acta phys. slov. 34 (1984), No. 2—3

POWER SPECTRA OF COSMIC RAY VARIATIONS IN THE REGION OF 3×10^{-8}—10^{-4} Hz[1]

M. STEHLÍK[2], K. KUDELA[2], Košice

The power spectral density of cosmic ray (CR) fluctuations observed at ground level during the years 1978—1981 has been calculated. The investigated frequency range consists of two parts, with a transient region of $\sim10^{-6}$—10^{-5} Hz. In the range of higher frequencies, the CR intensity fluctuations are directly connected with the pulsations of the turbulent interplanetary magnetic field. On the other hand, the low-frequency fluctuations of CR intensity are caused by the diffusion fluxes of particles, which is defined by the asymmetric part of the diffusion tensor (e.g. drift fluxes). Against this "background" CR fluctuations are observed, which contribute to aperiodic phenomena of the CR distribution (e.g. the Forbush decreases). It is indicated that for the computing of power spectra it is necessary to use the cross covariance analysis in order to eliminate the fluctuations connected with either local differences or differences of apparatus.

ЭНЕРГЕТИЧЕСКИЙ СПЕКТР ВАРИАЦИЙ КОСМИЧЕСКИХ ЛУЧЕЙ В ЧАСТОТНОЙ ОБЛАСТИ $3.10^{-8}-10^{-4}$ Гц

В работе исследуется спектральная плотность флуктуаций интенсивности космических лучей по наземным измерениям в период 1978 – 81 гг. Показано, что исследуемую область можно подразделить на две области с зоной раздела при частотах $10^{-6}-10^{-5}$ Гц. В области более высоких частот флуктуации интенсивности космических лучей непосредственно связаны с пульсациями турбулентного межпланетного магнитного поля. С другой стороны, диффузионные потоки частиц, определяемые несимметрической составляющей тензора диффузии, являются причиной флуктуации в области низких частот. На этом «фоне» флуктуаций космических лучей наблюдается вклад, обусловленный апериодическими явлениями в их распределении. Показано, что для исключения флуктуаций, связанных с местными или аппаратурными эффектами, необходимо использовать вместо автокорреляционного кросс-корреляционный анализ.

---

[1] Contribution presented at the International Symposium on Acceleration and Propagation of Energetic Particles in the Heliosphere in Smolenice, September 27 — October 1, 1982.

[2] Institute of Experimental Physics, Slov. Acad. Sci., Solovjevova 47, 040 01 KOŠICE, Czechoslovakia.

I. INTRODUCTION

In recent years many experimental works concerning the investigation of cosmic ray (CR) intensity fluctuations in the large range of frequencies from 3×10^{-3} Hz to 10^{-8} Hz have appeared [1—6]. The processes of the generation of fluctuations in the large range of frequencies include a variety of physical phenomena connected with both the spreading CR particles in the heliospheric magnetic field and its scattering caused by inhomogeneities of the interplanetary magnetic field [7].

Because of the anisotropy of pulsations of the interplanetary magnetic field (with the chosen direction parallel to the regular component of the magnetic field, which acquires the form of the Archimedial spiral in the interplanetary space [8]), there are observed the CR intensity fluctuations in dependence on the acceptance direction of the detector. Apart from these, there can appear suplementary effects, which deform the shape of the power spectrum as the function of the frequency [9—12], and which are consistent with the existence of the asymptotic direction of detected particles (on the Earth's surface). In the present work we investigate the CR fluctuation power spectrum dependence on the frequency in the range of moderate and low frequencies, by using classical methods of both autocovariance and crosscovariance analyses [13]. We illustrate the preference of the cross-covariance analysis based on the data of the pair of near stations (detectors). Theoretical predictions, concerning the frequency dependence of the CR fluctuation power spectrum are compared with experimental data.

II. METHOD

CR intensity fluctuations are investigated by using experimental data, detected by neutron supermonitors at four stations (see Table 1). The power spectra were calculated from daily means of pressure-corrected neutron data for the period 1978—1981 (1416 days), the period around the maximum of the solar activity. For calculating the high-frequency power spectrum, we confined ourselves to hourly data for the period of May 1st, 1979 — July 31st, 1979 (2208 hours), when the CR intensity showed no large aperiodic changes.

