REPORTES INTERNOS 96-6
Marzo 1996

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Precio: N$ 2.00

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Abstract

We present here a method for prognosis of interplanetary shock waves near of the earth. The method of prognosis is based on the fact that the velocities of shock wave circulation and cosmic rays are very different. Peculiar alterations of the power spectrum of cosmic ray fluctuations are used as indicators of the state of the interplanetary medium in the earth's environment.

INTRODUCTION.

The observed intensity of cosmic rays suffers significant fluctuations in the frequency region $f < 10^{-3}$ Hz. The origin of such fluctuations is the turbulence of the interplanetary magnetic field in which cosmic particles travel [1-3]. In [4,5] the author shows that the power spectrum of fluctuations of cosmic rays P(f) is related to an analogous spectrum of interplanetary magnetic field $P_B(f)$ in the frequency region $f > 10^{-5}$ for particles with energy greater than a few GeV, by means of the following relationship:

$$P(f)/n_0^2 = A(f)P_B(f)\delta_{\parallel}/B_0^2 \qquad (1)$$

where n_0 is the mean flux of cosmic rays, B_0 is the tension of the interplanetary magnetic field and $\delta_{\parallel}$ is the projection of the anisotropy of the cosmic rays in the interplanetary magnetic field. The power spectra of cosmic ray fluctuations in presence of perturbations of the interplanetary environment were analyzed in a great number of works (e.g. [6] and cited bibliography in it). In these works there were disclosed variations of the power spectrum of cosmic rays 1 ~ 2 days before the arrival of the shock wave to Earth in the region of low [7, 8] and high [9, 10] frequencies. However, these results are not free of a series of deficiencies, e.g.:

- The traditional methods for the estimation of the spectra, used in the mentioned works, based in the direct Fourier transformation of data in short intervals (which, as a rule, is necessary to work in this problem) produce large errors due to the presence of false peaks, and because they have a poor frequency resolution.

- In an important number of works there was not a sufficient fastening of variations of the power spectrum of cosmic rays with the complex of solar and geomagnetic data, nor with data of the interplanetary magnetic field and interplanetary plasma.
- In each one of those works only a small amount of events were analyzed, and the events itself were not classified in detail.

In this paper an attempt is made in order to eliminate these deficiencies. The methods used here to estimate the power spectra are described in detail in [8, 11]. These methods, unlike standard ones [12], are applicable to short interval of data, including those cases when the stationarity of the analyzed processes can be infringed. Results of their applications to the power spectra of cosmic rays and interplanetary magnetic field are reported here.

DESCRIPTION OF THE DATA.

In the present work 5-minute and hourly values of cosmic ray intensity (neutron and ionization components) were used. The data correspond to the following stations: Moscow (1984-1986), Tiksi (1980-1986), Baksan (1984), Appatiti (1984-1986), Utrecht y Kerguelen (1977). The hourly measurement of the parameters of interplanetary plasma V, n, T and interplanetary magnetic field $|B|$, B_x, B_y, B_z for the 1977-1985 period were obtained from King's catalogs. As basic instruments of investigation, the correlation and spectral analysis of time series were used [13]. The employed method of spectral analysis is based on the approximation of the time series $\{x_t\}$ by means of autoregression models with constant coefficients (in the stationary case) or time dependent coefficients (in the non stationary case):

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

where p is the order of the autoregression model, ξ_t represents the noise and $a_i(t)$ are the coefficients of the autoregression. The order of the model varies depending on the length of the series, and so, on the character of the studied processes; additionally, p grows with the length and the stability of the statistical characteristics of the time series. At the same time, for the non stationary case the coefficients (a_i) are expanded in series with the aid of cubic spleins functions:

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

where (s = -1, 0, 1) and the estimation of coefficients a_i reduces to the determination of a minimum: $\mathrm{Min}\{\Sigma(x_t - x)\}^2$ by means of the selection of the parameter $\{\alpha_{is}\}$, with $i = 1....p$ and $s = 1 ....N$, where

