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Spectral slope analysis of long-term cosmic-ray variations at Earth

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The flux of galactic cosmic rays (GCR) at Earth is modulated in the heliosphere by the heliospheric magnetic field and solar wind, that vary in the course of solar cycle. The modulation is caused by diffusion, convection, adiabatic cooling and drifts, where very important is scattering of particles on magnetic inhomogeneities in the turbulent solar wind and heliospheric magnetic field (HMF). Turbulent variations are often characterized by a power law in the power spectrum of the cosmic-ray variations. Previous works revealed a power law behaviour in the power spectral density (PSD) of GCR fluxes in the frequency range between $5.56 \cdot 10^{-6}$ and 2.14^{-6} Hz ($50-130$ hours) that varies with the solar cycle phases. Here we further develop these results by employing a broader and higher-quality dataset obtained from the world data repository (the WDCCR). Using data from 31 ground-based neutron monitors (NMs) spanning 65 years (nearly six solar cycles, 1953—2018) of measurements, we have studied the spectral slopes of the PSD of NM count rates. Using 2-year overlapping PSD intervals, we found that the spectral slope varies in time between approximately -1 and -2.6, with a mean value of -1.84 ± 0.01. Separating the results to specific solar cycle phases, we found that steep slopes close to -2.0 (typical for a random walk) appear during solar maximum times, and flatter slopes close to -1.7 (Kolmogorov-type spectrum) appear during solar cycle minimum times, indicating that different physical processes determine GCR transport in the Heliosphere at different phases of the solar cycle. We note that these results are in close agreement with the earlier results that used a different dataset.

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1. Introduction

Spectral frequency analysis of natural signals can help in understanding periodic variations and energy distribution across scales. Most common tools for such an analysis include Fourier Transforms, windowing, overlapping, tapering, wavelets and other similar methods estimating the frequency-power spectrum in noisy signals. Here we utilize the multitaper method for our spectral analysis, since it offers results with minimal variance that increases the robustnss of the results.

The flux of Galactic cosmic rays (GCR) can be assumed roughly constant in the local interstellar medium, but it varies greatly, especially in its lower-energy part in the vicinity of Earth as the result of modulation by solar activity [7]. This is evident, e.g., from the variability present in the neutron monitor (NM) count rates at Earth, which are directly connected with solar activity. Thus, variations of the GCR flux near Earth can be considered as a probe to the varying Sun and the Heliosphere. The modulation of GCR is a superposition of several effects, including the diffusion, convection, adiabatic cooling and drift [4]. Crucial for most of this processes is diffusion of CR particles on magnetic irregularities. These irregularities can originate from both large and strong propagating shocks (propagating barriers) like coronal mass ejection (CME) or corotating interaction region (CIR), and from smaller-scale instabilities in the solar wind in particular those related to turbulence. Distribution of turbulence in different scales can be characterized by a spectral power-law behaviour. In solar wind plasma, for example, values the spectral index (slope) of -1.5, -1.67 and -2 are observed for specific variables at specific circumstances as related to different processes, corresponding to Iroshnikov-Kraichnan, Kolmogorov and random-walk spectra (e.g., [2]). As discussed, e.g., by [8], the power-law spectrum slope of the GCR variability, as recorded by NM count rates, in the period range between 50 and 130 hours, may be used to probe the interplanetary turbulence.

In this work, we have extended the previous results by analyzing a larger number of NMs, adding data for the recent years 2017 and 2018 and carefully handling outliers, such as data jumps, ground level enhancements (GLEs) and Forbush Decreases. These improvements have lead to an increase of 41 % in the number of usable data points for analysis, allowing for a verification of the robustness of the results.

2. Data

The datasets analyzed here were acquired from the World Data Center for Cosmic Rays (WDCCR) in the form of hourly-averaged count rates, corrected for barometric pressure and efficiency, of ground-based NMs the years 1953 – 2018. We made use of 41 NMs selected by requiring to provide long and reliable (e.g., no apparent jumps, drifts or seasonal variability etc.) measurements for at least 20 years. The collected datasets was corrected for apparent artifacts, and GLEs and strongest Forbush decreases were excluded prior to the analysis. The list of used NMs is given in Table 2.

