On the rigidity spectrum of the 27-day variation of the galactic cosmic ray intensity in different epochs of solar activity

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***Abstr*act. We study temporal changes of the rigidity R spectrum of the first (27 days), the second (14 days), and the third (9 days) harmonics of the 27-day variation of the galactic cosmic ray (GCR) intensity using neutron monitors experimental data in the period 1965-2002. We show that the rigidity spectra of the first, second and third harmonics of the 27-day variation of the GCR intensity change in the similar way being hard in the maximum epochs, and soft in the minimum epochs of solar activity. This finding generally we ascribe to the geometrical effect of GCR modulation; particularly, to the alternation of the sizes of the modulation regions of the 27-day variation of the GCR intensity in different epochs of solar activity. The average size of the modulation region of the 27-day variation of the GCR intensity is less in the minimum epochs than in the maximum epochs of solar activity. Thus, the larger size of the modulation region of the 27-day variation of the GCR intensity involves higher energy particles of GCR in maximum epochs than in the minimum epochs of solar activity, when the size of modulation is smaller. We do not exclude an existence of other mechanism, as well. Furthermore, we show that the temporal changes of the power rigidity spectra of the first, second and third harmonics of the 27-day variation of the GCR intensity are in a negative correlation with the rigidity spectrum of the 11-year variation of the galactic cosmic ray intensity.**

***Keywords:* 27-day variation of GCR, rigidity spectrum**

I. INTRODUCTION

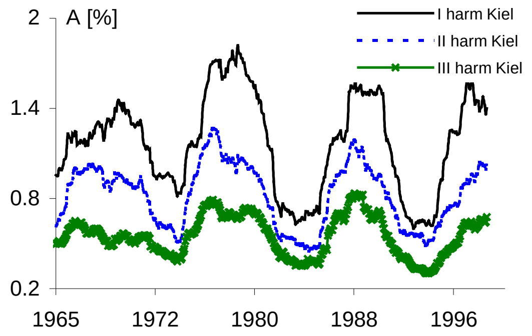
The long-period behavior of the power rigidity R spectrum $\frac{\delta D(R)}{D(R)}$ ($\frac{\delta D(R)}{D(R)} \propto R^{-\gamma}$) of the first, second and third harmonics of the 27- day variation of the galactic cosmic rays intensity were not studied at all up to recent period. In our papers ([1], [8]) we found that the rigidity R power law spectrum of the amplitudes of the first harmonic of the 27-day variation of the GCR intensity is harder in the $A>0$ polarity period (1996-97) and is soft in the $A<0$ polarity period (1986-87). However, this result is not general, as far was obtained only for two periods of different polarity epochs, and needs further studies. Recently we have shown that the rigidity spectra the first (27 days) and the second (14 days) harmonics of the 27-day variation of the GCR intensity calculated by Kiel and Rome neutron monitors data in the period of 1965-2002 change in the same way; the rigidity spectrum is hard in the maximum epochs, and is soft in the minimum epochs of solar activity (paper under review in the Adv. Space Res.)

Richardson and co-authors [12] have found a clear evidence that the size of recurrent cosmic ray modulations is ~ 50% larger during the A>0 cycle than during A<0 cycle. The behavior of the amplitudes of the first and second harmonics of the 27-day variation of galactic cosmic rays in the minimum epochs of solar activity in different solar magnetic cycles of the A>0 and A<0 has been studied by Alania and co-authors (e.g. [1], [4], [5], [9]).

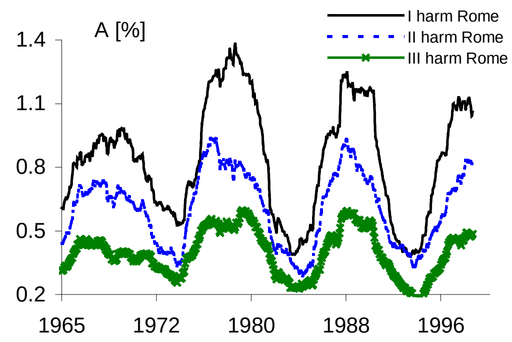
Our aim in this paper is to study the long-period changes of the rigidity spectrum of the third (9 days) harmonic of the 27-day variation of the GCR intensity and compare with the first (27 days) and the second (14 days) harmonics (not studied up to present at all) by neutron monitors experimental data in the period of 1965-2002. Moreover, we want to show that there is a difference between the amplitudes of the third harmonic of the 27 – days variation of the GCR intensity in different polarity periods as for the first and second harmonic amplitudes.

