

geofísica  
internacional

Geofísica Internacional

ISSN: 0016-7169

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México

Pérez Peraza, J.; Leyva Contreras, A.; Ya. Libin, I.; Ishkov, V.; Yudakhin, K.; Gulinsky, O.  
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Geofísica Internacional, vol. 37, núm. 2, april-june, 1998, pp. 87-93  
Universidad Nacional Autónoma de México  
Distrito Federal, México

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## Prediction of interplanetary shock waves using cosmic ray fluctuations

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Received: September 19, 1997; accepted: April 27, 1998.

### ABSTRACT

In the present paper the authors propose to use spectral autoregressive methods in order to improve the detection of variations in the spectral composition of the cosmic ray intensity and in the  $B_z$  component of the interplanetary magnetic field. By using this methodology, some regularities in the variation of the power spectra of the cosmic ray intensity are determined immediately before the arrival of a shock wave to Earth. So, the shock wave arrival is preceded by the appearance of a wave with period of 4 to 8 hours in the power spectra of the  $B_z$  component. The results confirm the possibility of the use of the cosmic rays and the geomagnetic activity as a tool for the diagnosis of the interplanetary environment and also for the prediction of the arrival of powerful shock waves to Earth, 1- 2 days in advance.

**KEY WORDS:** Shock waves, cosmic ray fluctuations, prediction.

### RESUMEN

En el trabajo se propone usar métodos espectrales y autorregresivos para mejorar los procesos de detección de variaciones en la composición espectral de la intensidad de rayos cósmicos y de la componente  $B_z$  del campo magnético interplanetario. Usando esta metodología, se determinaron algunas regularidades en la variación del espectro de potencias de la intensidad de los rayos cósmicos antes del arribo de una onda de choque a la Tierra. Así, el arribo de la onda de choque es precedido por la aparición de una onda con período de 4 a 8 horas en el espectro de potencias de la componente  $B_z$  del campo magnético. Los resultados confirman la posibilidad de usar los rayos cósmicos y la actividad geomagnética para el diagnóstico del medio interplanetario y la predicción del arribo de ondas de choque a la Tierra, con una anticipación de 1 a 2 días.

**PALABRAS CLAVE:** Ondas de choque, fluctuaciones de la radiación cósmica, predicción.

### INTRODUCTION

The observed intensity of cosmic rays fluctuates at frequencies  $f < 10^{-3}$  Hz ( $T > 20$  min). The origin of these fluctuations is the turbulence of the interplanetary magnetic field (Putskin, 1979; Dorman *et al.*, 1983; Dorman and Libin, 1984). Owens (1974a,b) shows that the power spectrum of fluctuations of the cosmic rays  $P_I(f)$  is related to the spectrum of the interplanetary magnetic field  $P_B(f)$  in the frequency region  $f > 10^{-5}$  Hz ( $T < 30$  hrs), for particles with energy greater than a few GeV, through the following relationship:

$$P_I(f)/(n_0)^2 = A(f)P_B(f) \delta_p / (B_0)^2 \quad (1)$$

where  $n_0$  is the mean flux of cosmic rays,  $B_0$  is the intensity of the interplanetary magnetic field and  $\delta_p$  is the projection of the anisotropy of the cosmic rays on the interplanetary magnetic field. The power spectra of cosmic ray fluctuations in the presence of perturbations of the interplanetary environment were analyzed in a number of papers (see Dorman and Libin, 1985, and bibliography cited therein), where variations of the power spectrum of cosmic rays in low frequencies (Gulinsky and Libin, 1979; Gulinsky *et al.*, 1988) and high frequencies (Kozlov, 1981 and 1986) 1 ~ 2 days before

the arrival of the shock wave to Earth, are reported. Those results are basically obtained by means of the Fourier transform and they are based on the hypothesis of the stationarity of the transformed functions, which diminishes the confidence in the results.

In the present paper, an attempt is made to improve the methodology used in previous studies. The methods used here to estimate the variations in the power spectra are described in detail in Gulinsky *et al.*, (1986, 1988) and may be applicable to short non stationary time series, as is the case in cosmic ray and interplanetary magnetic field data.