3. Power spectrum density (PSD) and slope calculation

We computed the power spectrum density (PSD) of count rates of each individual NM using 2-year data intervals, sliding each realization by one Bartels rotation (27 days), which means a

Table 1: List of Neutron Monitors used in the study, names correspond to the WDCCR abbreviations (see http://cidas.isee.nagoya-u.ac.jp/WDCCR/station_list.php for full names and other information of individual NMs).)

ALERT	CALGAR	CAPE_S	CLIMAX	DEEP_R	DOURBE	DURHAM
GOOSE	HERMAN	HUANCA	INUVIK	IRKUT2	IRKUT3	IRKUTS
JUNGFR	KERGUE	KIEL	KIEV	LEEDS	LOMNIC	MAGADA
MAWSON	MCMURD	MEXICO	MOSCOW	MT.WAS	MT.WEL	NEWARK
NOVOSI	OULU	POTCHE	ROME	SANAE6	SOUTH	TERRE
THULE	TIXIE	TOKYO	TSUMEB	YAKUTS	ZUGSPI	

96.3% overlap of PSDs. We have employed the multitaper method [1, 6] for computing the PSD. The method works by computing individual PSDs using a number of orthogonal taper functions, which produce a PSD with a high signal-to-noise ratio. The multitaper method is computationally heavy, but still feasible for modern computers. We note that a high number of used tapers may lead to widening of spectral peaks, but this is not a problem in our case of studying power-law behaviour in an undisturbed frequency range. A comparison of several commonly used methods for PSD estimation is shown in Figure 1 for the Oulu NM data. One can see that the multitaper method with sufficiently high half-bandwidth-product produces a much clearer spectrum, albeit the power of low-frequency peaks may leak into neighbouring frequencies, resulting in a flat spectrum for frequencies $< 10^{-8}$. On the other our range of interest is not affected by this. Since we use a 2-year sliding window for calculating each single PSD (from which we extract the slope information), our process is similar to a short-time Fourier transform that utilizes the multitaper method.

Following the methodology of [8] we further computed the power-law slope of each PSD in the period range between 50 to 130 hours ($5.56 \cdot 10^{-6}$ — $2.14 \cdot 10^{-6}$ Hz). The slope values were calculated by using weighted linear regression, where a possible bias caused by the uneven density of data points over frequency was compensated by assigning to the data points a weight inversely proportional to the data point density.

4. Spectral slope variability

Slope values for each NM were calculated for each 2-year realization, slid by 27 days. Within each interval, data were linearly interpolated, detrended to fill the gaps, and standardized. The computed slopes values were averaged across all NMs active for each interval. These averaged values of the slope are shown along with their standard deviations in Figure 2 (bottom panel). The mean standardized NM count rates and the number of active NMs as a function of time are also shown in upper and middle panels, respectively. A big number of NMs (>30) were simultaneously active during the period between ca. 1970 and 2000, with fewer monitors available closer to the start and end of the 1953 – 2018 period.

One can see in Figure 2 that the slopes vary significantly in the course of the solar cycle, with flatter spectral slopes (~ -1.5) observed at solar minimum times, whereas steep slopes (< -2) observed during solar maxima (except around 1978, after the cosmic ray "mini-cycles" [9]). By calculating the average slope of all the PSDs of all monitors, we obtained the mean slope of -1.84 ± 0.01.