In order to conserve the exact form of power spectra as the function of the frequency, (i.e. to have the possibility to calculate the power spectrum in an arbitrary amount of points), we have used the "indirect" method of computing (in spite of its small effectivity). This method, according to ergodic theory for stationary random functions, is based on the computation of the autocovariance function estimate:

$$A(i)=\frac{1}{N-i}\sum_{j=1}^{N-i} I(j)\,I(j+i), \qquad i=0,1,2,\dots,m, \tag{1}$$

where N is the full number of points, m the maximum time lag and $I(j)$ is the j-th point of the given series of equispaced data — the CR intensity. Analogically there is defined the cross-covariance function

$$C(i)=\frac{1}{N-i}\sum_{j=1}^{N-i} I_1(j)\,I_2(j+i), \tag{2}$$

Table 1

Station		Latitude	Longitude	Altitude	R_c GV	Counting rate Hour^{-1}
Apatity	AP	63.55 N	33.33 E	177	0.65	4.63×10^5
Jungfraujoch	JU	46.55 N	7.98 E	3570	4.48	5.90×10^5
Lomnický štít	LŠ	49.20 N	20.22 E	2632	4.00	7.80×10^5
Vostok	VO	78.47 S	106.80 E	3488	0.00	3.50×10^6

where I_1 and I_2 are two given series of data. (Of course, the computation of the even and the odd part of the crossvariance function is necessary.) Then the estimate $P(f)$ of the power spectral density (the power spectrum) is the Fourier transform of $A(i)$, i.e.

$$P(f)=2\left\{A(0)+2\sum_{i=1}^{m-1} W(i)\,A(i)\cos 2\pi f(i-1)\right\}, \tag{3}$$

where W is the Tukey spectral window [13].

In the computation of the power spectrum, relative data (in percents of the counting rate) were used, with the mean computed in the interval cosidered. In formula (3) we have used the Tukey spectral window. The maximum time lag $m = 200$.

III. RESULTS

First of all it has to be mentioned that the power spectrum estimates vary with the considered periods. In Fig. 1 the power spectra of two following periods are shown, the first from May 1st — July 31st, 1979 and the second from August 1st — October 31st, 1979. The former can be characterized by relatively quiet conditions in the heliosphere. The neutron supermonitor at Lomnický štít has registered only two decreases: June 6—7 ($\lesssim 5\%$) and July 7 ($\lesssim 6\%$). No significant increase either of the particle emission at the Sun, or of the K_p-index was observed [14]. But in the period from August 1st — October 31st, 1979 the network of the neutron monitors registered a few long-time and great decreases of the cosmic ray intensity, which were caused by the frequent perturbations in the heliosphere. The K_p-index achieved the value 5—6 four times, and the value 3—4 nine times. Especially the first two months of this period were characterized by the