### DATA AND METHODOLOGY

We use several series of 5-min and hourly values of cosmic ray intensity (neutron and ionization components). The data are taken from the following stations: Moscow (1984-1986), Tiksi (1980-1986), Baksan (1984), Apatiti (1984-1986), Utrecht and Kerguelen (1977). Hourly measurements of the parameters of interplanetary plasma  $V$ ,  $n$ ,  $T$  and of interplanetary magnetic field  $|B|$ ,  $B_x$ ,  $B_y$  and  $B_z$  for the 1977-1985 period were obtained from the catalogs of King (1977-1986).

The correlation function and the power spectrum are the basic instruments of analysis employed here (Kay and Maril, 1981). The methodology used here, unlike the standard one (Bendat and Pearson 1983) can be applied to the analysis of short length time series when the steady-state condition does not hold. The spectral analysis is based on the approximation of the corresponding time series  $\{x_t\}$  by means of autoregressive models with constant coefficients, in the stationary case, or time dependent coefficients in the non stationary one, namely:

$$x_t = \sum_{i=1}^p a_i(t)x_{t-i} + \xi_t, \quad (2)$$

where  $p$  is the order of the autoregressive model,  $\{a_i\}$  are the autoregressive coefficients and  $x_t$  is the noise. The order  $p$  of the model varies depending on the length of the series and on the character of the processes: it grows with the length and the stationarity of the series. For the non stationary case, the coefficients  $\{a_i\}$  are expanded with the aid of cubic spline functions:

$$a_i = \sum_{s=-1}^{N-1} \alpha_{is} B_s(t), \quad (3)$$

where  $s = -1, 0, 1$  and  $i = 1, 2, \dots, p$ . The coefficients  $\{a_i\}$  are estimated by minimizing  $\{\sum(\hat{x}_t - x_t)\}^2$ , where

$$\hat{x}_t = \sum_{i=1}^p \sum_{s=-1}^N \alpha_{is} B_s(t) \hat{x}_{t-i}, \quad (4)$$

selecting adequately the parameters  $\{a_{is}\}$ . Thus, the problem is reduced to solving a system of linear equations. In order to calculate the power spectrum at any given time  $t$ , the values  $\{a_{is}\}$  are substituted in the expression

$$P(f, t) = (2\pi)^{-1} \sigma^2 \sum_i \sum_s \alpha_{is} B_s(t) \exp(if(p-y)) \quad (5)$$

## RESULTS AND DISCUSSION

The selected time periods are shown in Table 1. The selection of data was based on the available information about solar activity, geomagnetic activity, interplanetary plasma and magnetic fields. We selected data sets of 5-min and hourly values for the 1977 and 1980-1994. The power spectra of cosmic ray fluctuations for 5- minutes and hourly intervals are almost insensitive to the choice of the data interval. In

**Table 1**

$S_{IMF}$ : sign of the interplanetary magnetic field;  $V_{min}$ ,  $\Delta V$ ,  $\Delta n$  and  $|B|$ : parameters of the solar wind;  $t_0$ : beginning of cosmic rays observations (date/hour); P.S.: power spectrum of cosmic rays; TMS: onset time of the magnetic storm (date/time); obs: observational peculiarities; sbl: sectorial border line; Fd: Forbush reduction; (a) for one station; (b) date of the probable presence of inverse shock wave; (c) magnetic storm; (d) magnetic storm with two active periods; T in minutes.

