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Long-term variations of galactic cosmic rays in the past and future from observations of various solar activity characteristics

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Abstract

The previously proposed model of cosmic-ray (CR) modulation in the heliosphere, which considers the relationship between long-term CR variations and parameters of the solar magnetic field, has been used to estimate the observed CR variations in the near-Earth space with accuracy allowing their prediction. It is shown that there are two possibilities: (1) to predict CR intensity for 1–6 months by using the delay of CR variations relative to the solar-activity (SA) effects and (2) to predict CR intensity for the next solar cycle. In the second case, prediction of the global solar magnetic field characteristics is crucial. Reliable long-term CR and SA data are necessary in both cases. CR variations for the next solar cycle are predicted by statistical method using solar magnetic field data from two magnetographs (Stanford and Kitt Peak). The CR behavior during centuries 17–20 has been reconstructed on the basis of a model relating CR modulation to solar and geomagnetic activity indices.

Keywords: Solar magnetic field; Solar cycle; Long-term variation of cosmic rays

1. Introduction

The study of heliospheric conditions and solar–terrestrial coupling with a view to space-weather forecast is based on understanding and prediction of time variations of cosmic-ray (CR) fluxes as an important element of space environment. The objective of this paper is to predict variations of CR fluxes for months and years ahead and reconstruct their behavior in the past on the basis of information available on the relationship between the modulation of galactic CR and parameters of the solar and geomagnetic activity. Such a problem can be stated and solved thanks to continuous monitoring of CR at a network of stations that have been operated for over half a century as a single omnidirectional, high-precision device. Both prognosis and epignosis of CR variations discussed below have been made using the multi-parametric model of CR modulation developed in our previous work (e.g., see (Belov et al., 2001a, b, 2002, 2003) and references therein). As shown in these papers, an adequate model description of CR variations can be obtained using the structural and quantitative characteristics of the solar global magnetic field, such as the tilt of the heliospheric current sheet α, the calculated mean intensity of the source-surface magnetic field B_{SS},

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and the polarity p of the the global solar magnetic field. By the polarity of the large-scale solar magnetic field p, we mean henceforth the polarity of its dipole component at the north pole of the Sun. In our model, p assumes the values ± 1 for the positive and negative polarity, respectively, and 0 for the reversal periods. The time limits of these periods are indicated in Belov et al. (2002). A model with just these parameters has been used to predict CR flux for the term from a month to a year and for the next activity cycle.

Unfortunately, CR data are unavailable for the distant past, as well as most of the present-day solar and geophysical data. We can only rely on the sunspot numbers known since 1749 (or sunspot group numbers since 1610) and the aa-index of geomagnetic activity and magnetic storm sudden commencements N_{SSC} recorded since 1868. However, even such a limited number of the solar activity indices allows us to reconstruct CR variations in the past. Another possibility is to use the measured densities of space-generated species (first of all, ^{10}Be), but these indirect data need independent corroboration.

2. Data and method of CR variation forecast for 1–12 months

The CR modulation depth observed at the Earth is a result of the combined action of solar and heliospheric conditions that control the CR behavior all over the heliomagnetosphere. The delay of the CR effects relative to processes in the Sun (hysteresis of CR) has been known since long ago (e.g., see (Simpson, 1963; Dorman and Dorman, 1967). Some new interesting studies of this phenomenon have appeared in the recent years (McCracken and McDonald, 2001; Usoskin et al., 2001). The delay of CR variations reflects complicated individual features of the activity cycles and is related to the solar magnetic cycle. We suggest using this particularity of CR variations to predict the CR flux in the near-Earth space.

In our recent work, we have tested the CR modulation models by density variations of 10-GV CR recorded at the ground-based network of stations. We are sure that the CR differential density is more convenient for modulation studies than the data from individual detectors. However, we are bound to use the latter for CR prediction until reliable real-time energy spectra of CR variations are available. The Moscow CR station meets the forecast demands fairly well. Its neutron monitor has been continuously recording particles with the effective energy of 10 GV since 1958. The obtained data are available in real-time through Internet http://cr0.izmiran.rssi.ru/mosc/main.htm.

