV to $\gamma=3.1$ for protons with $E>1$ TeV). This experimental fact [see *Watson*, 1997], provided it is true, may also be attributed to the existence of a cosmic ray source in nearby interstellar space.

5. Conclusion

1. The data of cosmic ray fluxes obtained in the atmosphere with radiosondes (1957-the present time) and at ground level with ionization chambers (1937-1992) and with neutron monitors (1953-the present time) were analyzed. The analysis included the comparision of cosmic ray fluxes in successive solar activity minimum periods. The data obtained with the detectors of different types show the negative trend of cosmic ray fluxes, $\delta\approx-(0.01\text{-}0.09)$%/yr. The data on ^{10}Be and ^{14}C concentrations confirm the long-term negative trend existence.
2. From the beginning of stratospheric measurements up to now the softening of the primary cosmic ray spectrum in the energy range $E=0.1$-1.5 GeV (or the increase of nuclear component in the total flux of primaries in the same energy range) is found.
3. The negative trend is not observed in 3-monthly averaged solar activity and interplanetary space characteristics in solar activity minimum periods. With an increase of the solar activity the cosmic ray spectrum could be harder (not softer). However, some doubts on the absence of solar activity increase remain. For example, the increases of geomagnetic activity *aa* index and coronal solar magnetic flux calculated using this index are observed during the past 100 years [*Clilverd et al.*, 1998; *Lockwood et al.*, 1999].

Since the data from the detectors of different types contain the negative trend, then the effect is not due to instrumental reasons. The gradual growth of solar activity could cause the negative trend in cosmic ray fluxes, but during the period under consideration such growth was not observed in the widely used parameters of solar activity and interplanetary space. There may be some unknown and subtle solar activity characteristics which are enhanced in successive solar activity minima and increase the galactic cosmic ray modulation. If so, it could be very important for solar and solar-terrestrial physics.

To provide an explanation for the negative trend in cosmic rays, we suggest that the nearby supernova explosion has occurred at the distance 30-150 pc about 10^4-5×10^5 years ago. The distance and explosion time were evaluated in the scope of spherical symmetric model with a point-like source. In such a model the observed sidereal anisotropy of cosmic ray particles in the energy interval $E=10^{11}$-10^{14} eV may be also explained. There are several celestial objects in the nearby interstellar space which could be responsible for such an explosion. It is necessary to continue accurate observations of cosmic rays in the atmosphere and at ground level to finally confirm the results and suggestion given above.

Acknowledgments. We express our gratitude to our coworkers who took part in the performance of long-term cosmic ray flux measurements in the atmosphere. This work was supported by the Presidium of the Russian Academy of Sciences and in part by the Russian Foundation for Basic Research (grant 98-02-16420).

Janet G. Luhmann thanks James A. Van Allen and another referee for their assistance in evaluating this paper.

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(Received February 2, 1999; revised August 3, 1999;
accepted August 23, 1999.)