II. EXPERIMENTAL RESULTS OF THE THIRD HARMONIC OF THE 27-DAY VARIATION OF THE GCR INTENSITY

We analyse the long-period changes of the power rigidity R spectrum of the third (9 days) harmonic of the 27-day variation of the GCR intensity in the period of 1965-2002. This type of research requires incessantly functioning neutron monitors in the long period to be studied. Unluckily, it is problematic issue, because only few neutron monitors could suit this require. Because of this reason we choose Kiel and Rome neutron monitors in the period of 1965-2002. To use two neutron monitors for the calcula-



(a) Case I



(b) Case II

Fig. 1ab: Temporal changes of the amplitudes of the first (black line), second (blue, dashed) and third (green) harmonics of the 27-day variations of the galactic cosmic rays intensity calculated using Kiel (a) and Rome (b) neutron monitors in 1965-2002. Data are smoothed over 39 Carrington rotations.

tion of the reasonably reliable rigidity spectrum exponent γ there must be considerable difference between the cut off magnetic rigidities R_m of the selected neutron monitors. This demand is satisfactorily fulfilled for Kiel and Rome neutron monitors; for Kiel neutron monitor the cut off rigidity is R_m= 2.29 GV, and for Rome neutron monitor R_m= 6.32 GV. The difference in the cut off rigidities of the Kiel and Rome neutron monitors data should be reflected in the ratio of the third harmonic of the 27-day variation of the GCR intensity calculated by these neutron monitors data. To decrease the statistical uncertainty of the calculated values of the rigidity spectrum exponent γ we consider amplitudes of the third harmonic of the 27-day variation of the GCR intensity smoothed with running 39 Carrington rotations (about 3 years). The running period about 3 years, at first glance is large, but comparing with the period which is analysed (38 years) it is insignificant (we study the long period changes of the rigidity spectrum).

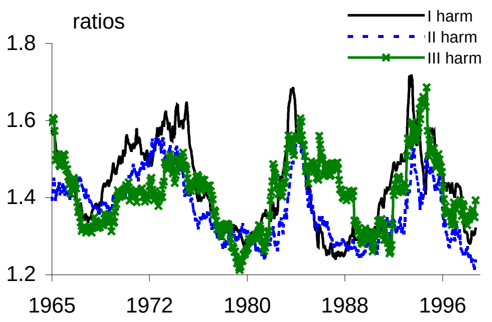


Fig. 2: The temporal changes of the ratios of the amplitudes Kiel/Rome of the first (black line), second (blue) and third (green) harmonics of the 27-day variation of the GCR intensity in 1965-2002. Data are smoothed over 39 Carrington rotations.

In Fig. 1ab are presented amplitudes of the third harmonic of the 27-day variation of the GCR intensity and for comparison amplitudes of the first and second harmonics smoothed with 39 Carrington rotations for Kiel (1a) and Rome (1b) neutron monitors data. In Fig. 2 are presented the ratios of the amplitudes of the first, second and third harmonics of the 27-day variation of the GCR intensity smoothed with running 39 Carrington rotations found by Kiel and Rome neutron monitors data. It is seen from Fig. 2 that the ratios (Kiel/Rome) change in a large scope versus solar activity, which shows that Kiel and Rome neutron monitors data can be successfully used for calculations of the long period changes of the rigidity spectrum of the first, second and third harmonics of the 27-day variation of the GCR intensity.

In the middle ’80 we can see some anomaly in the behaviour of the third harmonic which the reasons of existence we could not explain up to now.

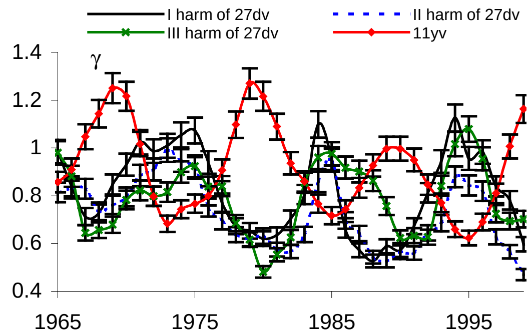
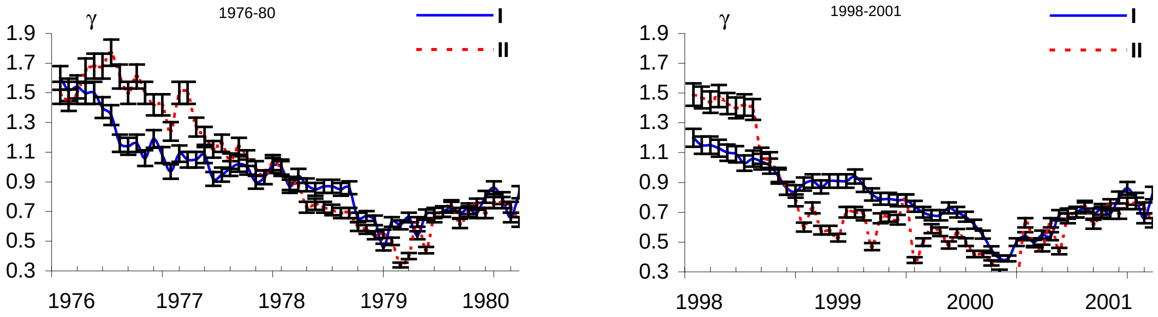