The modulation model we are dealing with in this work is a modification of the model described by Belov et al. (2001a, b, 2002). They provided a semi-empirical model description of the long-term CR modulation based on many years of helio- and cosmo-physical observations. The strength and polarity of the global solar magnetic field, the magnetic field of the Sun as a star, the tilt α, the intensity of the interplanetary magnetic field, and solar wind velocity were used as modulating parameters. The one-, two-, and multi-parameter regression analyses were performed for the solar and heliospheric parameters under discussion (and their combinations) and the amplitude of long-term variations of the 10 GV galactic CR. It is taken into account that variations observed at the Earth are controlled by the solar-wind disturbances that occur on the way from the Sun to the heliosphere boundary and, thus, they involve the effects of past solar activity. This accounts for the delay of CR relative to SA variations.

In this paper, a model of long-term modulation of CR has been constructed using a set of parameters of the global solar magnetic field. The choice of the parameters is explained in detail by Belov et al. (2002). Calculations were performed using the multi-parameter regression analysis, which allowed us to estimate the contribution of each parameter of the global solar magnetic field to the expected CR modulation taking into account their own maximum delay times τ_d. Such combination of the solar and heliospheric parameters proved to be good enough to enable an adequate description of CR variations over a few successive solar-activity cycles.

The method for determining the solar magnetic field parameters was developed by Hoeksema and Sherrer (1986) and was updated by Obridko and Shelting (1999) with the use of magnetic and optical observations. The time limits of the reversal of the global solar magnetic field polarity were obtained from various photospheric and source-surface observations. It should be noted that the model takes into account both the direct effect of the global magnetic field polarity on CR and its effect on CR modulation due to variations in the tilt α. It is shown that the behavior of CR correlates better with p variations at the source surface than in the photosphere. We have used CR data themselves to refine the obtained reversal limits assuming the CR modulation depth to be an index of solar activity that reflects its various manifestations most comprehensively.

Here, unlike our previous work, we have tried to calculate variations for a few months ahead (from 1 to 12 months). In the process, we have determined the integral indices of solar activity just omitting the data for the last months. Since the polarity forecast does not mainly involve any problem, the field polarity was determined using the full data set. Fig. 1 illustrates variations of the correlation coefficient ρ and standard r.m.s. deviation σ as a function of time (months) for three different time intervals.

The entire interval under consideration is 1977–2003. It comprises periods of different direction of the global solar magnetic field and the moments of the field reversal. The interval from 1981 to 1989 is the period of negative field polarity (qA < 0) and 1991–2000 is the period when the field polarity in the Sun was positive (qA > 0). The results obtained show that, during 1977–2003, the correlation between the long-term CR variations predicted for 1–12 months and the chosen SA parameters is fairly good for all three periods (ρ changes from 0.80 to 0.94 and σ, from 1.86% to 3.25%). This fact indicates the adequacy of the modulation model applied. Besides, one can clearly see that the results still improve (ρ grows, and σ decreases), if we consider shorter intervals with equal polarity of the global solar magnetic field. The best agreement between the observed and expected variations is obtained in the periods of positive polarity, which seems to testify, first of all, to a closer relationship between the CR modulation and the tilt α in those periods (Krymsky et al., 2001).

Fig. 2 illustrates long-term CR variations both recorded at the Moscow station and predicted for 1 and 12 months ahead. The month's forecast displays quite a high correlation with observations ($\rho = 0.94$), with $\tau_{d1} = 11$ months for the current-sheet tilt variations and $\tau_{d2} = 8$ months for the solar magnetic field intensity. The forecast for 12 months gives $\rho = 0.78$. Such correlation, though being much lower than in the first case, might be considered satisfactory. However, the analysis shows that, in this case, the contribution of the magnetic field intensity becomes negligibly small and $\tau_{d1} = 0$, i.e. the expected CR variations are determined solely by α during the last month available. The magnetic-field contribution becomes insignificant even in the 6–7 months' forecast. For 6–7 months, the solar wind can propagate to 30–40 a.u., which is significantly smaller than the full size of the heliosphere. This implies that, within the frames of our model, the magnetic fields in the inner heliosphere are much more important to CR modulation than the remote ones. The tilt α seems to have a large-scale effect. We must admit that the model applied herein meets difficulties when forecasting for half a year or more. And there is nothing to be surprised at. The forecast of the kind discussed above (it may be called orthodox) is only based on the solar parameters measured by the moment of issuing the forecast. Thus, the longer the term of the forecast, the larger the fraction of the inner heliosphere excluded from consideration. It is