Periods	$S_{IMF}$ TMS	$V_{min}$ km/s	$\Delta V$ km/s	$\Delta n$ cm <sup>-3</sup>	$ B $ nT	$t_0$ date/hour	P.S.	Obs.
18-21.01.82	+ 21/1517 /1731	330	100	90	15	20/14 21/11	18/12-20/00 T = 12	19.01 (b)
25-30.01.82	+ 28/0300(a) 29/1745	350 250	50 40	20 15	15	27/22 30/	26/00-27/00 T = 40; T = 12	25.01(b)
14-18.03.82	-/+ -	250	400	100	20	17/13 Fd	15/12-16/00 T = 40; T = 12	17. sbl
19-23.03.82	+ 21/1132	450	150	5	5	22/12	20/00-21/00 T = 50; T = 17	21.03(b)
14-18.04.82	+ 16/1702	350	100	15	10	16/17	15/12-16/00	
19-25.04.82	+ 24/2016	450	150	25	15	24/00 Fd	22/00-23/00 T = 50; T = 17	17-21.04 (c)
18-27.05.82	-/+ -	350	200	20	5	26/	25/00-26/00	26.05sbl 26.05(b)
07-10.04.86	+ 09/1034	350	50	10	-	-	8/00-09/00	
12-15.04.86	- 15/0435	320	120	20	-	-	13/00-14/00 T = 50; T = 12	
12-17.08.86	+/- 14/	350	160	30	-	14/12	13/00 T = 40; T = 15	
11-15.06.91	+/- 11/0229	380	120	20	-	13/08	11/00-15/00 T = 50; T = 12	
01-05.11.92	+/- 1/1200	350	100	25	-	2/03	2/00 T = 50; T = 20	

the frequency interval of fluctuations with periods of 1 to 24 hours the nature of the spectrum is basically determined by the 24 hours oscillation which is related to cosmic ray anisotropy and terrestrial rotation (Stehlik and Kudela, 1984), and by the resonance frequency of the 8 hour period, as in the case of Tiksi and Appatity stations, and by the 6-7-hour period, in the case of Moscow, Utrecht and Baksan stations (Dorman and Libin, 1984).

The power spectra of the interplanetary magnetic fields were calculated on the basis of hourly data, that is, for short series. In order to test the stability of the spectra, the calculations were done for different p-orders. For additional reliability, the power spectra of the interplanetary magnetic field components were also constructed on the basis of Prognoz-7 satellite data, from January 1978 to April 1979, with resolutions of 1 hour and 5 minutes. In these frequency ranges, the results show a high level of consistency with those of other authors (see for example Bloch *et al.*, 1984).

Even in quiet periods the time-dependent series of the interplanetary magnetic field components are essentially non stationary during the 27-days corotational period. However, within the sectorial structure of the interplanetary magnetic field it is possible to find steady-state intervals of 2-3 days (Nigam *et al.*, 1983; Kuzmin, 1984). As in previous observations (Obridko and Shelting, 1983, 1985), we find that power spectra for different steady-state intervals may differ significantly. In non perturbed intervals (Figure 1a and 1c), the power spectrum of the  $B_z$  - component shows a power law shape for fluctuations with periods greater than 10 hours, with a secondary maximum around  $T=5$  hours. During the day immediately preceding the shock wave arrival, the 5-hr wave increases and the low frequency oscillations decrease (Figure 1b), or a second maximum appears near the 10-hrs period (Figure 1d). In the two analyzed cases, the power spectrum of the perturbed oscillations rises in the high frequency region ( $T < 3$  hrs).

Typical spectra of cosmic rays series of one day in length are shown in Figures 2a (Tiksi, 21-22.04.82), 2c (Moscow, 07.04.86) and 2e (Moscow, 23.04.82) for data obtained 1 - 2 days before the shock wave arrival, i.e. during non perturbed periods. In the case of the 5-min series (Figures 2a and 2c), the spectra show a power-law shape in the period range of  $T > 20$  min, with some peaks in the region  $20 < T < 10$  min. In the case of the hourly series (Figure 2e), the power law shape is observed for  $T > 10$  hrs with a second peak at  $T \approx 5$  hrs.

The cosmic ray spectra immediately before the shock wave arrival from 5-min data are illustrated in Figure 2b (Tiksi station on 22.04.82) and 2d (Moscow station on 07.04.86). They exhibit a power law shape for  $T > 20$  min

with some small peaks in the high frequency region ( $T < 20$  min). Spectra from the Moscow station show high power in the low-frequency region because of anisotropy (Dorman *et al.*, 1980). The spectrum shown in Figure 2a coincides with the spectrum of the  $B_z$  - component (Figure 1c), as indicated by equation (1). During 1 - 1.5 days before the shock-wave arrival the power spectrum of cosmic rays undergoes significant changes. Figures 2b and 2d show characteristic spectra for perturbed periods as observed at Tiksi and Moscow on 23.04.82 and 08.04.86, respectively. The main feature of these spectra is the relative depression in the low frequency region ( $T > 20$  min). Dotted lines in Figure 2a, 2b and 2c correspond to spectra obtained with high p-orders; they show systematic peaks in the low frequency region, coinciding with the results of Sakai *et al.*, (1985), though we do not observe a significant power amplification at high frequencies.