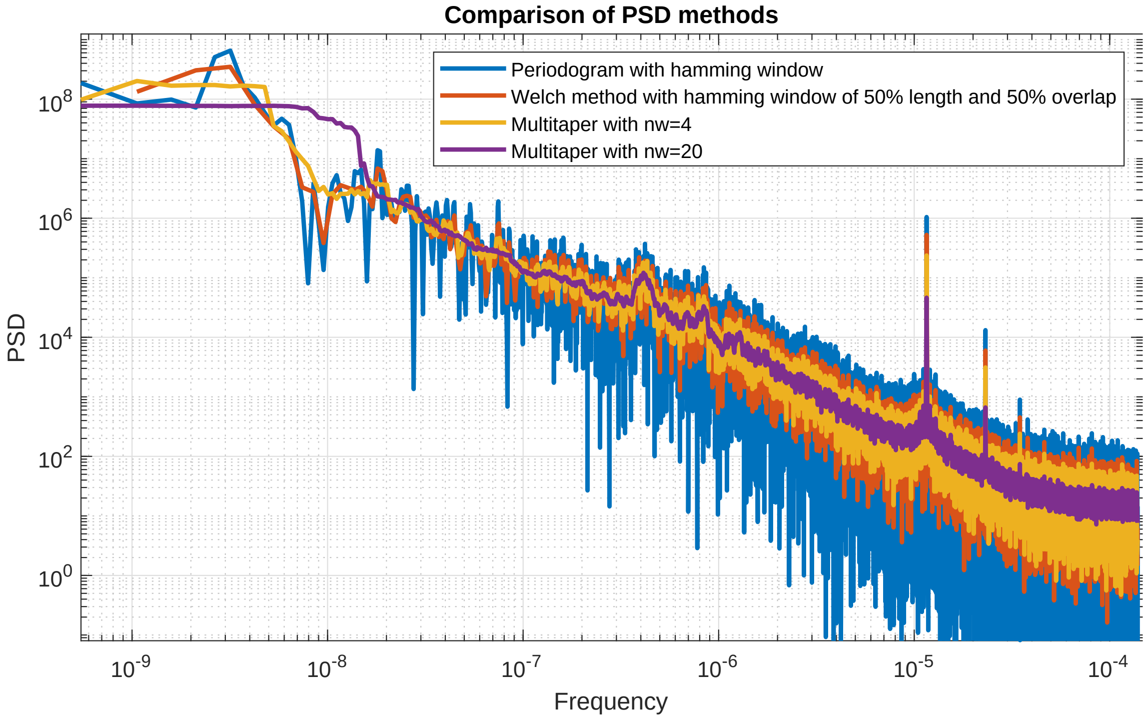

Figure 1: PSD of the Oulu NM data over the period 1974 – 2018 obtained using different PSD methods. "nw" stands for half-bandwidth product, which determines the number of tapers used.

Table 2: Solar cycle phase years

Cycle	Ascending	Maximum	Declining	Minimum
19	-	-	-	1964, 1965, 1966
20	1967, 1968	1969, 1970	1974, 1975	1976, 1977
21	1978, 1979	1980, 1981, 1982	1983, 1984, 1985	1986, 1987
22	1988	1989, 1990, 1991	1992, 1993, 1994, 1995	1996, 1997
23	1998, 1999	2000, 2001, 2002	2004, 2005, 2006, 2007	2008, 2009
24	2010, 2011, 2012	2013, 2014	2015, 2016	-

We separated the slope values according to the solar cycle phases, as listed in Table 2 (also denoted by the coloured bars in Figure 2). For each phase we calculated the mean and median slopes as shown in Figure 3. The pattern appears quite consistent. Steeper spectra, with the slope values around -2, appear around times of a solar maximum, while flatter spectra with the slopes being close to -1.7, around solar minima. Ascending and descending phases lie between these two clear cases, being a mixture between them.

