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On Mid-Term Periodicities in Cosmic Rays

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Abstract The contributions of quasi-periodic variations of cosmic rays for $T > 27$ days at the primary energies to which neutron monitors are sensitive have a rather complicated character. They were reported in several papers (*e.g.* Valdés-Galicia, Perez-Enriquez, and Otaola, 1996; Mavromichalaki *et al.*, 2003; Kudela *et al.*, 2002; Caballero and Valdés-Galicia, 2001) from individual stations and for various time intervals covered. The data archive of several neutron monitor stations developed within the NMDB project (www.nmdb.eu) now involves long time series of measurements at neutron monitors situated at different geomagnetic cutoff rigidity positions and at different altitudes. It is updated continuously. Using the daily averages of cosmic-ray intensity at three selected stations within NMDB: *i*) the temporal evolution of the selected quasi-periodicities, especially those of approximately 1.7 yr, 150 days and 26 – 32 days respectively, until 2008 are reviewed, *ii*) the similarities of the spectra are checked and *iii*) the occurrence of quasi-periodicities with those observed in solar, interplanetary and geomagnetic activities (Moussas *et al.*, 2005; Richardson and Cane, 2005) as well as in energetic particles below the atmospheric threshold are discussed (Laurenza *et al.*, 2009).

Keywords Cosmic rays · Neutron monitors · Periodicities

1. Introduction

The cosmic-ray variability over long time interval is relatively well known for the era of direct measurements and a summary of the experimental and theoretical knowledge on this

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can be found *e.g.* in Dorman (2004). The modulation leading to the variability of cosmic-ray flux and the quasi-periodicities related to that effect are still studied and described by the analysis of the neutron monitor data recently by Zarrouk and Bennaceur (2009). The description of the variability of cosmic rays is important for the discussions of its influence on the atmosphere. The modulation is important for cosmic-ray particles with energies < 50 GeV and its ionisation is predominant in atmospheric layers already above a few kilometres. A review on related subjects can be found in de Jager (2005). A current hypothesis is that the variable ionisation may affect the degree of cloudiness, and the discussion on that is continuing (Sloan and Wolfendale, 2008). The cosmic-ray flux at energies to which the neutron monitors are sensitive is modulated by a complex of physical processes in the heliosphere driven mainly by events on the solar surface. Thus, comparison of the temporal profiles of quasi-periodic characteristics representing the solar activity with those of cosmic rays is of great interest. Today there are records of neutron monitors at various places with different duration of operation. Here we present some characteristics of cosmic-ray variability, mainly of quasi-periodic character, using data of the three neutron monitors which are only a sample of the more extensive archive created at present within the NMDB project.

2. Integral Power Spectrum and Selected Quasi-Periodicities

Daily means from three neutron monitors, namely Kiel (from day 182 of 1957 until the end of year 2008), Oulu (from day 92 of year 1964 until the end of year 2008) and Lomnický štít (day 1 of 1982 until day 182 of 2007) are used. For the power spectra we used a FFT technique with the Welch window method. The data gaps are either extrapolated from neighbour days (if the gap is smaller than four days) or the technique is used for spectra of unevenly spaced data, which does not affect the spectra for the slightly longer gaps. Results are presented in Figure 1. The slope of the power spectrum density is larger above about $T = 20$ months, which is consistent with Kudela, Ananth, and Venkatesan (1991) based on data before 1990 at the Climax and Calgary neutron monitors. The two relatively well pronounced quasi-periodicities, namely those at approximately 1.7 yr and at ≈ 150 days are seen in both spectra.

The spectral composition of time series of cosmic rays (CR) has a rather complicated character. The slope fitted is affected by the contribution of several quasi-periodicities in the signal related to the quasi-periodic character of the solar wind, interplanetary magnetic field (IMF), as well as irregular appearance of coronal mass ejections affecting the modulation.

The comparison of the spectral shape of CR in two different frequency intervals at the two neutron monitors is presented in Figure 2. Kiel and Oulu cover a longer time interval of measurement than Lomnický štít. There is relatively clear consistency in the shape and in the values of the power spectrum density (PSD) at all three selections in the frequency interval covered. The middle panel illustrates a rather clear quasi-periodicity of approximately 1.7 yr, reported from other data and earlier periods. The lower panel, showing again a similarity in spectral shape, demonstrates probably the double peak structure of quasi-periodicity, namely at 154 and at 148 days.

