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Recurrent variations and Forbush decreases of galactic cosmic ray intensity

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Abstract. Although 27-day recurrent variations have been studied for about 60 years, their importance for understanding the global modulation of galactic cosmic rays (CR) is still not fully realised. The recent Ulysses observations in the polar regions of the heliosphere generated new ideas about the importance of 27-day recurrent variations in global processes which lead to galactic CR modulation effects. To investigate the fine structure of CR variations it is important to exclude the influence of Forbush decreases (Fds) on the different types of CR variations, especially when one investigates 27-day variations and recurrent Fds. We investigate 27-day variations and Fds during 1986-1996 based on the data of neutron monitors and Nagoya meson telescopes. To exclude the influence of Fds we used data corrected for Fds. We found that the amplitude of pure 27-day variations (i.e. free from influence of Fds and other non-stationary changes) depends only on the global magnetic field polarity reversal. Because the differences between amplitude corrected and uncorrected for Fds 27-day variations are significant during 1989 and 1991, we investigated these periods in detail. Our data provide clear evidence that the differences in the upper rigidity limit of modulation of 27-day variation and Fds lead to a decay of the Fd contribution in formation of 27-day variation with increasing rigidity of particles. Corrected for Fds data shows the existence of the 27-day CR variation caused by the long-lived magnetic irregularities travelling beyond 1 AU.

1 Introduction

Galactic CR recurrent variations are generated by solar wind and interplanetary magnetic field (IMF) structures. At Earth they recur with the synodic solar (equatorial) rotation period about 27 days, corresponding to a siderial period of 26 days, as observed by interplanetary spacecraft. Usually they are known as 27-day variations when observed from an Earth-orbiting spacecraft or a ground-based instrument. Although 27-day variations have been studied for over 60 years (see review of Simpson, 1998 and references in therein), it is not until the recent Ulysses observations near the polar regions of the heloisphere realized their importance for understanding the global modulation of CR.

Ulysses' surprising observations have reopened basic questions of CR and anomalous component modulation and generated new ideas about the importance of recurrent variations (Simpson, 1998a; Simnett et al., 1998 and references in therein). As a result the number of articles about recurrent variation has rapidly increased (see e.g. Bazilevskaya et al., 1995; Vernova et al., 1995; Sabbah et al., 1995; Alania et al., 1999).

Solar wind large-scale plasma structures known as corotating interaction regions (CIR) are generally recognized as sources of recurrent variations (McDonald et al., 1975; Barnes and Simpson, 1976; Simnett et al., 1998). However, the 27-day recurrent variations are often observed without any CIR and take the form of the recurrent Fds, as it was, for example, during 1980. Shah et al. (1979), Nachkebia and Shatashvili (1983, 1985) have shown that according to the CR neutron monitor data during 1966-1981 years more than 50% of Fds are recurrent, and rigidity spectrum of recurrent and non-recurrent (sporadic) Fds are different. So their nature, as it is expected, is different. The difference between the rigidity spectrum of 27-day variation and recurrent Fds was found as well (Nachkebia, 1986).

It's obvious that superposition of the effects responsible for the 27-day variation and recurrent Fds gives wrong values of the amplitude of CR modulation during these phenomena. Since 27-day variation exists more or less during all phase of solar activity (Shatashvili, 1977), it's necessary to take into account the contribution of Fds in creating of 27-day variations when one studies recurrent variation outside of the solar activity minimum. The question - how the Fds contribute to the recurrent variation,

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and if so by what mechanism, is not solved completely yet. In current work we tried to find answers to some of these questions.

2 The Data and Method

Generally we used daily data of the CR neutron monitors of the stations with different cutoff rigidities (R_c) Kiel (R_c $=2.29GV$) and Tbilisi (R_c $=6.91$ GV) to investigate 27-day variations during the last solar activity cycle (1985-1997). For some periods (1989 and 1991years) we also used hourly and daily data of the following neutron monitors: Thule (R_c $=0.00$ GV), Apatity (R_c $=0.65$ GV), Oulu (R_c $=0.81$ GV), Deep River (R_c $=1.02$ GV), Kiel (R_c $=2.29$ Gv), Moscow (R_c $=2.46$ GV), Climax (R_c $=3.03$ GV), Jungfraujoch (R_c $=4.48$ GV), Rome (R_c $=6.32$ GV), Tbilisi (R_c $=6.91$ GV), Potchefstroom (R_c $=7.30$ GV), Tokyo-Itabashi (R_c $=11.61$ GV). We also used Nagoya meson telescope data with median rigidity from 60 GV up to about 120 GV too.