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

the problem reduces then to solve a system of linear equations. To calculate the power spectrum at any given time t it is necessary the substitution of the values $\{\alpha_{is}\}$ in the corresponding expression

$$P(f,t) = (2\pi)^{-1}\sigma^2\left[\sum_i \sum_s \alpha_{is} \, B_s(t) \exp\left(if(p-i)\right)\right]^2 , \tag{5}$$

the selected periods for this work are shown in Table 1. The selection of data in each case is determined on basis to the disposable information on solar and geomagnetic data and on interplanetary plasma and magnetic fields. In this work we have selected all the data sets for 1977 and 1980-1994. The power spectra of the interplanetary magnetic fields were calculated on basis to hourly data, that is, in short intervals. To test the stability of the spectra the calculations were done for different p-orders; for additional reliability of our results the power spectra of the interplanetary magnetic field components were also constructed on basis to data of the Prognoz-7 satellite from January 1978 to April 1979, with resolutions of 1 hour and 5 minutes. In the frequency range analyzed here, our results show a high level of congruence with those of other authors, e.g. [14].

It is worth to mention that even in quiet periods the time-dependent series of the interplanetary magnetic field components produce processes which are essentially of non-stationary nature all the long of the 27 days corotation period; however, within the interplanetary magnetic field sectorial structure it is possible to find steady-state behaviors during time intervals of 2-3 days [15, 16], among which it may be distinguished "separation zones", i.e. zones of variation of the characteristics of the aleatory process of analysis. In coincidence with previous observations [17, 18] we find that power spectra in different steady-state intervals may differ significantly. In Figs. 1(a) - 1(d) we present some power spectra of the fluctuations of the B_z- component of the interplanetary magnetic field: it can be seen that such spectra have a power law shape in the frequency range which corresponds to fluctuations of periods lower than 10 hours, in addition to a slight increase in the frequency interval corresponding to periods of 5 - 7 hours.

The power spectra of cosmic ray fluctuations obtained with every 5 minutes and hourly data are less sensitive to the choice of the selected data interval for the analysis. This may be explained by the fact that, in the frequency interval of fluctuations with periods of 1 - 24 hours the nature of spectra is basically determined by the daily wave (24 hours-period), the which is related to cosmic ray anisotropy and the terrestrial rotation [19], as well as by the resonance frequency corresponding to the 8-hours period of the Tiksi and Appatity stations and to the 6-7 hors period of the Moscow, Utretch and Baksan stations [20].

Typical spectra of cosmic rays obtained from 5-minute data with 1-day window during intervals located immediately before excitation periods are shown in figures 2(e) (Tiksi, 22.04.82) and in 2(d) (Moscow, 07.04.86). These spectra have a power law nature in the period range of 24 hours to 50 minutes, with some peaks in the high frequency region (T ~ 50 min.). Spectra from the Moscow station show more power in the zone of low frequency, since it is precisely in this range where the effects of cosmic ray anisotropies have a significant influence [21]. In Fig. 2(a) is shown a typical spectrum obtained from hourly data of the Tiksi station during the quiet (unexcited) period of 21-22 April, 1982; its shape [taking into account eq. (1)] agree in some extent with the spectrum of the component B_z (Fig. 1c) for the same period. The well defined power law nature of the cosmic ray power spectrum is a consequence of the shape of function A(f) in the frequency region of periods $T < 5$ hours; the rise at $T = 5 - 7$ hours may be explained as a cyclotronic resonance, as well as a certain rise in the spectrum of component B_z. One to one and a half days before the arrival of the shock wave, cosmic ray power spectra suffer important variations; Figs. 2(b) and 2(d) show typical power spectra observed during those periods, for data of the Tiksi and Moscow stations. The fundamental peculiarity of these spectra is its flatnesses, as well as a power reduction at low frequencies. Figs. 2(a) and 2(b) show with pointed lines the spectra calculated with models of higher order. For some events peaks at $T = 50$ min. and $T = 15 - 20$ min. are observed; their presence in those events is of regular nature, in agreement with other results [22]. However, we do not observe a significant power amplification at high frequencies. Fig. 2(f) shows the cosmic ray power spectrum (hourly data), where it can be seen the variable behavior in frequencies corresponding to periods ≥ 2 hrs.

