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RAPID COSMIC RAY FLUCTUATIONS: EVIDENCE FOR CYCLIC BEHAVIOUR

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Abstract. We study rapid cosmic-ray fluctuations using 5-min resolution data from eight neutron monitors with different cutoff rigidities as well as from the ACE satellite. We define a proxy index of rapid cosmic-ray fluctuations as the mean power of the cosmic-ray power spectrum in the frequency range $10^{-4} - 1.67 \times 10^{-3}$ Hz (10 min to about 3 h). A dominant 11-year periodicity in the index is found in all neutron monitors. We also report on intermittent, short-term periodicities in the power of rapid cosmic-ray fluctuations. A strong mid-term periodicity of about 1.6 – 1.8 years, possibly related to a recently found similar periodicity in IMF, appears in CR fluctuation power since the 1980s. Another strong periodicity is found at 1 year, which is likely related to the relative position of the Earth in the heliosphere. These results also provide new challenge to test the cosmic-ray modulation theory.

1. Introduction

The intensity of cosmic rays (CR) varies at different time scales, from minutes to decades and even beyond. These variations can be studied using data from ground based neutron monitors (NMs). Here we study quasi-periodic variations from minutes to several hours, that are also called rapid CR fluctuations (Kozlov *et al.*, 1973; Kozlov and Rybnikova, 1978; Dorman and Libin, 1985; Starodubtsev, 1985; Perez-Peraza *et al.*, 1998; Kudela, Martin, and Bobik, 1999). The power spectrum of rapid CR fluctuations is related to the turbulence of the interplanetary magnetic field (IMF) (Owens, 1974; Toptygin, 1985; Berezhko and Starodubtsev, 1988). However, due to the different physical processes affecting the interplanetary medium, the nature of this turbulence is not well established. Different indices of CR fluctuations have been used to describe its behaviour in different frequency domains and time scales (see, e.g.; Kozlov, Tugolukov and Vasheniuk, 1990; Kudela and Langer, 1995; Kudela *et al.*, 2000). Berezhko, Brevnova, and Starodubtsev (1993) found a significant solar cycle variation in the CR fluctuation magnitude for 1980 – 1990 using 5-min data from the Tixie Bay NM. A solar cycle change was also found in the spectrum of small-scale turbulence (Starodubtsev, 1999). Recently, the solar cycle variation in CR fluctuations was verified for two solar cycles (1980–2002) using data from two remote polar NMs, Oulu and Tixie Bay (Starodubtsev and Usoskin, 2003). However, the cause of the solar cycle variations and its energy/rigidity dependence is still unresolved.

2. Data and Method

We use 5-min data of CR intensity from eight NMs (Table I), covering a wide range of geographical locations. All the stations provide 5-min data at least over one solar cycle, the longest series being available from the Oulu station since 1970. We use also 5-min data from the highest energetic channel (P8, 1.91–4.75 MeV) of ACE/EPAM/LEMS30 from the Level 2 database since late 1997.

Before the analysis, raw data were pre-processed as follows. We included only those days where gaps or apparent errors did not exceed 2 h. Days with ground level enhancements were also excluded. All measured data N were normalized to the percentage from the average level N_o within each day, $I = \frac{N-N_o}{N_o} \times 100\%$, and a linear trend was subtracted for each day. Finally, the data was subjected to a band-pass filter with the bandwidth ($\nu_1 < \Delta\nu < \nu_2$), where $\nu_2 = 1.67 \times 10^{-3}$ Hz (600 sec) is the Nyquist frequency. A typical CR fluctuation spectrum (see Figure 1) has two distinct parts: an approximate power-law spectrum at low frequencies and a flat part above about $\nu_1 = 10^{-4}$ Hz. This latter part is the subject of the present study (see also Berezhko, Brevnova, and Starodubtsev, 1993; Kudela and Langer, 1995; Starodubtsev, 1999; Starodubtsev and Usoskin, 2003). Significant dynamical changes occur in this frequency range and lead to a change in the level of the flat part between solar minimum and maximum, as seen in Figure 1. We have calculated the daily power spectra of CR fluctuations in the frequency range [ν_1, ν_2] using the standard Blackman–Tukey algorithm (Blackman and Tukey, 1958) with the

TABLE I

Parameters of the used neutron monitors: detector type, geographical latitude λ, longitude ϕ, geomagnetic rigidity cutoff P_c and the altitude h. Last two columns depict the best cross-correlation coefficient r and time delay τ (in bartels) between R_Z and the CR fluctuation index for the given NM.