To exclude the influence of Fds we used the simplest method – all Fds with amplitude more than 3% according to the high latitude stations (R_c < 2 GV, most of them are listed in Cane et al., 1996) were excluded. The CR intensity during Fds was changed into the intensity, calculated according to the formula:

$$I_{Fd} = I_{0,t} + Rn(I_{0,t}) \quad (1)$$

where I_{Fd} is galactic CR intensity corrected for Fds, $I_{0,t}$ is obtained by the line approximation of starting and ending points of Fds, $Rn(I_{0,t})$- random numbers with the same statistics as it was during the quietest 40 days of 1987.

As an example, CR daily intensity corrected for Fds (boxes) and uncorrected (lines) are given on the Fig.1.

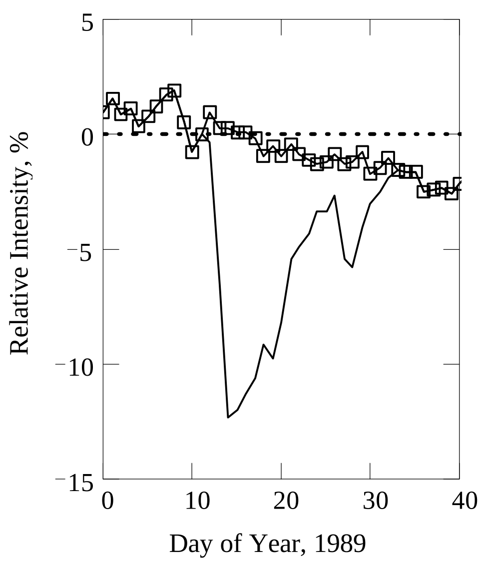

Fig.1. Cosmic ray daily intensity corrected for Fds (boxes) and uncorrected intensity (lines) during the Fds on 13 March and 27 March 1989, according to Kiel (Germany) neutron monitor data.

CR daily detrended intensity was treated by standard Fourier analysis to determine the amplitude of the 27-day variation during each solar rotation. Fig. 2 shows the yearly mean amplitude of 27-day variation of CR intensity during 1986-1996.

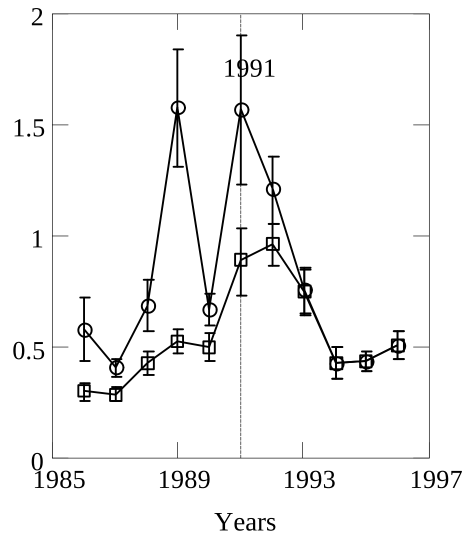

Fig. 2. The yearly mean amplitude of the 27-day variation of CR intensity during 1986-1996. CR daily detrended intensity was treated by standard Fourier analysis. The circles correspond to the original data of Kiel neutron monitor (corrected only for pressure), the boxes – corrected for all Fds with amplitude > 3% according to high latitude neutron monitors. The vertical dot line corresponds to the moment of global magnetic field reversal (1991).

3 Discussion of the Results

Many authors (see e.g. Bazilevskaya et al., 1995; Vernova et al., 1995; Sabbah et al., 1995; Alania et al., 1999) noted that the power spectrum density of 27-day variation of CR intensity manifests a distinct 11-year modulation in phase with the solar activity but has the dips near the periods of the solar magnetic field inversion. There are no dips if one uses data corrected for Fds (boxes - Fig.2). It's obvious, that pure 27-day variations (i.e. free from influence of Fds and other non-stationary changes of intensity – Fig. 2, boxes) depend only on global magnetic field polarity reversal. The reason of dips is clear – the superposition of 27-day variation and Fds gives wrong 27-day variation with enlarged amplitude. During 1989, 5 Fds was observed with amplitude 7-15 %, only one Fd with amplitude 7% during 1990 and 10 Fds with amplitude 7-22% during 1991 (see Cane et all., 1996). Due to the fact that the differences between corrected and uncorrected for Fds 27-day variation are significant during 1989 and 1991 years, we investigated these periods in details.

