"Physics of Auroral Phenomena", Proc. XXVIII Annual Seminar, Apatity, pp. 115-118 , 2005

Polar Geophysical Institute

SOLAR ACTIVITY AND COSMIC RAYS IN 1973–2003

I.V. Getselev, T.A. Ivanova, V.P. Okhlopkov, M.V. Podzolko (*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*)

Abstract. Solar activity parameters, solar and galactic proton fluxes measured by satellites, balloons and neutron monitors are compared. The peculiarities of their distribution in various cycles of solar activity are considered. Time series frequency spectra are calculated, with their main periodical components found. The variations of sunspot numbers, cosmic ray proton fluxes, fluences and spectra are presented and their possible causes are discussed. The approximation functions for the time series of data are found and the sunspot number and proton flux forecast for 2005 and 2006 is made by extrapolation. Sunspot number forecast made in this way is compared with that obtained by currently used traditional means. Their good consistence is mentioned.

Introduction

In order to consider the peculiarities of geophysical environment in various solar cycles, the data on sunspot numbers [1], cosmic ray proton flux measurements by balloons in Murmansk and onboard IMP-8 spacecraft [2], as well as by neutron monitor in Moscow [3] have been used. The principal method of processing is the frequency analysis of the data.

Data processing and frequency analysis

The original direct Fourier transform has been used for numerical evaluation of frequency spectra. Since we deal with a discrete realization of the processes, the Fourier transform can be constructed only for finite frequency band, and this band is determined by the value of the main period. In this case, numerical implementation of Fourier transform is equivalent to computation of Fourier series. Having calculated the cosine and sine components of Fourier series for *x(t)* realization, we can represent the frequency spectra as

$$A(f) = \frac{4}{N^2} \cdot \left\{ \left[\sum_{t=1}^{N} x(t) \cdot \cos(\omega k t) \right]^2 + \left[\sum_{t=1}^{N} x(t) \cdot \sin(\omega k t) \right]^2 \right\}^{0.5} \qquad (1)$$

Here $\omega = 2\pi/N$ is the main circular frequency, ωk are the harmonics, f is the linear frequency.
The calculated frequency spectra for geophysical environment time series are used in temporal variation analysis and forecast.

Temporal variations and solar activity forecast (sunspot numbers)

In order to solve the problem, the following algorithm has been used. For each time series we calculate the frequency spectra and find the lines of the spectra that exceed the 95% significance level. Using the amplitudes and phases for these lines, we calculate the sum of these main harmonics, which is used for time series approximation. The appropriateness of the obtained approximation function for the forecast is estimated by comparing with the original data and approximation fault analysis. These investigations have shown that for the 2005–2006 forecast, monthly averaged sunspot numbers over the period from 1973 to 2004 are the most appropriate.
In Figure 1 the results of frequency spectra calculations for the chosen dataset of sunspot numbers (*Rz*) are presented. Along the X-axis the frequency in 1/month is given, along the Y-axis – the spectra line amplitudes normalized to the maximum value. It follows from Figure 1 that three harmonics with the periods of 124, 65 and 40 months exceed the 95% significance level.
Calculated by the method described above, the parameters of these three harmonics are used for the approximation. The initial phase is counted out from April 1, 1973. The approximation obtained by summing the three sinusoids is

$$Y(t) = 66.92 \cdot \sin\big(2\pi(t + 63.96)/124\big) + 11.96 \cdot \sin\big(2\pi(t + 5.57)/64.7\big) + 7.95 \cdot \sin\big(2\pi(t + 16.35)/39.68\big) \qquad (2)$$

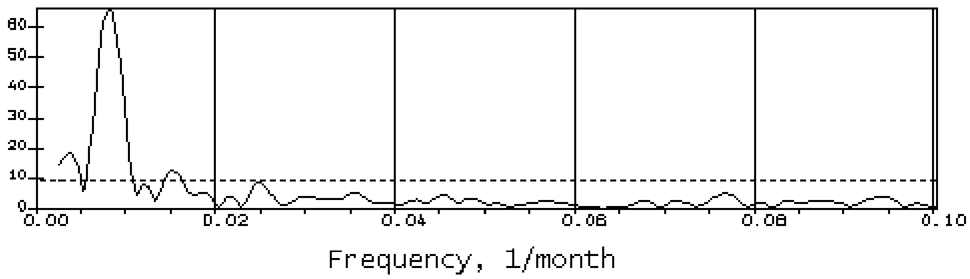

Figure 1. Frequency spectra of monthly averaged sunspot numbers from 1973 to 2004. The 95% significance level is shown with the dashed line.