Station	Type	λ (°N)	ϕ (°E)	P_c (GV)	h (m)	r	τ
Tixie Bay	12NM64	71.6	128.9	0.5	15	0.69 ± 0.04	11
Oulu	9NM64	65.0	25.5	0.8	15	0.58 ± 0.03	13
Calgary	12NM64	51.1	−114.1	1.1	1128	0.65 ± 0.03	11
Kerguelen	18NM64	−49.4	70.3	1.2	33	0.75 ± 0.04	5
Kiel	18NM64	54.3	10.1	2.3	54	0.67 ± 0.04	12
Lomn. Štít	8NM64	49.1	20.1	3.8	2634	0.77 ± 0.03	0
Hermanus	12NM64	−34.4	19.2	4.9	26	0.85 ± 0.02	3
Rome	18NM64	41.9	12.5	6.3	60	0.69 ± 0.05	6

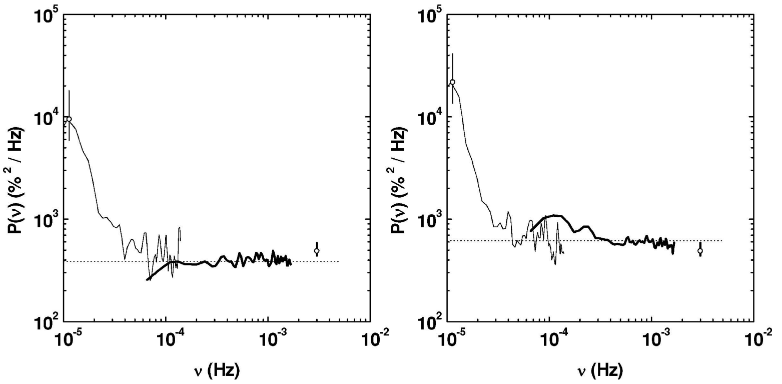

Figure 1. Typical spectrum of CR fluctuations at the Oulu cosmic ray station calculated for a 27-day period in March 1997 (solar minimum: *left panel*) and in June 1990 (solar maximum: *right panel*). Error bars depict the 95% confidence interval.

Tukey correlation window. The average power in this frequency range is called the daily p-value. An index of CR fluctuations P is defined as the 27-day average of the daily p-values, e.g., in order to avoid the possible influence of longitudinal inhomogeneities in the solar wind and corona.

3. Results and Discussion

The obtained long-term evolution of the CR fluctuation P index is shown in Figure 2 for the eight NMs, together with the CR intensity (Oulu NM) and the sunspot numbers shown in the top panels.

3.1. 11-YEAR CYCLE

A strong roughly 11-year cyclic variation in phase with the solar activity cycle is apparent in Figure 2. The longest series of Oulu NM covers three solar cycles and depicts the cyclic variation throughout the whole time interval. This essentially extends the earlier finding of the 11-year cyclic variability of CR fluctuations (Berezhko, Brevnova, and Starodubtsev, 1993; Starodubtsev and Usoskin, 2003). The use of data from many stations allows us not only to improve the statistical significance and physical reliability of the phenomenon but also to study its energy/rigidity dependence. Although data from different CR stations cover different time spans, the 11-year variation of P is clear in all, thus confirming the observed phenomenon. The large cross-correlation coefficients (0.58 – 0.85; see Table I) between R_z and P using Bartel rotation averaged data are highly significant (all are better than 10^{-6}). The best correlations were found for delays ranging from 0 – 13 Bartels rotations, in agreement with the time delay for CR intensities (see, e.g., Usoskin *et al.*, 1998).