The power spectra of the three stations (including also a high-altitude one) during the long time period for which the data are simultaneously available is illustrated in Figure 3. The spectral indices of PSD versus frequency are similar. The long interval of measurements covers epochs with both solar magnetic field polarities. Sabbah and Duldig (2007) showed different slopes at higher energies for positive and negative polarity. The value of the spectral index here is between the values for $A > 0$ and $A < 0$ in the cited paper.

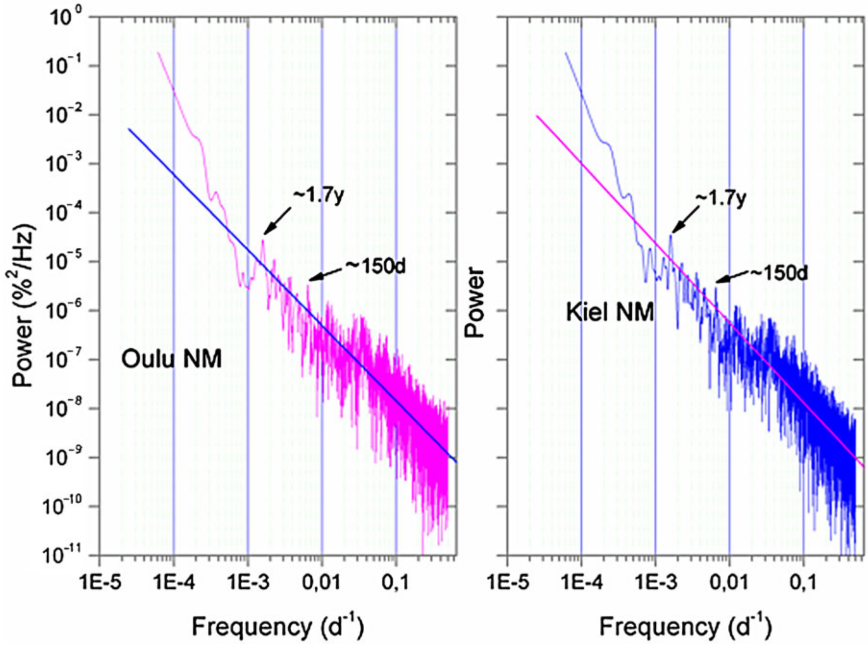

Figure 1 Power spectra of Oulu and Kiel neutron monitors constructed from daily means of pressure-corrected data for the period from day 92 of year 1964 until the end of year 2008.

The power spectrum density in wide interval of frequencies has a form of power-law with the index of approximately 1.7. Thus for revealing the local quasi-periodicities in the spectra for the frequency range around ≈ 27 days we have used the technique of minimum variance described *e.g.* by Kay (1988). By using different techniques we found one to provide a stable solution regarding the occurrence of quasi-periodicities. We have selected the frequency window between 0.03 and 0.04 day^{-1}, detrended the data and normalised the signal to unit power for all three neutron monitors. By Fourier filtering in that frequency interval and consequent reconstruction and subsequently using the minimum-variance method we obtained the PSD in the vicinity of ≈ 27 day period. This is presented in Figure 4. Although the values of PSD at the three neutron monitors are not identical, the similarity of the shape and positions of the maxima (27.4 – 27.5 and 29.9 – 30.3 days well above the statistical significance of 0.95 and with the gap in between) at all monitors are probably not accidental. Hasler, Rudiger, and Staude (2002) showed the complicated structure of differential rotation of the solar disc deduced from the chromospheric line emissions. The authors indicate that beside the basic period around 27 days there are signals at 32 – 35 days corresponding to the rotation rate at very high latitudes. Since cosmic-ray modulation is affected also by the high-latitude structure of IMF, the detailed studies of the fine structure of quasi-periodicities in the region mentioned above should be of importance for the future.