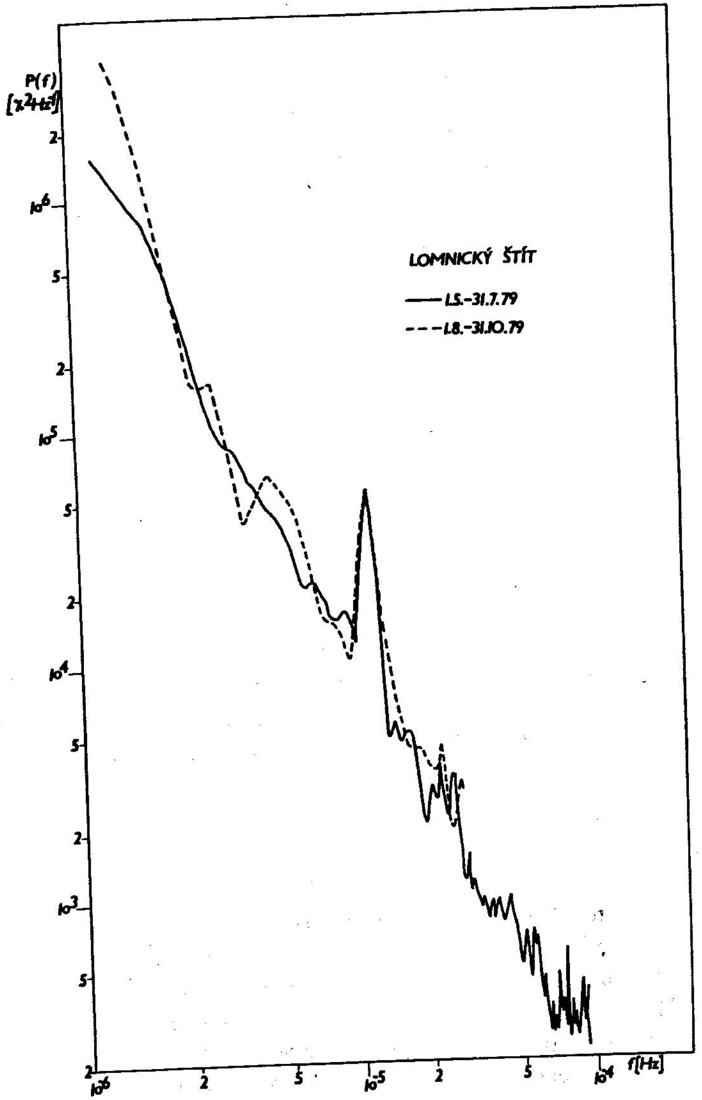

Fig. 1. Power spectra at Lomnický štít, pressure-corrected neutron hourly data for the two periods May 1st — July 31st, 1979 and August 1st — October 31st, 1979.

great helio-longitudinal asymmetry in the distribution of solar activity, which was manifested by the great 27-day variation in the cosmic ray intensity. From the power spectrum of the second period it follows that the diurnal variation is more "scattered" and the semidiurnal variation is absent. But there is observed an

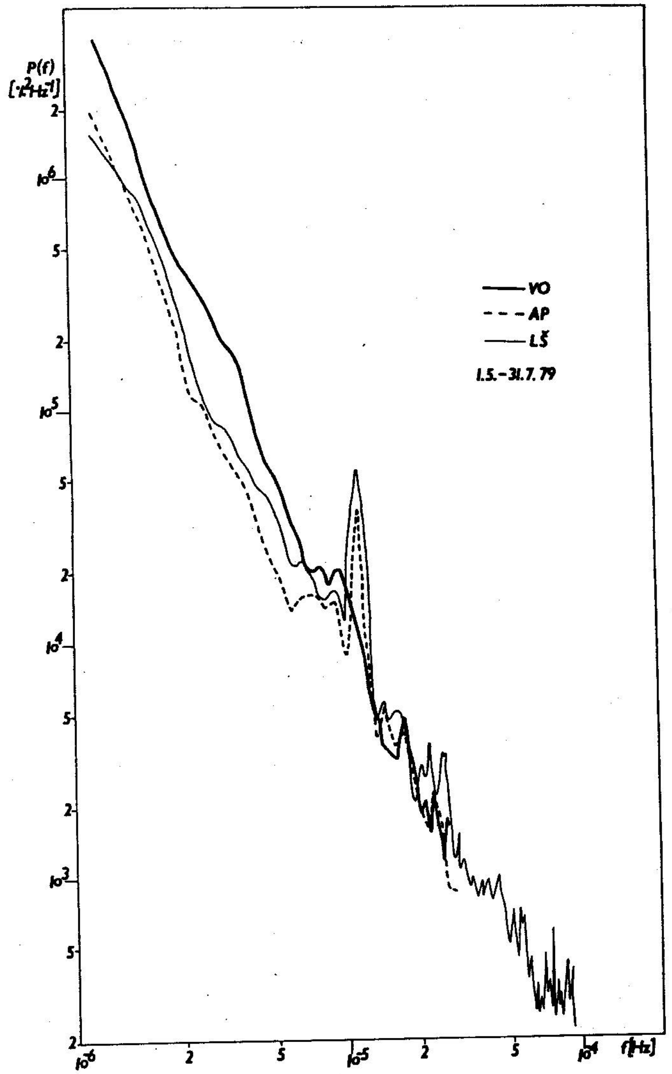

Fig. 2. Power spectra of Apatity (AP), Vostok (VO) and Lomnický štít (LŠ) for the period May 1st — July 31st, 1979.

increase of the power spectrum in comparison with the first period, within nearly the whole range of frequencies. Especially a significant increase is observed at frequencies which correspond to the periods of 2.5; 4 and more than 8 days.