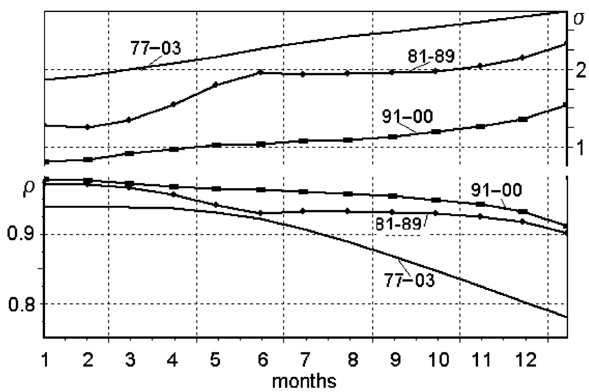

Fig. 1. Correlation coefficient ρ and r.m.s. deviation σ (%) for three time intervals: 1977–2003 (solid line), 1981–1989 (circles), and 1991–2000 (rectangles) as a function of time of the forecast (months).

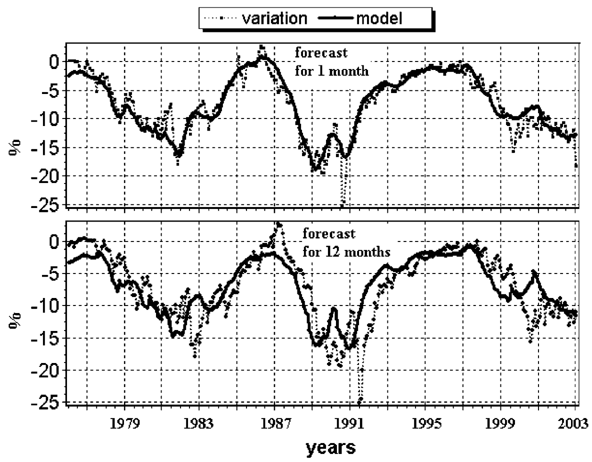

Fig. 2. Long-term CR variations observed with the Moscow neutron monitor (points) and predicted for 1 and 12 months ahead (solid curves).

clear that neglecting the effect of a significant fraction of the heliosphere on CR one can hardly expect to obtain ideal results. Of course, the orthodox forecast can be improved. More promising seems the approach that involves prediction of the main parameters of the solar magnetic field. Then, the forecast of CR variations would be based both on the measured solar indices and on their expected future behavior. Among such widely predictable indices, there are sunspot numbers available through Internet. Unfortunately, substituting sunspot numbers for the magnetic field intensity B_{SS} in our model deteriorates it significantly. We have arrived at the necessity of predicting the parameters of the solar global field, and we believe that even a rough estimate of the expected tilt of the current sheet and global magnetic field intensity would improve the CR variation forecast significantly.

3. Data and method of forecasting CR variation for the following cycle

The long-term forecast of CR variations is based on a long series of observational data on CR fluxes and parameters of the solar global magnetic field. Density variations of the 10 GV CR are used as a test series in simulating the long-term modulation. The global field characteristics we are dealing with are α, B_{SS}, and p. All these parameters are calculated at the solar wind source surface.

We have used here the Stanford data on the large-scale photospheric magnetic field for the period from 1976 to 2003 obtained with a relatively low resolution ($3'$) (Wilcox Solar Observatory). Re-calibration of the Stanford magnetometer raised doubts as to the uniformity of its measurements, and they were supplemented with Kitt Peak observations ($1''$ resolution) for 1975–2003 (National Solar Observatory Kitt Peak, 2003). A comparative analysis of the magnetic field data from both observatories shows a significant difference between them. The discrepancy was also revealed in (Obridko and Shelting, 2003) where the Stanford and Kitt Peak magnetic data were studied using the correlation and Fourier analyses. Owing to this discrepancy, it is difficult to choose either data series for calculating B_{SS}; therefore we have used both. Perhaps, the difference in the data is due to the fact that the observatories measure fields of different spatial scales. The low-resolution ($3'$) magnetograph at Stanford is recording mainly the large-scale magnetic field of the Sun, while the higher resolution Kitt Peak magnetograph ($1''$) provides records of strong local magnetic fields. The difference in CR modulation at opposite polarity of the global magnetic field, revealed by the model description, may be due to the changing effect of cyclic variations of the local and large-scale fields recorded at both observatories on long-term CR variations. Besides, it may be important that, at these observatories, the magnetic field is measured with different recorders using different spectral lines.