For the calculation of the rigidity spectrum parameters we used the least square method (Despotashvili et al., 2001). Energy (rigidity) dependence of 27-day variation is described very well with power form – coefficient of correlation between the experimental data and theoretical (calculated) value equals to 0.98. Tab.1 below summarises the results of the calculation of rigidity dependence of recurrent variation during 1989 and 1991 years separately for corrected/uncorrected for Fds data according to 12 neutron monitors and 7 Nagoya meson telescopes. Here *P* – power of the rigidity spectrum, *r*- rigidity spectrum index, R_{max} – the upper rigidity limit modulation of 27-day variation, in the brackets are given ranges of R_{max} and *r* taken into account accuracy of the data.

Table 1. Rigidity spectrum parameters for recurrent variation

Year	Type of Data	R_{max} , GV	-0.01 *r*	*P* , % / Gv
1989	Corr. for Fds	70(50-1000)	48(26-74)	1.04 ± 0.02
1989	Uncorr. for Fds	40(40-60)	24(10-58)	2.66 ± 0.06
1991	Corr. for Fds	200(60-1000)	78(50-80)	1.60 ± 0.02
1991	Uncorr. for Fds	70(50-1000)	56(30-80)	2.77 ± 0.03

Due to the large CR anisotropy during Fds (see e.g. Hofer and Flückiger, 1997), we calculated the rigidity spectrum parameters of isotropic intensity for only the most powerful Fds during 1989 and 1991 years. We assume that 25 hour moving averaged hourly data describe the shock connected decreases (Nachkebia et al., 2001). The rigidity spectrum of Fds vary with large scale (Tab. 2), so it's difficult to estimate the contribution of Fds in formation of recurrent variation. However we noted a tendency that the upper rigidity limit of pure (corrected for Fds) recurrent variation is more than for Fds. This idea is supported by results of calculation of the CR intensity power spectrum density (PSD) during 1989, 1991 (Fig.3,4).

Table 2. Rigidity spectrum parameters for some Fds during 1989 and 1991 years.

Year Date	R_{max} , GV	-0.01 *r*	*P*, %/ GV
1989 Feb. 13	100(50-1000)	56(20-70)	5.37 ± 0.15
1989 March 13	40(30-50)	52(44-60)	20.41 ± 0.38
1989 May 23	1000(60-1000)	90(62-96)	6.23 ± 0.16
1989 June 8	1000(50-1000)	88(66-100)	5.33 ± 0.10
1989 June 13	60(40-200)	48(10-74)	6.99 ± 0.17
1989 Sept. 3	90(60-1000)	80(66-96)	10.52 ± 0.20
1989 Oct. 20	100(70-1000)	78(68-88)	17.01 ± 0.30
1989 Nov. 28	50(40-70)	46(42-64)	16.11 ± 0.33
1989 Dec. 27	40(30-100)	68(24-104)	6.24 ± 0.23
1991 March 24	200(100-1000)	60(48-68)	15.51 ± 0.30
1991 April 25	40(30-50)	34(24-44)	10.89 ± 0.28
1991 Oct. 28	40(30-50)	24(18-30)	15.69 ± 0.30
1991 Nov. 8	1000(70-1000)	74(46-82)	7.20 ± 0.23

We used a Bartlet filter with window ½. The PSD of corrected for Fds data (bottom panels) has a sharp maximum near 27 days according to all discussed stations. The PSD of original data (top panels) has a wide maximum which becomes sharper with increasing median rigidities. This data provide clear evidence that differences of upper