The analysis of the evolution of the power spectrum of the component B_z before the arrival of the shock wave shows that the spectrum variations of this component has not a behavior so regular as that of cosmic rays. Nevertheless, it should be mentioned that in a series of cases, before the shock wave arrival, a clear oscillation of such component is observed with a period of

6 - 8 hours. The typical example may be appreciated in Fig. 1(b) for the intervals 20 - 22 March, 25 - 30 April, 16 - 18 May and 21 - 27 May of 1982. The wave is so relevant in these cases that in occasions can be directly identified on the B_z-component graphics (hourly data) even without making use of spectral analysis. With data of the King's catalog it is possible to determine other 20 more cases, between 1997 and 1981, where waves show periods of 6 - 8 hours. Fig. 1(d) shows an additional example of the B_z-component spectrum before the shock wave arrival. The comparison of this spectrum with that of cosmic rays allows to see (Fig. 2f) that in contrast with the situation in quiet periods, both spectra have different character. This feature is observed, as a general rule, in all the analyzed events.

SUMMARY AND CONCLUSIONS

Results may be synthesized as follows:

- Before the arrival of a shock wave, the cosmic ray power spectra suffer significant changes in frequencies corresponding to fluctuations of periods in the interval of 50 min. to 24 hours.
- The presence of peaks is not always an announcement of perturbations, because peaks at high frequencies may occur or do not as well during quiet periods as before a shock wave arrival. However, in quiet periods a significant power amplification is not observed in the high frequency domain.
- The power spectra of cosmic rays before the arrival of a shock wave differ significantly of the spectra of the component B_z of the interplanetary magnetic field.
- The variation of the B_z-component spectra before the arrival of the shock have not a regular character. However, in certain cases, with the arrival of the shock wave it can be associated the appearance of a wave with period of 6 to 8 hours (sharply defined) with a permanence of near 24 hours.
- The variable behavior of cosmic ray spectra has a simple explanation: the appearance in the interplanetary space of a shock wave generates an additional flux from acceleration by reflection of local particle on the shock, in which case the anisotropy is the algebraic sum of the anisotropy in the quiet solar wind, $\mathcal{A}_q$, and that of the generated particle flux by reflexions, $\mathcal{A}_r$, i.e. $\delta_{\parallel} = (\mathcal{A}_q + \mathcal{A}_r)_{\parallel}$. Since both anisotropies have almost opposite sign, hence the anisotropy is reduced. Taking in consideration the earth rotation, it is clear that this leads to a power decrease at the low frequencies of the spectrum, so that according to eq. (1), when $\delta \longrightarrow 0$ the magnetic field fluc-

tuations have weak influence on cosmic rays. A more detailed explanation about the influence of anisotropy on cosmic ray spectra is given in [21], where it is taken into account the different nature of particle refexions according to the particle rigidity range. The appearance of a wave with $f \geq 10^{-6}$ Hz ahead of the shock front and the stochastic acceleration processes in such a front that generate the additional particle flux is dicussed in a number of works (e.g. [17, 20, 23]) as well as in the references cited in those papers.

The formation mechanism of the wave with period of 6 - 8 hours is not yet enough clear and requires still of further analysis.. What can be mentioned at this regard is that in occasions such a formation process takes place between two shock waves in agreement with [24], and in other cases one of the shocks is a reverse shock wave.