The tilt α used in the proposed CR modulation model was obtained from the Stanford data for 1976–2003. Polarity variations of the global magnetic field were derived from different photospheric observations and calculations made at the solar-wind source surface. The expected CR variations were determined by the multi-parameter regression analysis. This analysis allows us to estimate the contribution of long-term variations of each global-field parameter to CR modulation taking into account their corresponding maximum delay τ. The contribution of the field intensity to the calculated total modulation proves to be twice as large for the Stanford data as for the Kitt Peak ones. Using Stanford data for modulation forecast involves the effect of the field intensity B_{SS} in the remote regions of the solar magnetosphere. So, in this case, the long-term modulation of CR is not only determined by the tilt α, but also depends significantly on the field intensity B_{SS}.

The prediction method suggested above is based on the solar parameters measured by the time of issue of the forecast. Therefore, it does not allow the CR behavior to be estimated for a period longer than 6–7 months. Here, we consider another method based on a preliminary forecast of the main characteristics of the solar global magnetic field. The magnetic field parameters (α and B_{SS}) were predicted on the basis of Stanford (B_{SS}-ST) and Kitt Peak (B_{SS}-KP) observations. The forecast of the polarity p is mostly simple. It is known that the polarity will be negative within the nearest years (until the maximum of the next cycle). In our model, the sign reversal is expected at the beginning of 2012.

4. Results and discussion

At present, the solar-activity indices are predicted by different methods based on the analysis of the behavior of total sunspot areas, 2800 MHz radio flux density, various geomagnetic indices, and other solar and interplanetary parameters. In this work, we have applied a statistical approach to predict the parameters of the solar global magnetic field. We believe that, in spite of its statistical nature, the forecast of CR variations made with allowance for the expected cyclic variations in the structural (α) and quantitative (B_{SS}) characteristics of the solar magnetism is physically well grounded.

The data series were analyzed and the expected α and B_{SS} values were determined following the procedure described in http://www.statsoft.com/textbook/sttimser.html. The data have been analyzed under the assumption that the successive values in a time series are measurements taken at equal intervals. The auto-regression integrated moving average (ARIMA) method allows us to simulate a time series of data with their trend and seasonal variations taken into account and to issue a forecast.

The CR behavior predicted up to 2011 shows that the next CR minimum is to take place at the end of 2006 or beginning of 2007, according to Kitt Peak observations, and in the middle of 2006, according to Stanford data (Fig. 3). Here, we are dealing with the CR variation forecast based on Stanford data, since these data have been used to estimate B_{SS} and α. In our future work, we are going to determine α from Kitt Peak data and to carry out a comparative analysis of the forecast obtained. The ARIMA method applied is rather complicated technically. The result depends on the length and quality of the data series under examination and is not fully deprived of subjectivism. We suggest that global magnetic-field data should not only be used for the study of solar activity, but also for the space weather forecast. An important element of the latter—the forecast of CR fluxes—allows us to proceed to predicting variations in the Earth's climate.