3. Long-Term Evolution of the Spectra

For non-stationary time series as in the case of cosmic rays at neutron monitor energy, the contributions of various quasi-periodic signals to the power spectrum density over long time

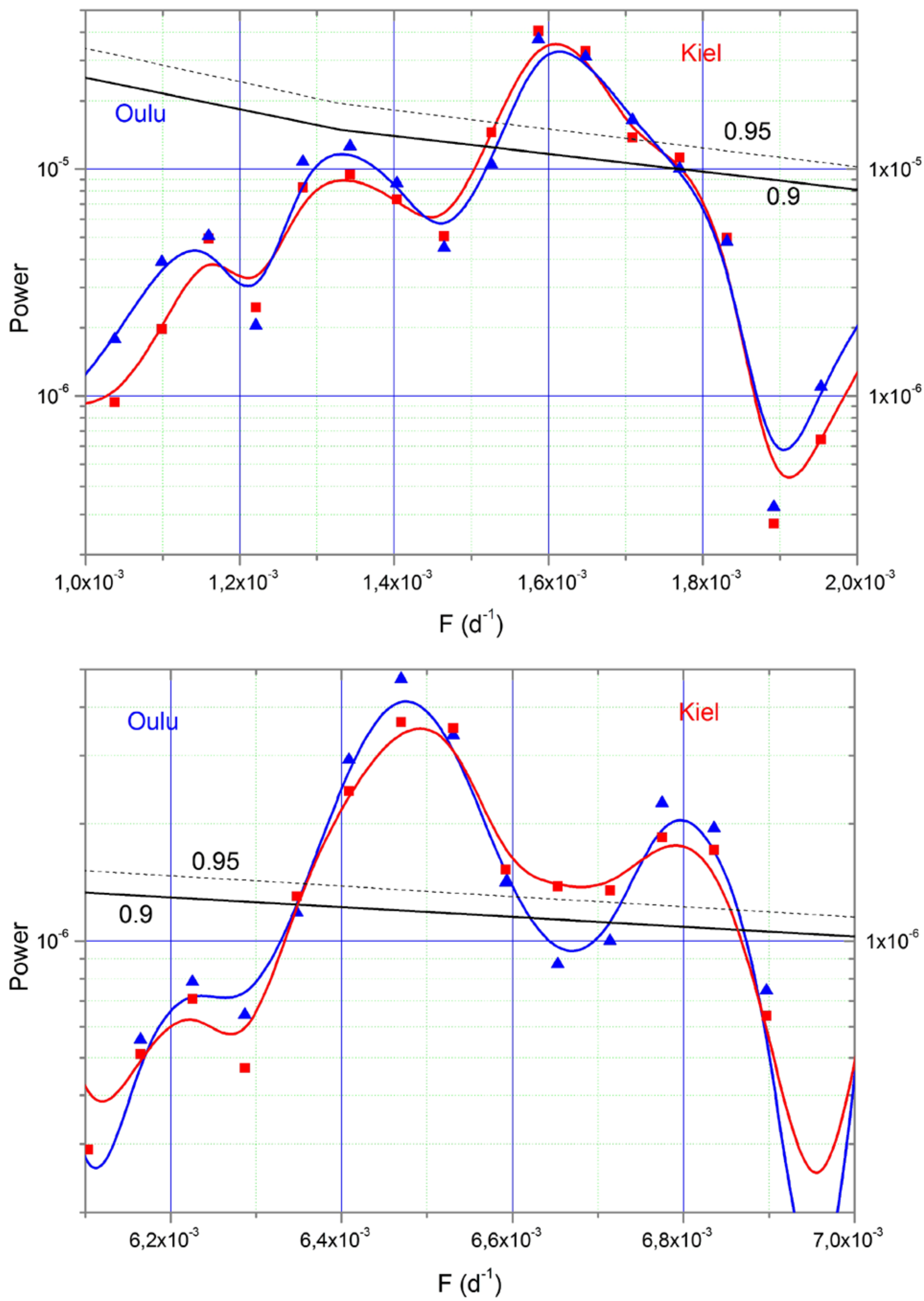

Figure 2 Power spectral densities (PSD) of neutron monitor time series at the two stations for the period shown in Figure 1. A B-spline technique is used for the curves plotted. The full line and dashed line are significance levels of 90 and 95%, respectively. The peak around 1.7 yr (upper plot) and a double structure near 150 days (lower plot) are seen.