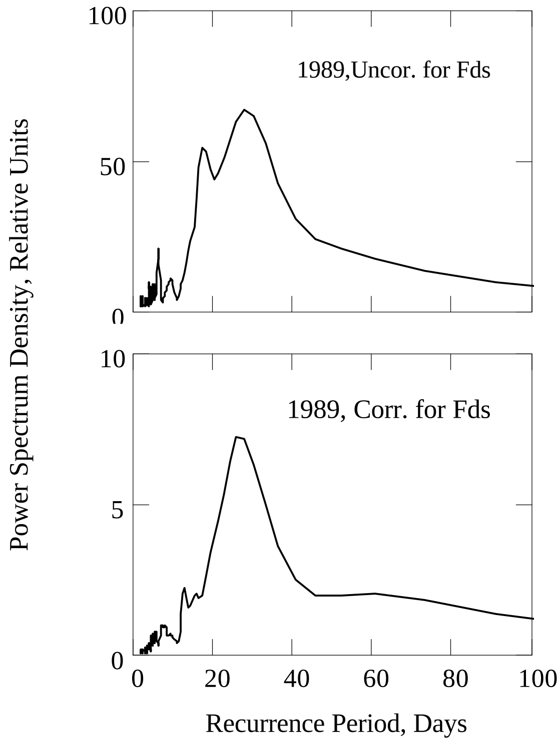

Fig. 3. Power spectrum density of detrended Kiel neutron monitor data during 1989. To guide the eye the x-axis presents the period of recurrence instead of frequency.

rigidity limit of modulation of 27-day variation and Fds lead to a decrease of Fds contribution in the formation of 27-day variation. So superposition of Fds and 27-day variations leads to an increase of the amplitude of recurrent variation, but contribution of Fds in formation of recurrent variations decrease with increasing of rigidities of particles. One of the possible scenario of above discussed facts might be following. CR Fds generally consist of two steps (Barnden, 1973; Flückiger, 1985; Sanderson et al., 1990; Cane et al., 1994) caused by the combination of shocks and coronal mass ejections (CME). They are local characteristics of interplanetary media and produce the modulation of relatively low energy particles. Recurrent variations are connected not only with local parameters of interplanetary media, but with global processes in heliosphere (Simnet et al., 1998, Simpson, 1998a), which leads the modulation of relatively high energy particles. Maybe it is the reason that maximum of recurrent variation delays to the maximum of neutral sheet tilt distribution (plot isn't presented).

We tried to evaluate some ideas about connection between quasi-permanent 27-day CR variation and long-lived magnetic irregularities travelling beyond 1 AU (Bazilevskaya et al., 1995). The superposed epoch analyses was made for the Kiel neutron monitor data from 1986 to 1996 years. 62 zero days are selected as the beginning of Fds according to Cane et al. (1996). The recurrent variation is clearly seen during the second rotation and equals to

(0.51± 0.32) % and (0.17± 0.07) % for direct and corrected for Fds data respectively. Important note – the selected Fds aren't uniformly distributed over a Bartel's rotation, about 20 cases are recurrent Fds with the period of recurrence 27±2 days. So they can form 27-day variation

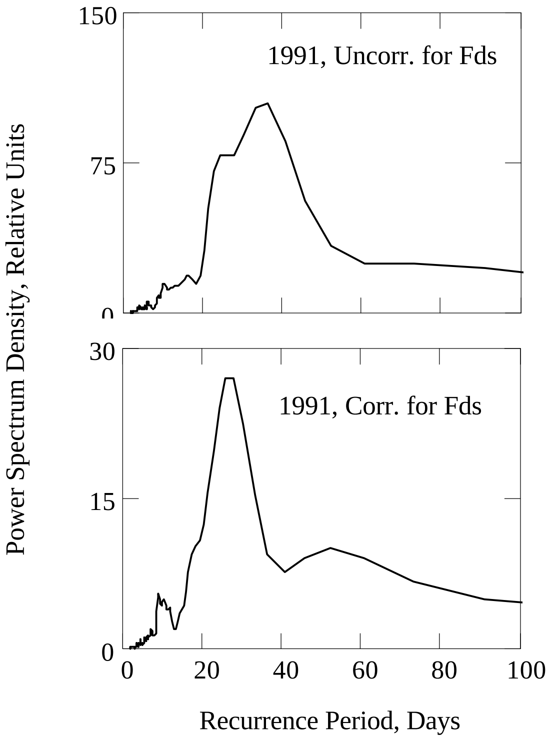

Fig. 4. Power spectrum density of detrended Kiel neutron monitor data during 1991. To guide the eye the x-axis presents the period of recurrence instead of frequency.

during the second rotation, but corrected for Fds data show the reality of existence of 27-day CR variation caused by the long-lived magnetic irregularities travelling beyond 1 AU. Further studies of the fine structure of the recurrent variations and Fds are needed to provide new insight into global modulation phenomena.

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