Figure 2f shows the power spectrum obtained on the basis of hourly values of cosmic ray intensity at Moscow, on 23.04.82, the day before the arrival of a shock wave. This spectrum shows fluctuations with periods  $T > 2$  hrs.

The  $B_z$  - component before the shock wave arrival shows no systematic regularities as in the case of cosmic ray spectra. Nevertheless, in some cases a well-defined oscillation with a period of 6 - 8 hrs occurs, as for the intervals 20 - 22 March, 25 - 30 April, 16 - 18 May and 21 - 27 May of 1982 (Figure 1b). Sometimes the oscillation can be observed directly in the  $B_z$  - time series without the help of spectral analysis. From the catalog of Couzens and King (1986), about 20 events in the period 1977-1981 with a 6 - 8 hrs wave can also be directly identified. Comparison of results in Figures 1d and 2f (cosmic ray power spectrum) show that, unlike quiet periods, spectral characteristics of  $B_z$  and cosmic rays are different during perturbed periods, i.e. immediately before the shock wave arrival.

## CONCLUSIONS

Before the arrival of a shock wave, the cosmic ray power spectrum suffers significant changes, displayed by oscillations with periods in the range of 20 min. to 24 hrs. The presence of peaks is not always a precursor of perturbations. High frequency peaks may or may not occur during quiet periods or before a shock wave arrival. However, in quiet periods no significant power amplification is observed in the high frequency domain.

Before the arrival of a shock wave the power spectra of cosmic rays differ significantly from the spectra of the  $B_z$  component of the interplanetary magnetic field. The variation in  $B_z$  spectra before the arrival of the shock does not have a regular character. However, sometimes the arrival of the shock wave can be associated with the appearance of a