In Figure 2 the approximation function calculated from equation (1) is shown along with the monthly averaged sunspot numbers derived from the observations in the period from 1973 to 2004.

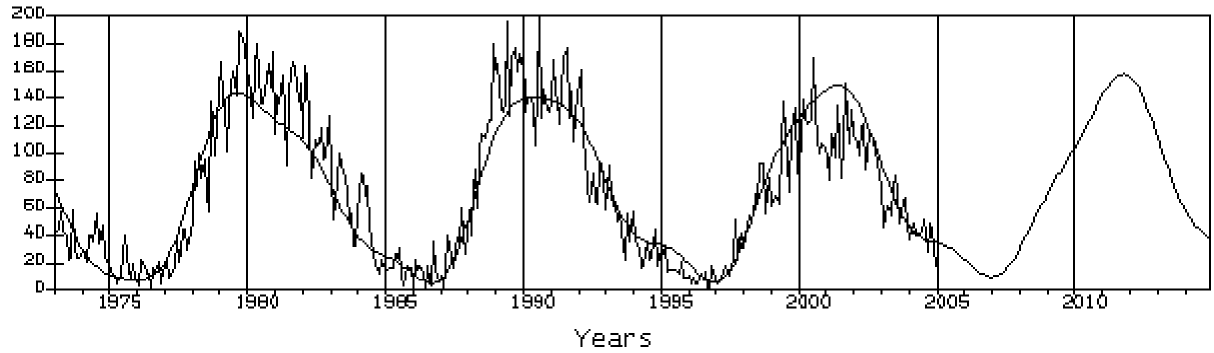

Figure 2. Monthly averaged sunspot numbers in the period from 1973 to 2004 and their approximation by the sum of the three harmonics.

A good consistence with the data (as follows from Figure 2) allows one to use the obtained function for the forecast of *Rz* for the next years. In Figure 2 the approximation function is extrapolated to the year of 2010 and further. A more accurate estimation predicts the mean monthly averaged value of Rz = 31.7±6.4 for the year of 2005 and Rz = 16.3±6.4 for 2006.

Cosmic ray proton flux variations and forecast

Cosmic ray proton flux behavior has been studied with using the frequency analysis of their time series by the method described above.

The main components of the frequency spectra have been calculated for the measurements performed with balloons (Murmansk), neutron monitor (Moscow) and IMP-8 spacecraft. As should be expected, the 11-year and 22-year variations have the highest amplitudes for all data sets considered. The amplitudes of shorter variations essentially depend on the proton energy. With using the selection filter, 2-year variations of the fluxes of protons with energies > 1, 2, 4, 10, 30 and 60 MeV have been found. The analysis shows that in various solar cycles the amplitudes for the same phases are quite different. While in 1973–1976 and 1994–2001 the amplitude decreases with proton energy increasing, in other periods it is nearly constant. The most stable quasi-2-year cycle manifests in galactic cosmic rays [4].

In Figure 3 the results of frequency spectra calculations for the fluxes of protons with energies > 30 MeV measured by IMP-8 are presented. Along the X-axis the frequency in 1/month is given, along the Y-axis - the normalized values of the harmonics amplitudes. The lower dashed line corresponds to 90% significance level, the upper one – to 95% level.

In Table 1 are presented the parameters of the main frequency spectral components of the protons with energies > 30 MeV which spectra lines exceed the significance levels. The sum of these harmonics is the approximation function for the corresponding time series.

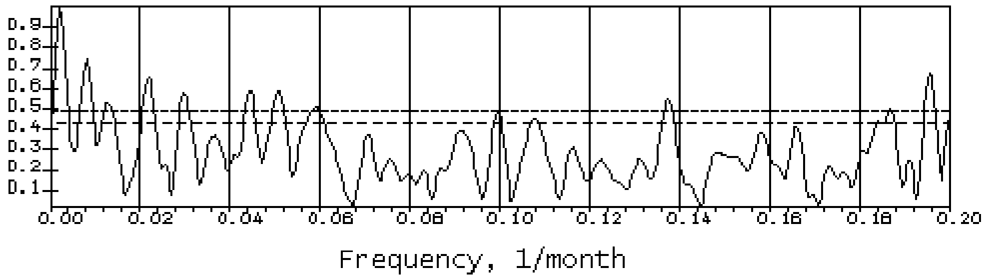

Figure 3. Frequency spectra of the fluxes of protons with energies > 30 MeV. The 90% and 95% significance levels are shown with the dashed lines.