We conclude that the employment of the discover regularities in the behavior of cosmic ray fluctuations is a useful tool for diagnosis of perturbations in the interplanetary medium, allowing to predict the arrival of powerful shock waves to the earth and geomagnetic perturbations with 1 - 2 days in advance, in agreement with work [25]. In spite of methodlogical differences in the analysis with other authors, results lead however to similar conclusions, which confirms from our point of view, the applicability of cosmic ray fluctuations for monitoring the state of the interplanetary medium in the earth neighborhood, and so, for the goal of pronostics.

AKMOWLEDGMENTS

Authors desire to thanks the DGIA (Dirección General de Intercambio Académico) of UNAM (Universidad Nacional Autónoma de México) for the economical support to Prof. Igor Ya. LIBIN during his visit to the Instituto of Geofísica of UNAM.

REFERENCES

1. Putskin V.S. Cosmic rays in large-scale and strong turbulent magnetic field. Astrophys. and Space Sci., 1979, V. 61, pp. 251-258.

2. Dorman L.I., and I.Ya. Libin. Fluctuation phenomena in cosmic rays observed at Earth, in the stratosphere and in the cosmic space. Izv. A. Sc. USSR, phys. series, 1984, T. 48, No. 11, pp. 2143-2145.

3. Dorman L. I., M. Ye. Katz, S. F. Nosov, M. Steglik, A. K. Yukhimuk. Fluctuations of the cosmic ray intensity in strong magnetic field. Izv. A. Sc. USSR, phys. series, 1983, T. 47, No. 9, pp. 1861-1863.

4. Owens A.J., Cosmic Rays Scintillations 2: General theory of interplanetary scintillations. J. Gepophys. Res., 1974, V. 75, No. 7, pp. 907-910.

5. Owens A.J., Cosmic Ray Scintillations 3: The low-frequency limit and observations of interplanetary scintillations. J. Geophys. Res., 1974, V. 79, No. 7, pp. 907-910.

6. Dorman L.I., and I. Ya. Libin, Short-term variations of cosmic ray intensity. Uspekhi fizicheskikh nauk, 1985, T. 145, No. 3, pp. 403-440.

7. Gulinsky O. V. and I. Ya. Libin, Fluctuation phenomena in cosmic rays as observed by the multidirectional telescope of IZMIRAN. Pre-print IZMIRAN No. 30 (258), Moscow, IZMIRAN, 1979, 24 pg.

8. Gulinsky O. V., I. Ya. Libin, R. Ye. Prilutzky, J. PΦrez-Peraza, et al., Spectral analysis of small-scale fluctuations of cosmic rays on the basis of surface observations, Kosmicheskiye luchi, No. 24, Moscow, 1987, pp. 63-87.

9. Kozlov V.I. Turbulent pulsations of magnetic fields in presence of shock waves, Geomagnetism and Aeronomy, 1981, T. 21, No. 6, pp. 1115-1117.

10. Kozlov V.I. Fluctuations of cosmic rays and dynamical processes in solar wind, in: Modulation of cosmic rays in the solar system, Yakutsk, 1986, pp. 80-95.

11. Gulinsky O.V., I.Ya. Libin, R.Ye. Prilutzki, Fluctuations of cosmic rays during periods of perturbation, Geomagnetism and Aeronomy, 1986, T. 26, No. 4, pp. 529-534.

12. Bendat J. and A. Pearson, Application of correlation and spectral analysis Moscow, Mir Publishing House, 1983, 312 p.

13. Kay S.M. and S.L. Maril, Modern Methods in Spectral Analysis. TIIER, 1981, T. 69, No. 11, pp. 5-48.

14. Bloch G. M, B. M. Kujzhevsky, I. Ya. Libin, A. M. Lemberger, Spectral characteristics of low-energy solar cosmic rays obtained on the basis of data from "Prognos-6" satellite. Geomagnetism and Aeronomy, 1984, T. 24, No. 1, pp. 11-15.