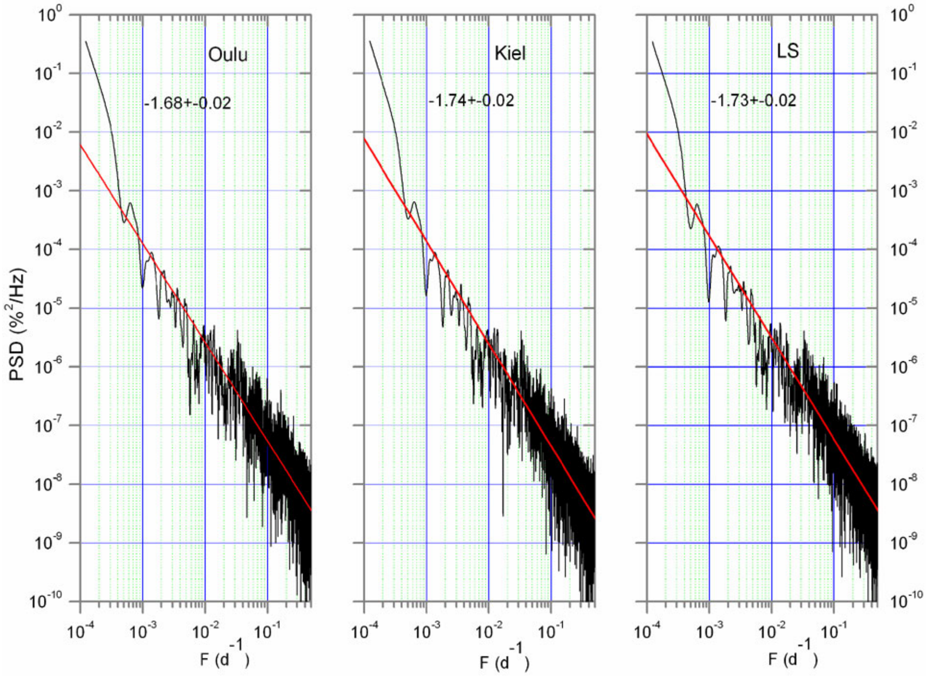

Figure 3 The power spectra of cosmic-ray time series measured at the three neutron monitors for the period shown in Figure 1. The data are normalised to 100% at the epoch of 1988.0794. The slopes of PSD are indicated with n according to the fit $\mathrm{PSD}(f) = \mathrm{const.} f^{-n}$.

scales as discussed in Section 2 can be studied by wavelet methods which have frequently been used in recent years in many studies of solar-terrestrial relations. The wavelet technique is a relatively new one, used recently in many geophysical studies. Instead of integral spectra provided by the Fourier transform, the wavelet transform provides the insight on the variable contribution of different harmonical components to the signal during the time. The discrete wavelet transform is described *e.g.* in Kumar and Foufoula-Georgiou (1997) and a comprehensive survey on wavelet techniques, including the continuous wavelet transform with a description of the practical use, can be found in Torrence and Compo (1998).

Out of the available measurements for this type of analysis we used Climax neutron monitor data with the most extensive data coverage. Since the PSD decreases with frequency we have selected a window of the frequencies corresponding to the periodicities 200 to 40 days. For that purpose we utilised Fourier filtering and reconstruction in that range. The wavelet spectra for the time interval covering almost five complete solar cycles are shown in Figure 5. The quasi-periodicity of approximately 150 days appears most significantly around the change of solar magnetic field polarity marked as S+N− in the three repeating situations. Around the solar maxima periods there appear more intensifications at various quasi-periodicities below 100 days. They are practically absent during the solar minima periods. For the S+N− polarity onsets near the solar maxima periods there are seen the double structure signatures with a gap in between which may probably correspond to the Gnevyshev gap, described *e.g.* in Storini *et al.* (2003).