Table 1. Main frequency spectral components for the protons with energies > 30 MeV.

Period, months	Amplitude, $cm^{-2}s^{-1}sr^{-1}$	Initial phase, months
124.0	0.132	73.0
79.5	0.093	44.1
45.6	0.116	35.9
33.7	0.102	8.3
27.4	0.065	1.5
22.5	0.105	9.1
19.7	0.104	2.7
17.0	0.090	5.7
14.2	0.066	10.0
10.9	0.069	10.0
10.1	0.086	3.0
9.3	0.079	5.0
8.6	0.055	6.4
7.3	0.097	3.8
5.3	0.088	3.2
5.1	0.120	3.5

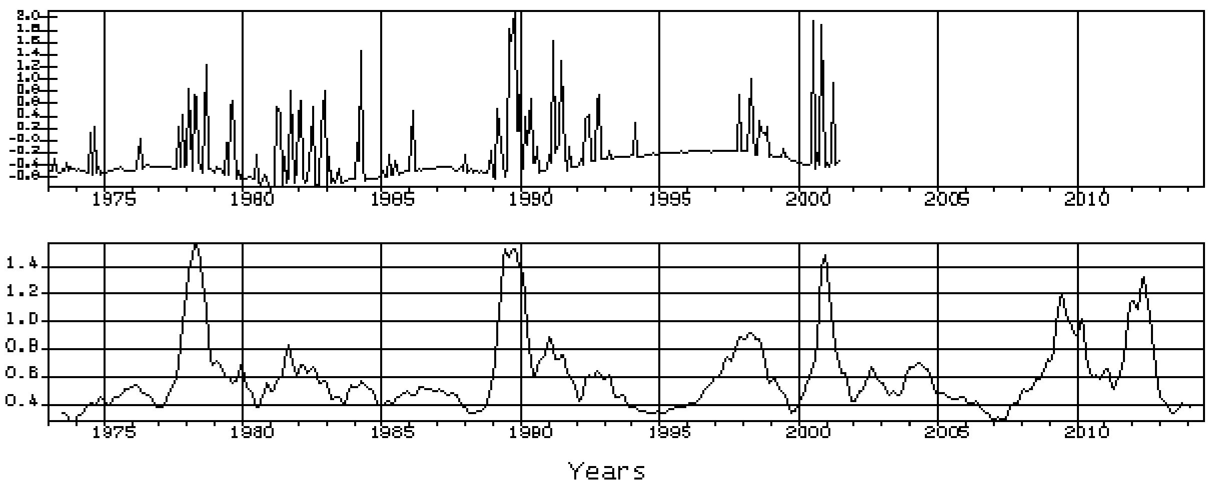

Figure 4. Top: Time series of monthly averaged fluxes of protons with energies > 30 MeV (the logarithms of the proton flux in $cm^{-2}s^{-1}sr^{-1}$). Bottom: their approximation function.

At the top of Figure 4, the time series of monthly averaged fluxes of protons with the energies > 30 MeV used as initial data is shown. At the bottom of Fig. 4, the approximation function obtained by summing the frequency spectra harmonics, which spectra lines exceed the 95% significance level (Table 1), is presented.
As follows from Figure 4, the approximation function describes the proton flux time series quite well, so it could be used for proton flux forecast for the nearest years. The approximation we have found suggests the mean annual flux of protons with the energies > 30 MeV to be 0.44±0.2 $cm^{-2}s^{-1}sr^{-1}$ for 2005 and 0.38±0.2 $cm^{-2}s^{-1}sr^{-1}$ for 2006.

References

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4. V. P. Okhlopkov, L. S. Okhlopkova., T. N. Charahthcyan, Two-year Solar Cosmic Ray Variations, Geomagn. and Aeronomy, 1979, 19, N3, p. 432–438.