The behavior of CR in the past is described on the basis of the same modulation model that is used for the CR forecast. The only difference is the choice of the solar-activity parameters. In the long-term retrospective analysis, the mean field value B_{SS} has to be substituted by the Wolf numbers W and for the period before 1749, by the sunspot group numbers. However, this is insufficient, because no comprehensible and reliable model of CR modulation can be conceived without taking into account the solar magnetic field polarity and the tilt of the heliospheric current sheet. One can easily reconstruct the polarity p, since the periods of the field reversal are closely related to the sunspot maxima. As for the tilt α, its most probable values for each phase of the solar cycle from 1976 have been determined by the method of superposition of epochs. The parameters of the regression relationship between CR variations and those of W, α, and p were calculated for the period of 1976–2003, for which direct observations of the corresponding solar characteristics are available. Using the obtained regression parameters, sunspot numbers, and regularities in the behavior of SA indices over 11- and 22-year cycles, we have reconstructed the history of CR variations for each month beginning with 1610 (top part of Fig. 4). For the later period (since 1868), we have used another model, in which the parameters listed above are supplemented by the

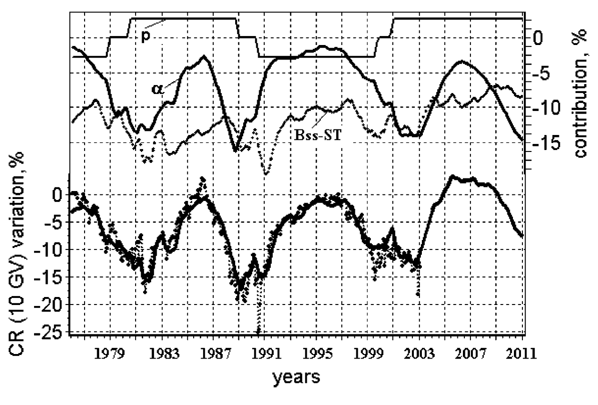

Fig. 3. Observed and calculated monthly mean CR variations for 1976–2011 (bottom) and contributions of B_{SS}-ST (Stanford data), α, and p to the calculated variation (top). Forecast is made for the period from 2004 to 2011.

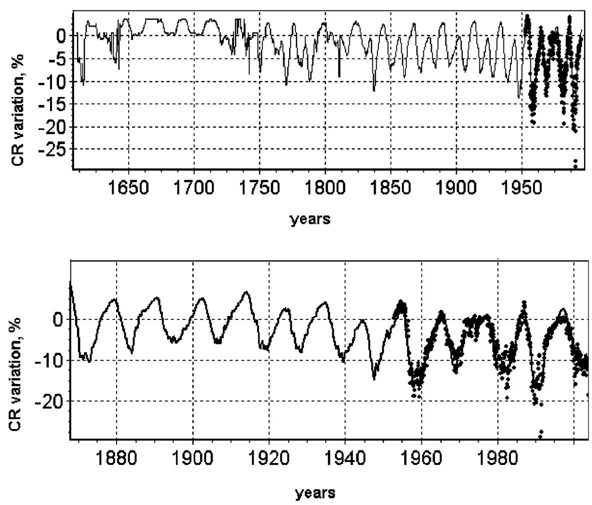

Fig. 4. CR variations since 1610 reconstructed by modulation model (Belov et al., 2001a, b) using the sunspot group data (top part) and variations since 1868 reconstructed from sunspot numbers and aa-index data (bottom part).

aa-index of geomagnetic activity (bottom part of Fig. 4). Note that the weakest CR modulation was observed from the second half of the 19th to the first third of the 20th century. The following period beginning with cycle 18 was the epoch of the greatest CR modulation for the last four centuries.

5. Summary

The proposed multi-parameter model of CR modulation in the heliosphere makes it possible to estimate the observed CR variations with a high accuracy and to proceed to their forecast. We have developed a method of forecasting CR fluxes at the Earth for the period from 1 to 12 months. The method is based on the global magnetic field characteristics calculated at the source surface using observation data from an isolated CR station available in real-time. CR fluxes have been predicted for the following months and the quality of such forecast has been estimated.

A basic item in the long-term forecast of CR variations is the forecast of the solar magnetic field parameters. The CR behavior predicted by statistical method up to 2011 shows that the next CR minimum is to take place at the end of 2006 or beginning of 2007, according to Kitt Peak observations, and in the middle of 2006, according to Stanford data. The forecast is made taking into account the data from both observatories because of the differences in their long-term magnetic-field measurements. The behavior of CR in the past reconstructed from variations of the sunspot numbers and indices of geomagnetic activity shows that the CR modulation during the last five solar cycles was much stronger than in the previous 300 years.

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