Fig. 3: The changes of the rigidity spectra exponent γ of the first (solid, black line), second (dashed blue) and third (green) harmonics of the 27-day (smoothed over 39 Carrington rotations) and 11-year (red; from [2]) variations of the GCR intensity calculated using Kiel and Rome neutron monitors in 1965-2002.

We calculate rigidity spectrum of the amplitudes of the 27-day variation of the GCR intensity harmonics based on the method presented, e.g. in ([7], [14]):

$$\frac{\delta D(R)}{D(R)} = \begin{cases} A R^{-\gamma} \; for & R \le R_{\max} \\ 0 \quad for & R > R_{\max} \end{cases}$$

where R_{max} is the upper limiting rigidity beyond which the 27-day variation of the galactic cosmic ray intensity disappears, and A equals the amplitude of



(a) Case I (b) Case II

Fig. 4ab: Temporal changes of the rigidity spectra exponent γ of the 27-day variation of the GCR intensity (smoothed over 13 Carrington rotations) in 1976-1980 (4a) and 1998 – 2001 (4b) calculated using **I** (4a): seven neutron monitors (4a – solid blue line); **I** (4b): six neutron monitors (4b – solid blue line) and **II** (4ab): Kiel and Rome (dashed red line).

27-day variation of the galactic cosmic ray intensity harmonics for R=1GV. Following to [13] we take R_{max}=100GV, and then calculate the exponent γ.

Results of calculations of the rigidity spectra exponent γ of the first, second and third harmonics of the 27- day variation of the GCR intensity in the period of 1965-2002 are presented in Fig. 3. For comparison there are also presented the temporal changes of the rigidity spectrum exponent γ of the 11-year variation of the GCR intensity obtained in [2].

Fig.3 shows that the rigidity spectrum of the harmonics of the 27- day variation of the GCR intensity is soft (the average exponent γ =0.96 for the third harmonic) in the minimum epochs, and is harder for the maximum epochs of solar activity (γ =0.59 for the third harmonic), being in a negative correlation with the rigidity spectrum of the 11-year variation of the GCR intensity (the correlation coefficient between the exponent of the rigidity spectrum of the third harmonic of the 27 – day and 11-year variations is $\rho = -76\,\%$).

The first demonstrated, but still fully unexplained result - the dependence of the rigidity spectrum of the 27- day variation of the GCR intensity on the solar activity grounds a natural question about its reasonability, as far that is obtained based only on two cosmic ray stations-Kiel and Rome's experimental data in the period 1965-2002. In connection with this, it is worth to note that there is practically impossible to find well acting cosmic ray stations for a long period, e.g. for 35-40 years, other than these. It is an important requirement to obtain homogeneous results, for comparing, few 11-year solar cycles. Proving our results we calculate rigidity spectrum exponent γ of the 27-day variation of the GCR intensity using few neutron monitors data for two shorter periods (1976-1980 and 1998-2001) including the minimum and the maximum epochs. Results of calculations are presented in Fig. 4ab. Fig. 4a presents results of calculations (solid line) using few neutron monitors data: Apatity, Kiel, Lomnicky Stit, Oulu, Potchefstroom, Rome and Tbilisi and the fragment from Fig. 3 calculated by Kiel and Rome neutron monitors data (dashed line) in period 1976-1980. Fig. 4b presents results of calculations (solid line) using few neutron monitors data: Apatity, Kiel, Moscow, Potchefstroom, Rome and Tsumeb and the fragment from Fig. 3 calculated by Kiel and Rome neutron monitors data (dashed line) in period 1998-2001.