15. Kuzmin V.A., Fluctuations of the tension of interplanetary magnetic field and those of the flux of cosmic rays in the sectorial border lines, Proceedings of the 4th Symposium KAPG on Solar-terrestrial Physics, Sochi, 1984, pp. 83-84.

16. Nigam S.K., K.N. Misra, D.P. Tiwari, R.P. Misra, R.L. Singh, Interplanetary magnetic field structure and second harmonic of cosmic ray intensity, Proceedings of the 18th ICRC, Bangalore, 1983, V.3, pp. 342-345.

17. Obridko V.N. and B.D. Shelting, Characteristics of the spectrum of fluctuations of interplanetary magnetic field and the level of solar activity, Solar Data, 1983, No. 9, pp. 80-83.

18. Obridko V.N. and B.D. Shelting, Fluctuation characteristics of the inter-

planetary magnetic field in the region of $3x10^{-4}$ - 10^{-2} Hz, Geomagnetism and Aeronomy, 1985, T. 25, No. 6, pp. 881-885.

19. Stehlik M. and K. Kudela, Power spectra of cosmic ray variations in the region of $3x10^{-8}$ - 10^{-4} Hz, Acta Phys. Slov., 1984, V. 34, Nos. 2-3, pp. 75-85.

20. Dorman L.I. and I.Ya. Libin, Cosmic ray scintillations and dynamic processes in space, Space Sci. Rev., 1984, V. 39, pp. 91-152.

21. Dorman L.I., I.Ya. Libin, K.F. Yudakhin, Probable interpretation of changes in the form of power spectrum of cosmic ray fluctuations in the presence of perturbances of the interplanetary environment, Geomagnetism and Aeronomy, 1986, T. 26, No. 2, pp. 204-208.

22. Sakai T., M. Kato, E. Takei, Periodic variations of cosmic ray intensity with period of 37 minutes observed on April 25th, 1984. J. Geomagn. and Geolbec., 1985, V. 37, No. 6, pp. 659-666.

23. Bezrodnikh I.P., V.A. Kuzmin, V.I. Kozlov, Dynamics of frequencial spectrum of interplanetary magnetic field fluctuations and of cosmic rays, Geomagnetism and Aeronomy, 1982, T. 22, No. 6, pp. 1016-1018.

24. Morozova E.I., N.F. Pissarenko, W. Riedler, K. Schwingenschuh et al., The magnetic field turbulence near interplanetary shock fronts, Advances in Space Research, 1984, V. 4, Nos. 2-3, pp. 331-334.

25. Kozlov V. I., Early diagnosis of interplanetary perturbances by means of registration of scintillation modulation of cosmic rays. Preprint, IKFIA, Yakutsk, 1985, 20 p.

FIGURE CAPTIONS

Fig. 1 Power spectra of Bz 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).

Fig. 2 Power spectra of cosmic rays for 5-minutes data of Tiksi (a-b) and Moscow (c-d) stations, and for hourly data of Moscow station.
- a) non perturbed period (21-22 April, 1982);
- b) before shock wave (23 April, 1982);
- c) non perturbed period (7 April, 1986);
- d) before shock wave (8 April, 1986);
- e) non perturbed period (21-22 April, 1982);
- f) before shock wave (23 April, 1982).

Table 1. S_{IMF} = sign of the interplanetary magnetic field; V_{min}, ΔV, Δn and $|B|$ = parameters of the solar wind; t_o = beginning of cosmic rays observations (date/hour/min); P.S. = power spectrum of cosmic rays; TMS = onset time of the magnetic storm; 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.