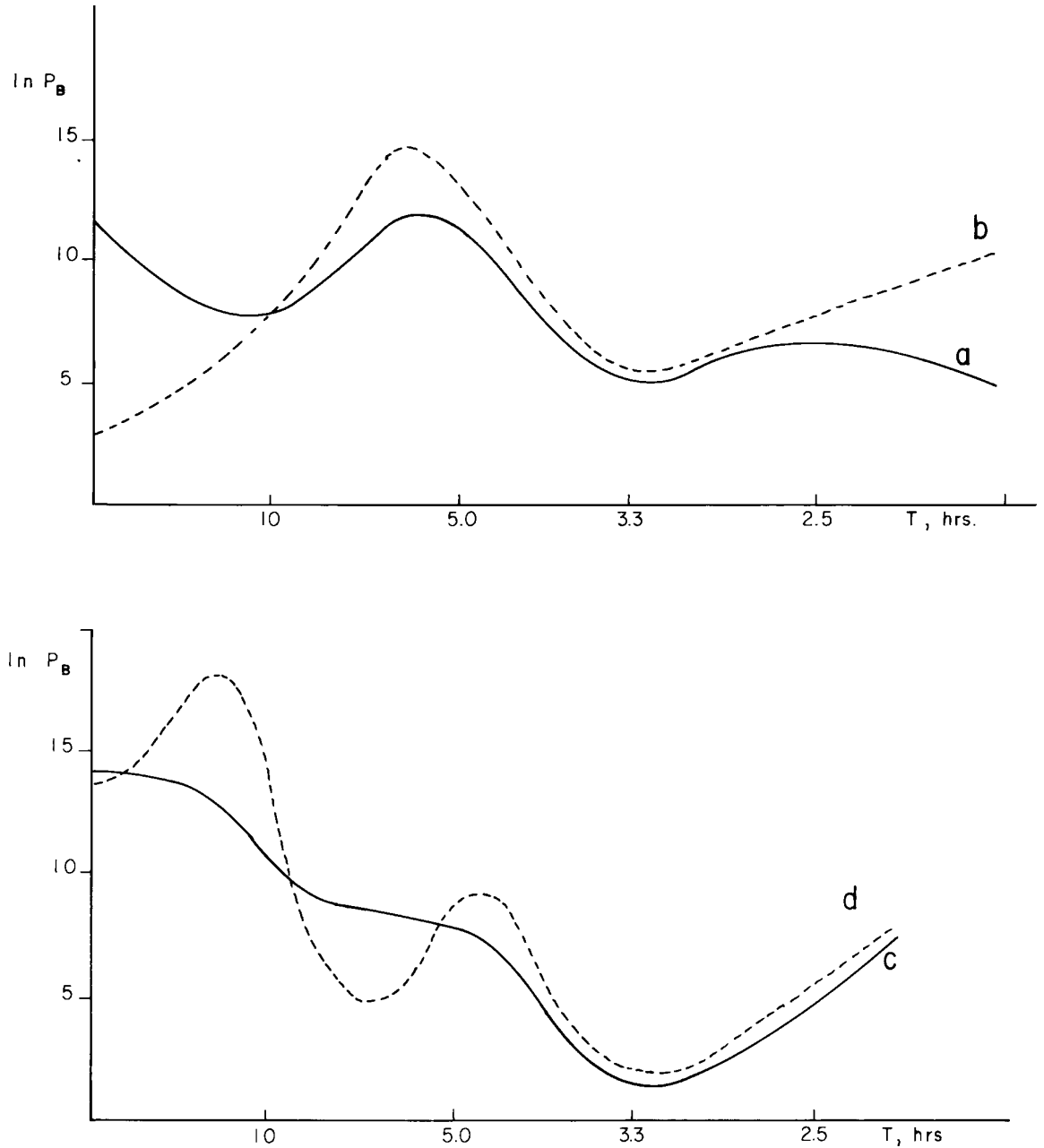


Fig. 1. Power spectra of  $B_z$  component. a) non perturbed period (15-17 May, 1982), b) before the perturbation (18 May, 1982), c) non perturbed period (21-22 April, 1982), d) before the perturbation (23 April, 1982).

sharp wave with a period of 6 to 8 hours which stays clear during nearly 24 hours.

The variable behavior of cosmic ray spectra is due to the appearance in the interplanetary space of a shock wave that generates an additional flux from acceleration by reflection of local particles at the shock. The anisotropy is the

sum of the anisotropy in the quiet solar wind,  $A_q$ , plus the generated particle flux by reflexions,  $A_r$ , i.e.  $\delta_p = (A_q + A_r)_p$ . Both anisotropies have nearly opposite phase, hence the resultant anisotropy is reduced. Taking into account the Earth's rotation, this leads to a power decrease at the low frequencies of the spectrum. According to eq. (1), when  $\delta_p$  tends to 0 the magnetic field fluctuations have a weak influence on cosmic rays.