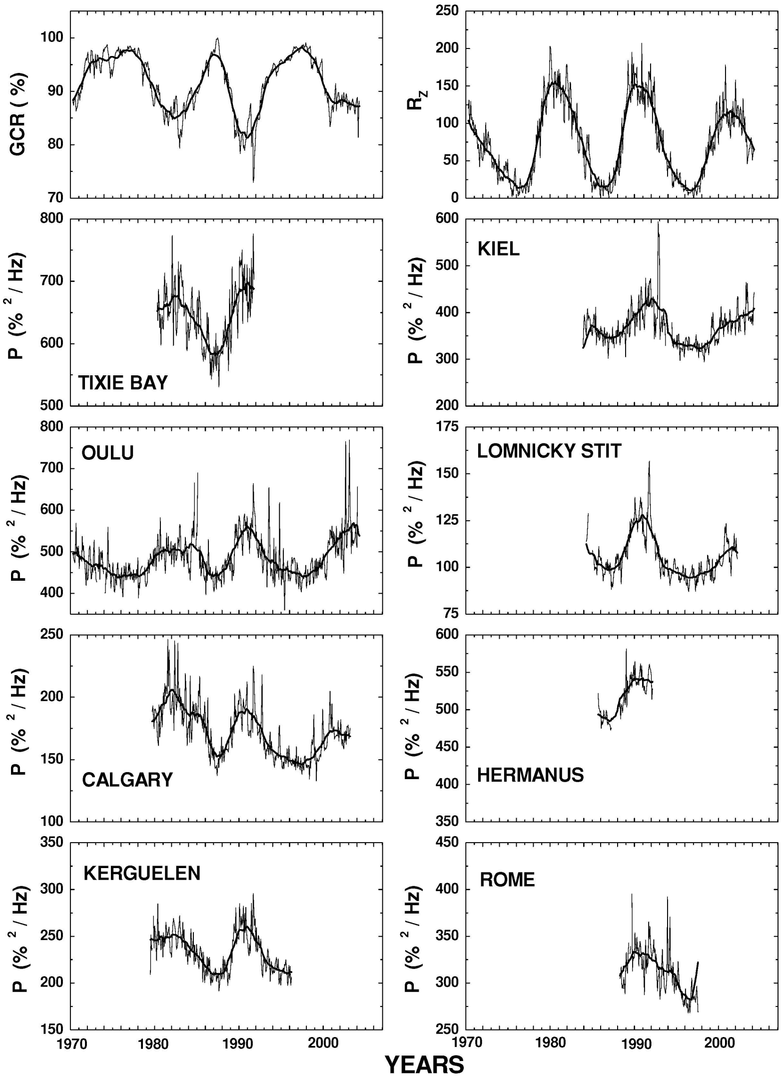

Figure 2. CR fluctuations for eight NMs as denoted in the panels. *Thin* and *thick curves* correspond to the 27-day averaged and 2-year running mean values, respectively. *Top panels* represent the time profiles of CR intensity (Oulu NM) and sunspot numbers.

We have defined the amplitude of the 11-year variation as $\Delta P = (P_{\max} - P_{\min})/2$, where $P_{\max}$ and $P_{\min}$ correspond to the smoothed P values for the maximum and beginning of cycle 22 (which is covered by all stations except Rome). The dependence of the amplitude ΔP on the geomagnetic cut-off rigidity R_c of the CR station is shown in Figure 3. ΔP decreases with increasing R_c by a factor of $\sim$5 between polar and mid-latitude stations, implying the extraterrestrial nature of the phenomenon. A power law approximation of this dependence yields a spectral

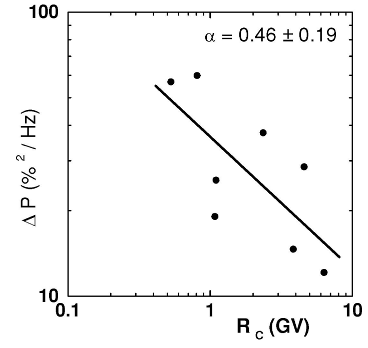

Figure 3. Dependence of the amplitude of 11-year variation of CR fluctuations on the geomagnetic cut-off rigidity (see Table I). The *solid line* depicts the best fitting power law with the spectral index α.

index of about 0.5. In order to extend this study to higher rigidities, 5-min data from equatorial CR stations would be needed. However such data are not available. On the other hand, the lower energy/rigidity range cannot be studied using NM data, but would require long-term space-borne CR measurements.