Periods	S_{IMF}	TMS	Vmin Km/s	ΔV Km/s	Δn cm^{-3}	|B| nT	t_o date/hour	P.S. of cosmic rays T(min.)	Obs. (pecui.)
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	50 250	20 40	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) 26.05(d)
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	

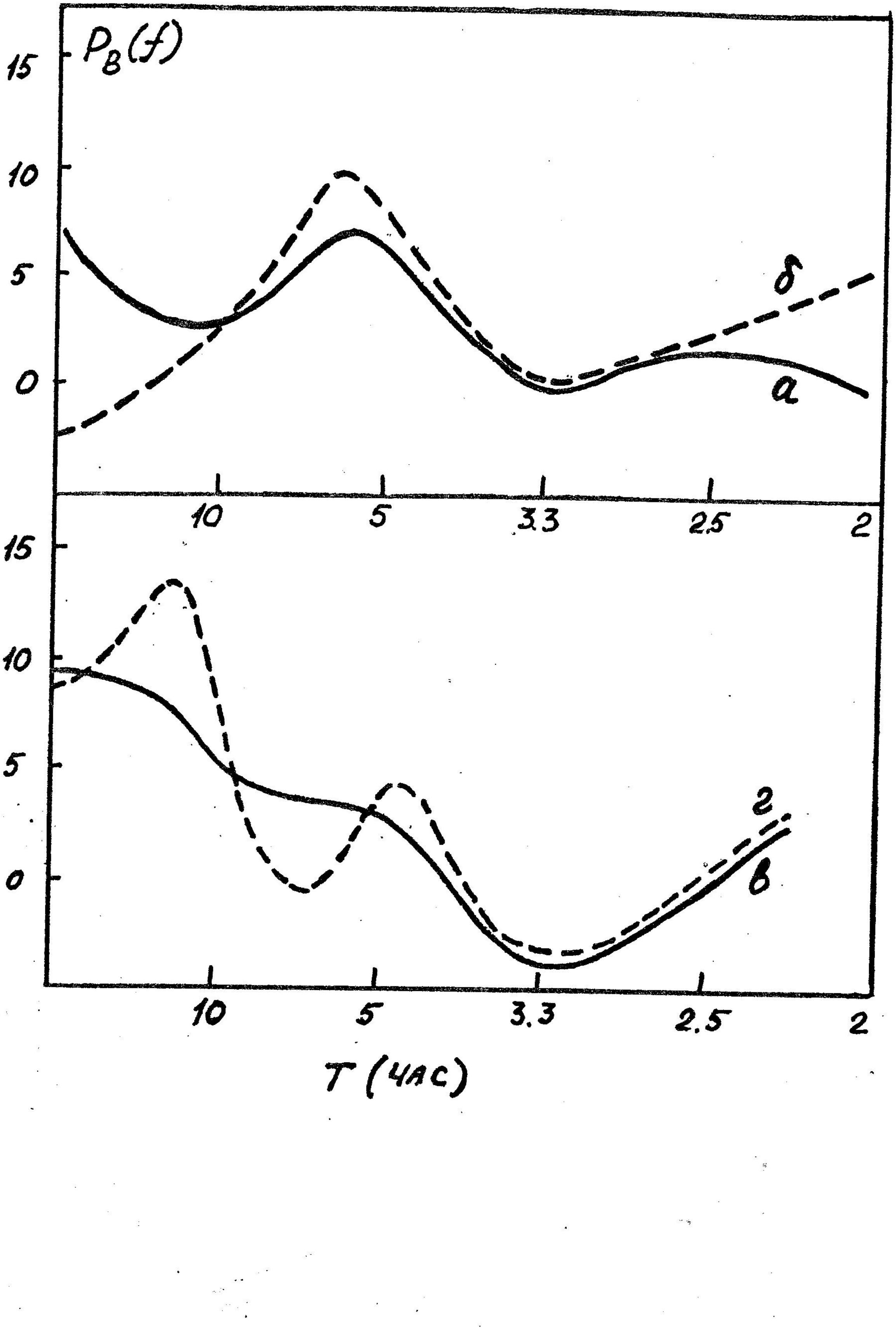
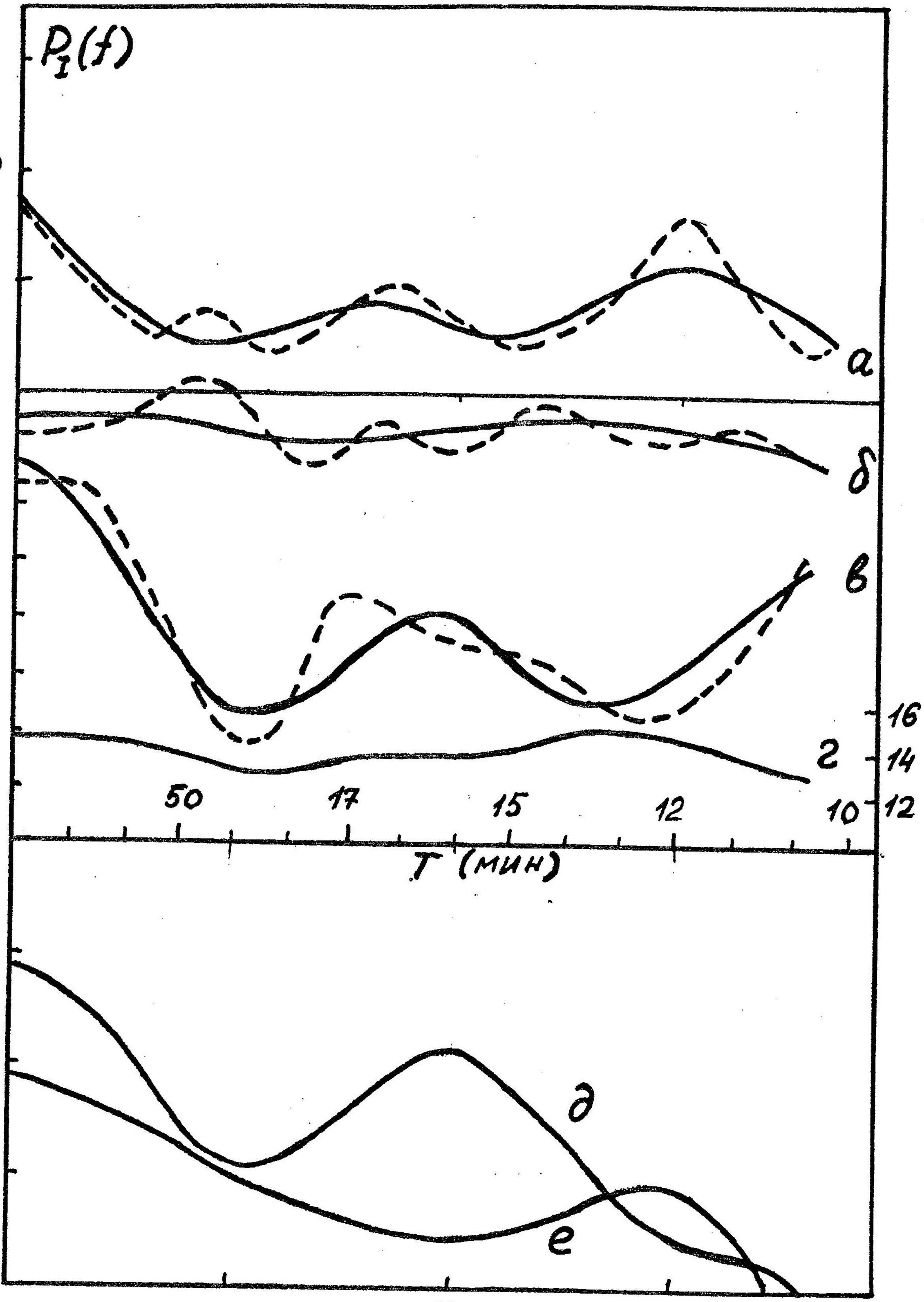


Рис 1



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T (час)

Fig. 2