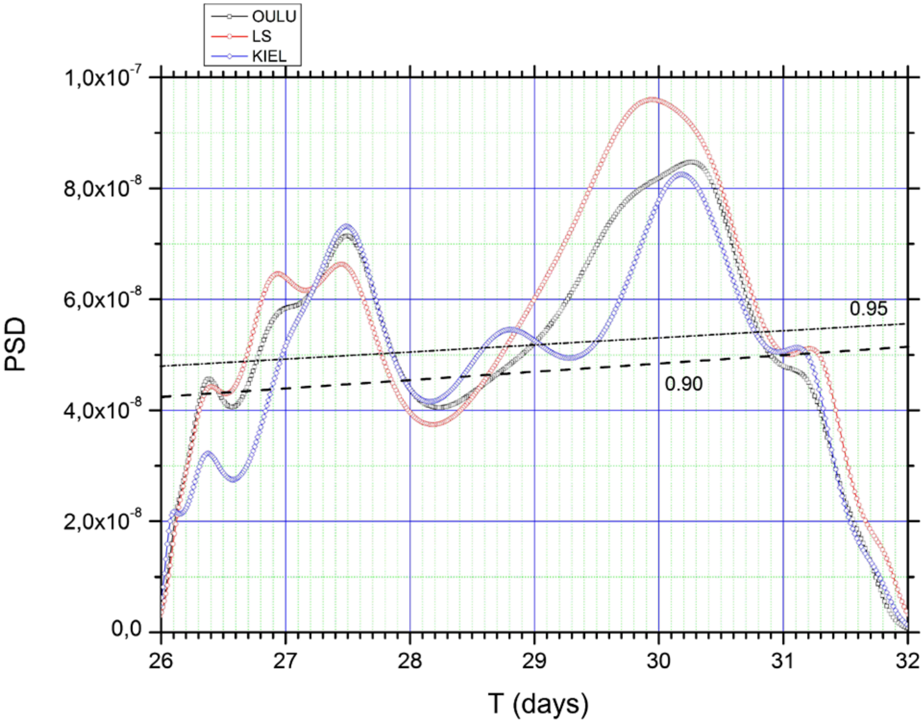

Figure 4 The periodogram (PSD as a function of period) around the solar rotation period at the three neutron monitors for the period shown in Figure 1. The dashed and dotted lines are significance levels of 90 and 95%, respectively.

4. Discussion and Summary

Using relatively long time data sets of the selected neutron monitors (*e.g.* Climax or the newly constructed and updated NMDB data archive), the earlier indications of quasi-periodicities in cosmic rays, based mainly on earlier data sets, shorter time intervals and other neutron monitor positions, were confirmed at three positions with different cut-off rigidity and altitude. The ≈ 1.3 yr periodicity (not shown here) discussed *e.g.* for the solar wind (Richardson and Cane, 2005) is also observed. Out of the quasi-periodicities reported recently at lower energies (below the atmospheric threshold) in Laurenza *et al.* (2009), the one at 1.7 – 2.2 yr could probably be attributed at higher energies to the double peak structure in the upper panel of Figure 2. The quasi-periodicity of about 154 days in solar flares was reported in Kile and Cliver (1991). This is seen also in the cosmic-ray spectra (lower panel of Figure 2 and its variable contribution to the signal over long time period in Figure 5). The spectral slope of PSD at the three stations is mutually consistent, and it agrees with that reported before at higher frequencies (*e.g.* Bershadskii, 2002) and with the observed slope of the IMF B reported by Burlaga and Ness (1991), which is close to a Kolmogorov type of spectrum. The complicated character of the PSD and its similarity on three NM stations near 27 days is needed to be studied in more detail in comparison with data analysed by solar physicists. Continuation of the detailed study of the spectral properties of cosmic-ray time series at various energies require the compilation and checking the quality of the existing cosmic-ray data available in various laboratories and comparison with characteristics