Although the time interval covered by the ACE/EPAM/LEMS30 data (since late 1997) is too short to study the 11-year cyclicity, the temporal behaviour of both intensity and fluctuation index of these low energy (1.91–4.75 MeV) CR is contrary to that of ground based NM data (Figure 4). This can be understood, e.g., within the following scenario. When a solar/interplanetary particle event occurs, which is typical around solar maximum, strong fluxes with large gradients of low-energy particles are observed. Such particles can generate MHD waves (see, e.g.,

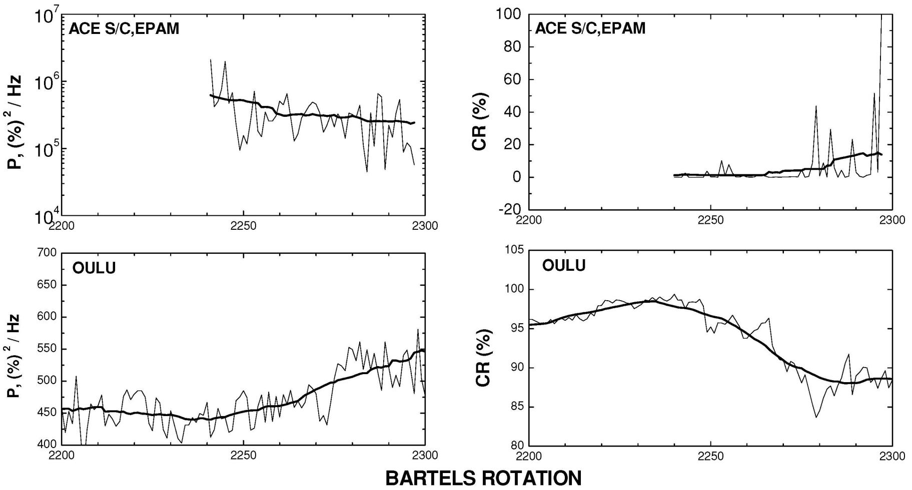

Figure 4. The fluctuation index (*left panels*) and intensities (*right panels*) of cosmic rays measured by the ACE/EPAM (*top panels*) and Oulu NM (*bottom panels*).

Berezhko, 1986; Reames, 1989; Berezhko, 1990), which modulate galactic CR intensities leading to the observed CR fluctuations. Two possible mechanisms of the origin of CR fluctuations are discussed: Alfvén or fast magnetosonic waves. The relation between power spectra of CR fluctuations $P_n(\nu)$ and of IMF $P_B(\nu)$ in the case of Alfvén turbulence, which only modulates the anisotropic part of the CR distribution function, is (Owens, 1974):

$$\frac{P_n(\nu)}{n_o^2} = \frac{P_{B_\perp}(\nu)}{B_o^2}\, C(\nu)\, \delta_\parallel^2, \tag{1}$$

where $C(\nu) \sim 1$ is the dimensionless resonance function, n_o and B_o are the average values of CR flux and IMF strength at 1 AU, respectively, and $\delta_\parallel \sim 1\%$ is the CR anisotropy. On the other hand, the relation between CR and IMF fluctuation spectra in the case of fast magnetosonic waves, which modulate not only the anisotropic part ($\sim 1\%$) but also the isotropic part of the CR distribution function is (Berezhko and Starodubtsev, 1988):

$$\frac{P_n(\nu)}{n_o^2} = \frac{P_B(\nu)}{B_o^2}\left(\frac{(\gamma + 2)C_a(C_w + U\sin\phi)}{3\sqrt{2}\kappa_\perp \nu}\right)^2, \tag{2}$$