The power spectra of Vostok, Apatity and Lomnický štít neutron monitor stations are compared in Fig. 2. The CR fluctuations for $f \gtrsim 1.3 \times 10^{-5}$ Hz have approximately the same level at all stations, while for $f < 10^{-5}$ Hz the power spectrum of the polar station Vostok significantly prevails. This fact may be connected either with the higher level of the low frequency fluctuations for particles coming from directions perpendicular to the plane of the solar equator, or it can characterize the particles of lower rigidities registered at the Vostok station. The value of the diurnal peak depends on the asymptotic latitude of the station [9, 12, 14].

The power spectrum for the CR intensity of arbitrary stations is disturbed by the noise and variations of a local character. These can be eliminated if we use the cross-covariance function amplitude for the calculation of the power spectrum [15]. In Fig. 3 there are drawn power spectra (heavy line) of the stations at the Jungfraujoch and Lomnický štít, which have similar characteristics (see Table 1). There are shown also power spectra of individual stations for comparison. One can see that the problem of the supplementary noise is relevant already at frequencies above 3×10^{-6} Hz and this has a great influence for frequencies below 3×10^{-5} Hz, although the level of the Poisson noise is about one order lower.

When the method of the crosscovariance function is used only those frequencies remain, which are observed in the CR fluctuations simultaneously at both stations. A high covariance is observed, for example, at the frequency of 2.32×10^{-5} Hz (semidiurnal variation), 1.45×10^{-5} Hz, and, of course, at the frequency of 1.16×10^{-5} Hz (diurnal variation).

The theoretical investigation of the CR fluctuations for $f < 10^{-6}$ Hz is in the previous contribution [16]. The low-frequency fluctuations are caused by diffusion fluxes of particles, which is defined mainly by the asymmetric part of the diffusion tensor if the power spectrum of the inhomogeneous interplanetary magnetic field takes the constant value at these frequencies. By [16], the power spectrum of the CR fluctuations is

$$P(f) = A\,\{1 + (f_1/f)^2\} \tag{4}$$

where

$$A = \frac{B}{(1 + (f/f_0)^2)}.$$

In these relations $B \approx 5 \times 10^5\,(\%)^2\,\mathrm{Hz}^{-1}$; $f_0 \approx 10^{-5}$ Hz; $f_1 \approx 2 \times 10^{-6}$ Hz.

From (4) one can obtain for $f \ll f_0$ that

$$P_1(f) \approx B\,\{1 + (f_1/f_0)^2\}, \tag{6}$$

or

$$P_2(f) \approx B f_1^2/f^2 \quad \text{for} \quad f \ll f_0, f_1.$$

Functions (4) and (6) are represented in Fig. 4. There are given also the power spectra for Jungfraujoch and Lomnický štít, which were calculated from both the autocovariance and the crosscovariance functions in the period 1978—1981. One can see that in the "background" CR fluctuations (4) there are additional peaks caused by frequent perturbations in the interplanetary medium (because of the solar activity maximum) [14]. Some effects connected with solar rotation, like for example corotating structures [17], cause an increase of the power spectrum at the frequency range of $(2 \div 5) \times 10^{-7}$ Hz. The increase at frequencies of 6×10^{-7}—2×10^{-6} Hz can be caused by the Forbush decrease. In [10] a computation was presented of the contribution of the Forbush decreases to the power spectrum, and