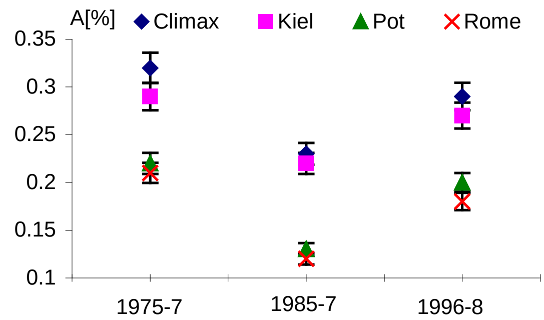


Fig. 5: The temporal changes of the amplitudes of the third harmonic of the 27-day variation of the GCR intensity obtained for different neutron monitors in the A>0 (1975-77 & 1996-1998) and A<0 (1985-1987) polarity periods

We observe that the changes of the profiles and magnitudes of the exponent γ are comparable (practically the same) in a scope of accuracy of calculations for both periods 1976-1980 and 1998 – 2001. The rigidity spectrum is soft in the minimum epochs (1976, 1998) and is hard in the maximum epochs (1980, 2001) of solar activity. Thus, we confirm that Kiel and Rome neutron monitors data in first approximation are good enough to find reliable average values of the rigidity spectra exponent γ of the 27-day variation of the GCR intensity harmonics in period 1965-2002.

We believe that the behavior of the rigidity spectra of the harmonics of the 27-day variation are related with different character of the creation of the 27-day variation of the GCR intensity in the

Table I: Average amplitudes of the 1st, 2nd and **3rd** harmonics of the 27-day variation of the GCR intensity in different A>0 and A<0 polarity periods [%]

Station	Cut off rigidity [GV]	Harmonics	1975-77 A>0	1985-87 A<0	1996-98 A>0
Climax	3.03	1st	0.58 ± 0.05	0.42 ± 0.04	0.65±0.06
		2nd	0.38 ± 0.05	0.31± 0.02	0.47± 0.06
		3rd	0.32 ± 0.04	0.23± 0.02	0.29± 0.03
Kiel	2.29	1st	0.57 ± 0.04	0.37 ± 0.04	0.58 ± 0.06
		2nd	0.39 ± 0.04	0.29± 0.02	0.42± 0.04
		3rd	0.29 ± 0.03	0.22± 0.02	0.27± 0.03
Pothefstroom	7.30	1st	0.39 ± 0.03	0.26 ± 0.02	0.38±0.04
		2nd	0.27± 0.03	0.17± 0.01	0.29± 0.03
		3rd	0.22± 0.02	0.13± 0.01	0.20± 0.02
Rome	6.32	1st	0.37 ± 0.03	0.24 ± 0.02	0.39 ± 0.04
		2nd	0.27± 0.03	0.17± 0.01	0.29± 0.03
		3rd	0.21± 0.02	0.12± 0.01	0.18± 0.02

minimum and in the maximum epochs; particularly, the vicinity of the heliolongitudinally asymmetric region where the 27-day variation of the GCR intensity is created is less for minimum epochs than for the maximum epochs of solar activity [6]. We do not exclude an existence of other mechanisms, too. At the same time, the behavior of the rigidity spectrum of the 11-year variation of the GCR intensity generally is related with the changes of the turbulence of the interplanetary magnetic field vs. solar activity [3]

Using the harmonic analysis method (e.g. [11]) the amplitudes of the first, second and third harmonics of the 27-day variation of the GCR intensity have been calculated based on the data of few neutron monitors with different cut off rigidity. Results of calculations for four neutron monitors: Climax, Kiel, Pothefstroom and Rome are presented in Table and Figure 5 for three minimum and near minimum epochs of solar activity. It is seen from Table and Fig. 5 that the amplitudes of the third harmonic of the 27-day variation of the GCR intensity are greater in the A>0 than in A<0 polarity period. The similar results for the first and second harmonics of the 27-day variation were obtained before (e.g. [10]).

III. CONCLUSIONS

1. We show that the rigidity spectrum exponent γ of the first (27 days), the second (14 days) and the third (9 days) harmonics of the 27-day variation of the GCR intensity calculated by Kiel and Rome neutron monitors data change in the similar way; the rigidity spectrum is hard in the maximum epochs, and is soft in the minimum epochs of solar activity.

2. We show that the temporal changes of the power rigidity spectra exponent γ of the first, second and third harmonics of the 27-days variation of the GCR intensity are in negative correlations with the temporal changes of the exponent γ of the rigidity spectrum of the 11-year variation of the GCR.

3. The amplitudes of the third harmonic of the 27-day variation of the GCR intensity are greater in the A>0 than in A<0 polarity periods of solar magnetic cycle.

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