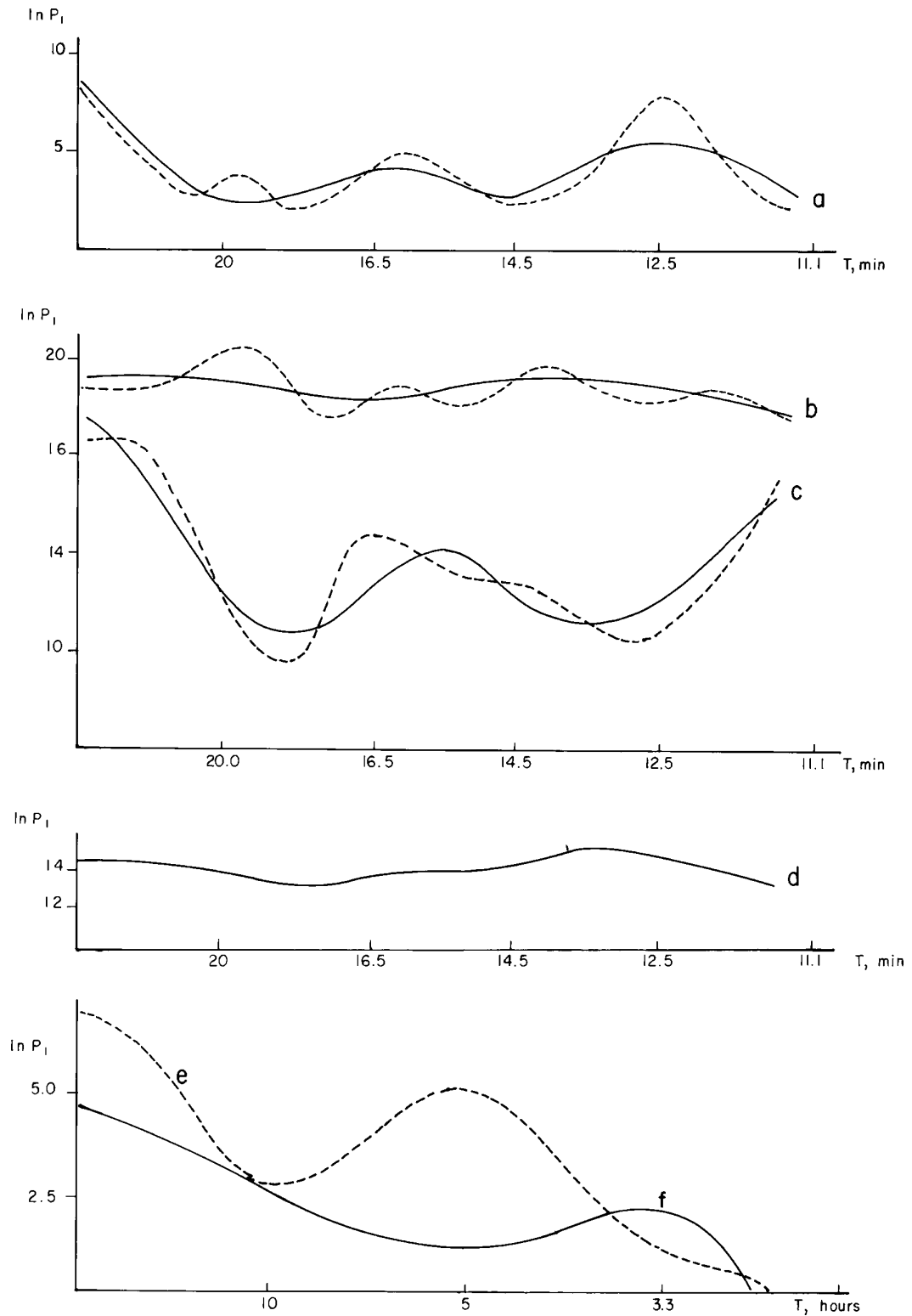


Fig. 2. Power spectra of cosmic rays for 5-minutes (a-d) and hourly values (e,f). a) non perturbed period (Tiksi, 21-22 April, 1982); b) before shock wave arrival (Tiksi, 23 April, 1982); c) non perturbed period arrival (Moscow, 7 April, 1986); d) before shock wave arrival (Moscow, 8 April, 1986); e) non perturbed period arrival (Moscow, 21-22 April, 1982); f) before shock wave arrival (Moscow, 23 April, 1982). Dotted lines - spectra obtained for high p-order models (see text).

A more detailed explanation of the influence of anisotropy on cosmic ray spectra is given in Dorman *et al.* (1986), where the different nature of particle reflexions according to the particle rigidity range is taken into account. The appearance of a wave with  $T > 28$  hrs ahead of the shock front and the stochastic acceleration process that generates the additional particle flux are discussed in Obridko and Shelting (1985), Dorman and Libin (1984), Bezrodnikh *et al.* (1982), and references cited in those papers.

The mechanism of generation of the wave with a period of 6 - 8 hours is not clear and requires further analysis. Sometimes, the generation of the wave takes place between two shock waves (Morozova *et al.*, 1984) and, on other occasions one of the shocks is a reverse shock wave.

Regularities in the behavior of cosmic ray fluctuations may be a useful tool for the diagnosis of perturbations in the interplanetary medium, helping to predict the arrival of powerful shock waves to the earth and geomagnetic perturbations, from 1 to 2 days in advance, in agreement with the results of Kozlov (1985). In spite of methodological differences, this appears to confirm the applicability of cosmic ray fluctuations for monitoring and predicting the state of the interplanetary medium in the Earth's neighborhood.

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