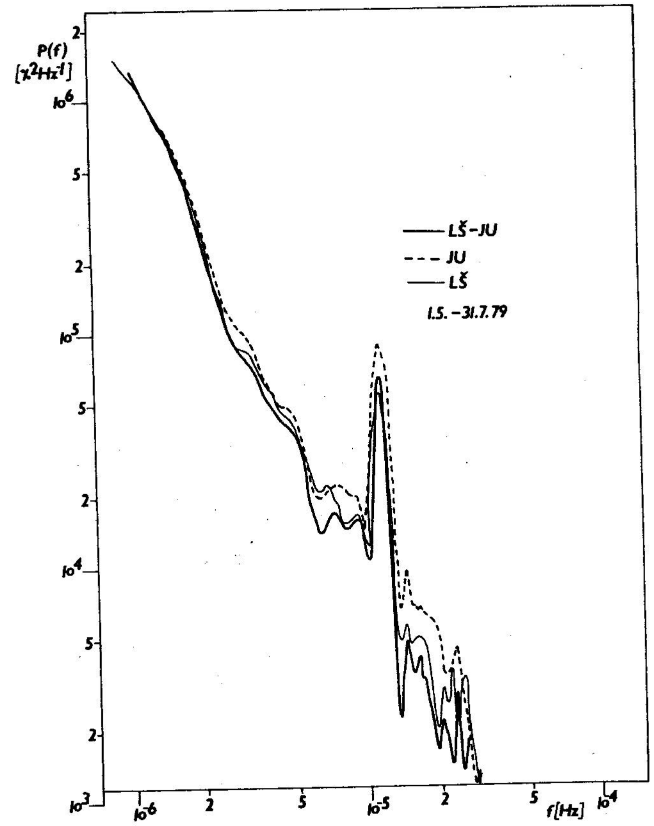

Fig. 3. Power spectra of the Jungfraujoch (JU) and Lomnický štít (LŠ) computed by the autocovariance method. The heavy line indicates the power spectrum computed by the crosscovariance method (LŠ—JU). The period is the same as in Fig. 2.

it was shown that the effects connected with the Forbush decreases can provide the observed value of the power spectrum.

A more complex picture is presented in Fig. 5. There are power spectra computed only by the crosscovariance method, using both the daily means data (for the frequencies below 2×10^{-6} Hz) and the hourly data (above 10^{-6} Hz). The curves overlap, however, one differs from the other in the range of $(1 \div 2) \times 10^{-6}$ Hz, because of the choice of $m = 200$. The thick curve corresponds to formula

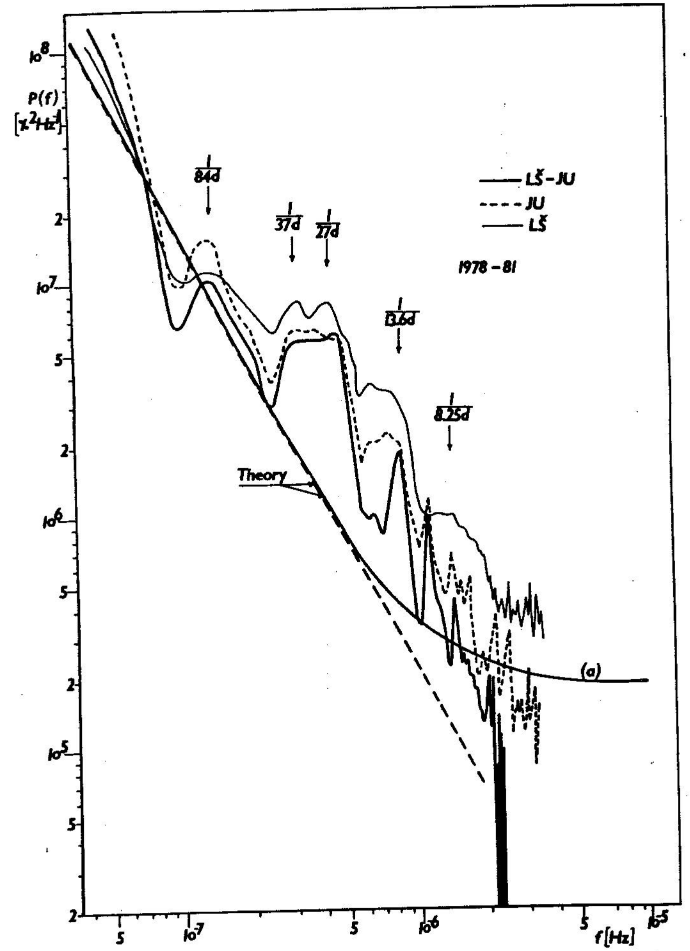

Fig. 4. Power spectra as in Fig. 3 computed from the daily means for the period January 1st, 1978 — November 16th, 1981. The curve corresponds to the theoretical prediction by the formulae (6); the dashed curve corresponds to the prediction by (4)—(5).