where $\gamma = 2.7$, C_a and C_w are the Alfvén and wave velocities, U is the solar wind speed, ϕ is the azimuth IMF angle, and $\kappa_\perp$ is the CR perpendicular diffusion coefficient. While Equation (1) adequately describes the behaviour of the CR fluctuation spectrum up to $\nu \sim 10^{-4}$ Hz, it diverges from observations for higher frequencies. This may be due to the very small anisotropy factor $\delta_\parallel^2$. On the other hand, Equation (2) agrees with observational spectra also for the frequency above 10^{-4} Hz. In the above scenario, low-energy particles lose their power in the corresponding frequency range because they excite MHD-waves of the magnetosonic type. This leads to the observed decrease of lower-energy CR fluctuation index with increasing solar activity and to the increase of high-energy CR fluctuation index. Since the 11-year variation of the CR fluctuation index in phase with solar activity is not present in the energy range below ~5 MeV, its lower limit lies somewhere between 5 MeV (ACE data) and ~1 GeV (polar NMs).

3.2. MID-TERM QUASI-PERIODICITIES (MTQP)

Figure 2 reveals large shorter-period variations in the CR fluctuation index P, on top of the 11-year cycle. In order to study the period and time evolution of these variations in more detail, we have performed a wavelet analysis of this data series as well as of CR intensity at Oulu NM and of the IMF intensity given by the OMNI database (Figure 5).

Note first the strong 1.6–1.8-year MTQP power in CR intensity which starts in the 1970s and extends until the 1990s (Valdes-Galicia, Perez-Enriquez, and Otaola, 1996; Mursula and Zieger, 1999). The CR intensity spectrum also includes two shorter and less intense bands at about 1.2–1.4 years in the 1970s and 1990s