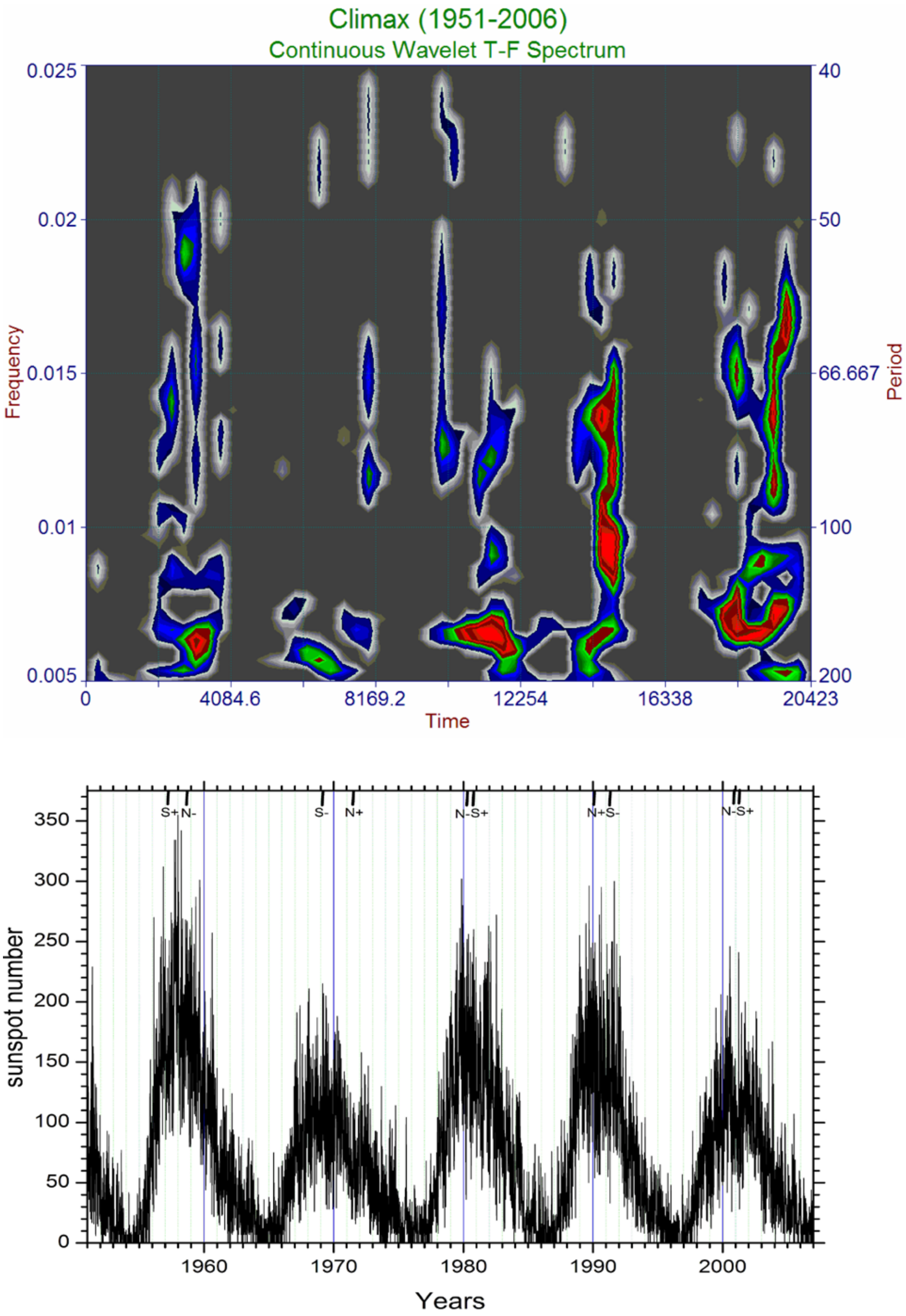

Figure 5 Upper panel: The wavelet time-frequency spectrum of the Climax neutron monitor. The abscissa is in days from 1 January 1951. The colour codes used are grey from 10 to 50%, cyan from 50 to 90%, green from 90 to 95%, yellow from 95 to 99%, and red from 99 to 99.9%. The Morlet mother function with the wavenumber parameter (the number of oscillations within the wavelet itself) of 16 is used. Lower panel: The smoothed sunspot numbers from http://sidc.oma.be/sunspot-data/. The reversals of solar magnetic fields are marked.

of IMF, solar wind and geomagnetic activity. Using additional data of neutron monitors and muon telescopes for this purpose is in progress.

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