(4). The dashed curves correspond to the predications, which do not take into
account the non-field-aligned diffusion of CR particles (curve a) or the power
spectrum magnetic field dependence on the frequency (curve b). From an asympto-
tic behaviour of the CR power spectra it follows that the spectral index μ of the CR
fluctuations is equal to 2 in the range of low frequencies and $\mu = \nu$ (ν is the spectral
index of the interplanetary magnetic field) in the range of high frequencies (in our
case we put $\nu = 2$).

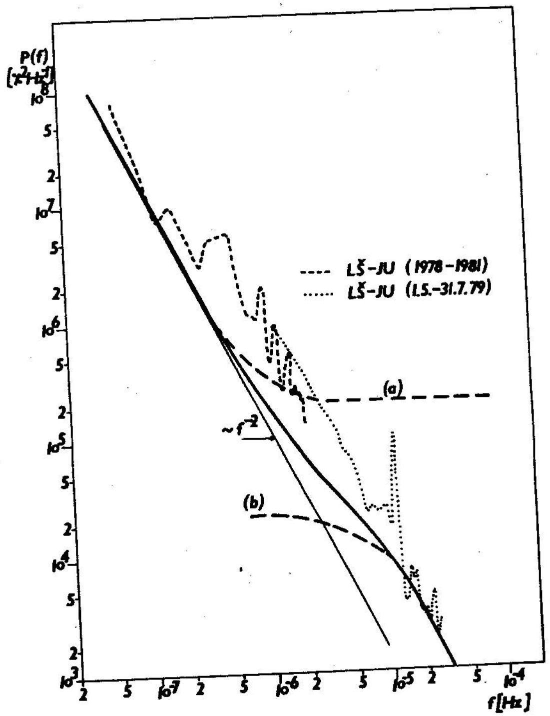

Fig. 5. The comparison of the theoretical predicted and the observed power spectra (see text).

Here we must mention that the relatively high value of $\mu = 2$ for high frequencies can be connected with the non-threedimensioned turbulence of the magnetic field in interplanetary space. In that case the value ν can be smaller ($\nu = 1$, for example) [18].

By theory [16] the value μ changes with the ratio f_1/f_0 in the "transient" range. In our case it would be by the minimal value $\mu_{min} \doteq 1.65$. Because of the amount of perturbations in the period 1978—1981 $\mu \approx 1.95$ in this range, and the real transient range is shifted toward the lower frequencies.

Let us remark further that in the period 1978—1981 the increase of the power spectrum is observed at the frequency which corresponds to 28.5 days in accordance with [17, 19].

IV. DISCUSSION AND CONCLUSIONS

In the present work we have analysed the observed CR intensity fluctuations by using the method of both the autocovariance and crosscovariance analysis. The whole frequency range of the power spectrum changes can be divided into two parts. The low-frequency range with the dependence $\sim f^{-2}$ [16] results due to the diffusion "waves", but the frequent perturbations in an interplanetary medium (and consequently, the changes in the distribution of CR fluxes), which are not taken into account in the theory [16, 20], influence the shape of the power spectra. It concerns the frequency range 5×10^{-7}—2×10^{-6} Hz [10].

The power spectrum in the high frequency range is directly determined by the turbulent interplanetary magnetic field. The asymptotic shape at high frequencies depends on the type of the turbulence and its spectral index v. In our case it is $\sim f^{-2}$).

The mutual consistency of the asymptotic curves needs a further analysis in the transient range and depends on the value of both f_0 and f_1. The shift between these asymptotic curves decreases when f_1 and f_0 are approaching ($f_1 \lesssim f_0$). The smaller f_0 would mean that the magnetic field power spectra increase in the range below $f = 10^{-5}$ Hz (which is more probable in a 3-dimensional scheme). On the other hand, the greater f_1 would mean the smaller value of the diffusion coefficient.