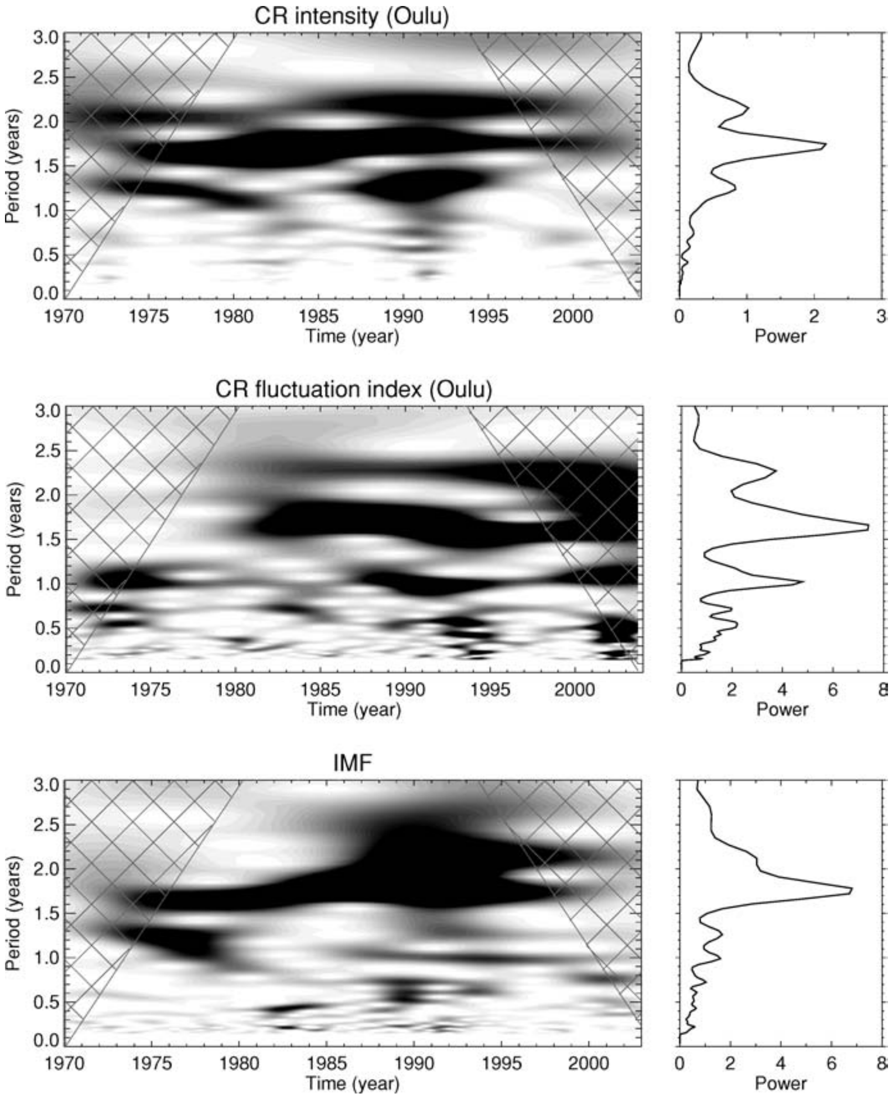

Figure 5. Wavelet dynamic spectrum (*left*) and power spectrum (*right*) of the detrended time series. *Top, middle* and *bottom panels* correspond to CR intensity at Oulu NM, rapid CR fluctuations at Oulu, and IMF intensity (OMNI database) respectively. *Hatches* denote the uncertainty areas at ends.

(Mursula and Zieger, 1999). These three bands closely correspond to the similar MTQP bands found in solar wind and geomagnetic activity (Mursula and Zieger, 2000; Mursula, Zieger, and Vilppola, 2003). These alternating-period bands have recently been suggested to be related to similar fluctuations in the solar convection zone, and thereby to solar dynamo action (Mursula and Vilppola, 2004). Another burst at about 2.2 years appears in the 1990s.

The MTQP power structure in IMF intensity (lower panel of Figure 5) resembles greatly that in CR intensity (upper panel). The main feature is the long 1.6 –1.8-year band whose relative strength is stronger than that of the other bands. In particular, the 1.2–1.4-year band remains quite weak and disappears in the 1990s. Comparing the CR and IMF intensity spectra in the MTQP period range, it is clear that while IMF fluctuations are important for CR modulation, being largely responsible for the 1.6 –1.8-year fluctuations, the solar wind also affects CR fluctuations, probably causing the 1.2–1.4-year fluctuations in the 1990s.

The MTQP power structure of rapid CR fluctuations (middle panel of Figure 5) shows fair similarity with that of the IMF intensity. The 1.6 –1.8-year band is the dominant feature in the MTQP range but it only starts in the 1980s, i.e., later than in the IMF, and seems to continue longer than in the IMF (subject to the wavelet edge uncertainty). Most notably, the lower-period bands at about 1.2–1.4 years do not appear in the CR fluctuation spectrum at all. This is in agreement with the above view that only the IMF properties, not solar wind, affect the CR fluctuations.

3.3. ANNUAL CYCLICITY

Note also that below the MTQP period range, narrow bands at the period of exactly 1 year appear in the power spectrum of CR fluctuation index. This periodicity is related to the relative position of the Earth and the structure of the heliospheric current sheet, and will be studied in a separate work.

4. Conclusions

Concluding, we have studied CR fluctuations using 5-min data from eight neutron monitors covering up to three solar cycles. The CR fluctuation power has a clear 11-year cyclic variation which is in phase with solar activity in all analyzed series. The solar cycle amplitude decreases with the geomagnetic cutoff rigidity in a rough power relation with $\alpha = 0.46 \pm 0.19$. We have argued that the rapid CR fluctuations (above 10^{-4} Hz frequency) have an interplanetary origin and are most likely due to the magnetosonic turbulence in IMF. A persistent 1.6 –1.8-year periodicity appears in CR fluctuation power since 1980, which greatly resembles the similar variations in IMF intensity. Solar wind speed fluctuations do not cause variations in CR fluctuation power. We also note on an intermittent appearance of an exactly 1-year variation of CR fluctuation power.

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