An examination of the auto- and cross covariance methods shows the necessity of using the crosscovariance method in a process of the power spectrum computation for two stations with sufficiently close characteristics. In this way it is possible to effectively eliminate the influence of both the local and the apparatus perturbations (variations) on the true power spectra of the CR fluctuation in interplanetary space.

Concluding it is necessary to emphasize that the changes of the spectral index of the CR fluctuations are caused by the contribution of additional frequencies (connection with the diurnal or 27-day variations, for example), or by various aperiodic phenomena in the wider range of the frequency (the Forbush decreases, for example). Consequently, the value of μ depends on the choice of limits of the frequency range investigated and this can acquire the value $1<\mu<2.5$. For defining the spectral index of the background fluctuations it is necessary to refer the index μ to a sufficiently great frequency range (at least 3 orders).

REFERENCES

[1] Attolini, M. R., Cecchini, S., Guidi, I., Galli, M.: Planet Space Sci. *23* (1975), 1603.

[2] Attolini, M. R., Cavani, C., Cecchini, S., Galli, M.: *Proc. 15th Int. Cosmic Ray Conf.*, Vol. 11, Plovdiv 1977, p. 287.

[3] Attolini, M. R., Cecchini, S., Galli, M.: *Proc. 15th Int. Cosmic Ray Conf.*, Vol. 11, Plovdiv 1977, p. 287

[4] Attolini, M. R., Cecchini, S., Galli, M.: *Proc. 16th Int. Cosmic Ray Conf.*, Vol. 12, Kyoto 1979.

[5] Gehrels, N. L., L'Heureux, J.: *Proc. 15th Int. Cosmic Ray Conf.*, Vol. 4, Plovdiv 1977.

[6] Dorman, L. I., Katz, M. E., Kudela, K., Stehlík, M.: Izv. AN SSSR ser. fiz. (in print).

[7] Dorman, L. I.: *Eksperimentalnye i teoreticheskye osnovy astrofiziki kosmicheskikh luchey.* Nauka, Moskva 1975.

[8] Parker, E. N.: Phys. Rev. *110* (1958), 1445.

[9] Owens, A. J., Jokipii, J. R.: J. Geophys. Res. *79* (1974), 907.

[10] Attolini, M. R., Cecchini, S., Galli, M.: *Proc. 15th Int. Cosmic Ray Conf.*, Vol. 11, Plovdiv 1977, p. 284.

[11] Owens, A. J.: *Proc. 16th Int. Cosmic Ray Conf.*, Vol. 4, Kyoto 1979.

[12] Dorman, L. I., Katz, M. E., Dubinský, J., Stehlík, M.: *Proc. 17th Int. Cosmic Ray Conf.*, Vol. 4, Paris 1981.

[13] Jenkins, G. M., Watts, D. G.: *Spectral Analysis and its Applications.* Holden Day 1968.

[14] Benkova, N. et al., Eds.: *Cosmic Data*, Monthly Review No 5—10, Nauka, Moscow 1980.

[15] Attolini, M. R., Cecchini, S., Guidi, I., Galli, M.: Lett. Nuovo Cim. *11* (1974), 386.

[16] Dorman, L. I., Katz, M. E., Nosov, S. F., Stehlík, M.: Acta Phys. Slov. (in print).

[17] Attolini, M. R., Cecchini, S., Galli, M.: *Proc. 17th Int. Cosmic Ray Conf.*, Vol. 4, Paris 1981.

[18] Dorman, L. I., Katz, M. E., Nosov, S. F., Stehlík, M., Fedorov, Ju. I., Shakhov, B. A.: *Proc. 18th Int. Cosmic Ray Conf.*, Vol. 00, Bangalore 1983.

[19] Nagashima, K., Morishite, I.: *Proc. 17th Int. Cosmic Ray Conf.*, Vol. 10, Paris 1981.

[20] Dorman, L., Katz, M. E., Stehlík, M.: *Proc. 15th Int. Cosmic Ray Conf.*, Vol. 3, Plovdiv 1977.

Received January 18th, 1983