5. Discussion and Conclusions

We used data covering 65 years (1953 – 2018) of cosmic-ray variability from 41 different NM stations to calculate, by means of the multitaper method, PSD estimates and spectral slopes in the

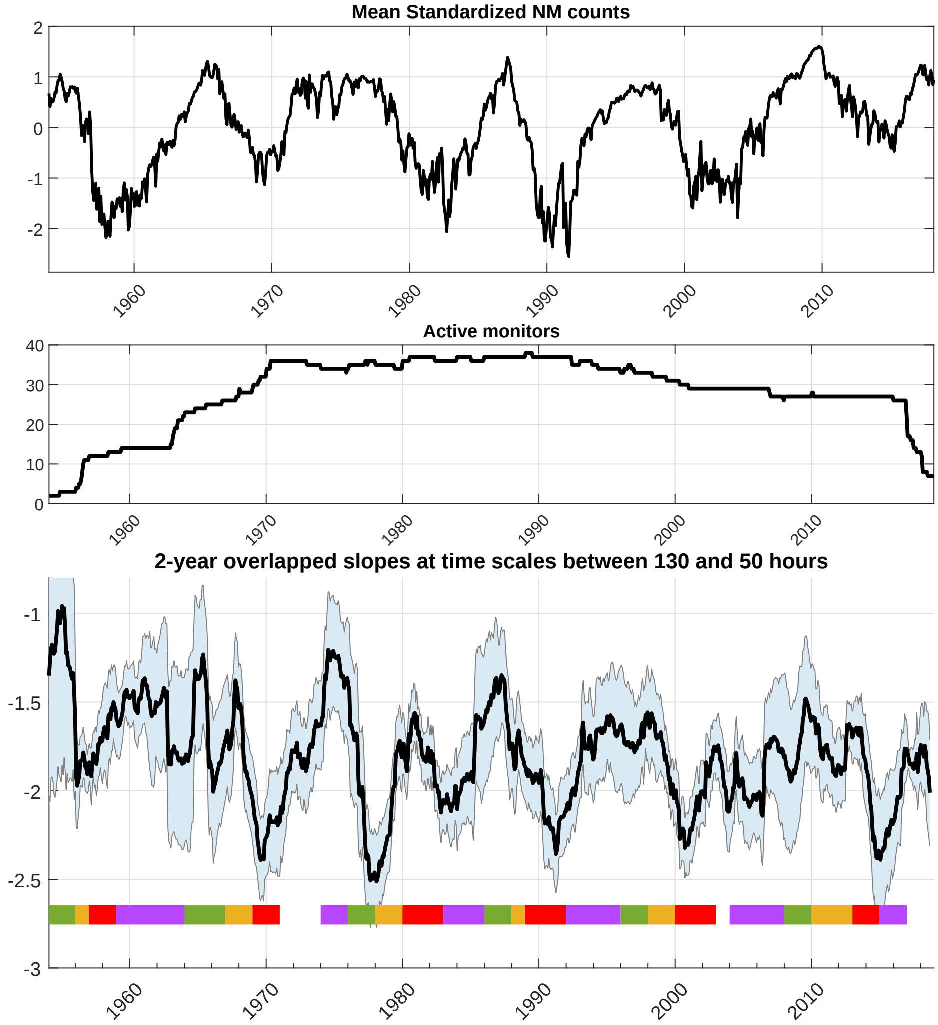

Figure 2: [Top]: Superposition of standardized count rates of all available NMs. [Middle] Number of active NMs as function of time. [Bottom]: The PSD slope value calculated in a 2-year window slid by 27 days. 1σ limits are denoted by gray shading. Colours bars below correspond to solar cycle phases; green=minimum, yellow=ascending, red=maximum, magenta=declining

range of periods between 50 and 130 hours. The analysis is similar to our earlier study [8], but using a new, more robust dataset and a careful handling of outliers.

While the mean power-law slope of the cosmic-ray variability PSD in the period range 50 – 130 hours is -1.84 ± 0.01, we found that the slope significantly varies in time depending on the solar cycle phase. The spectrum is steeper (the slope is close to -2) around the solar maximum time, suggesting for the dominant random-walk process of GCR modulation in the heliosphere. On the other hand, the spectrum is significantly flatter with the slop being around -1.7, which is close to the Kolmogorov-type spectrum of -5/3. The slopes during the ascending and descending

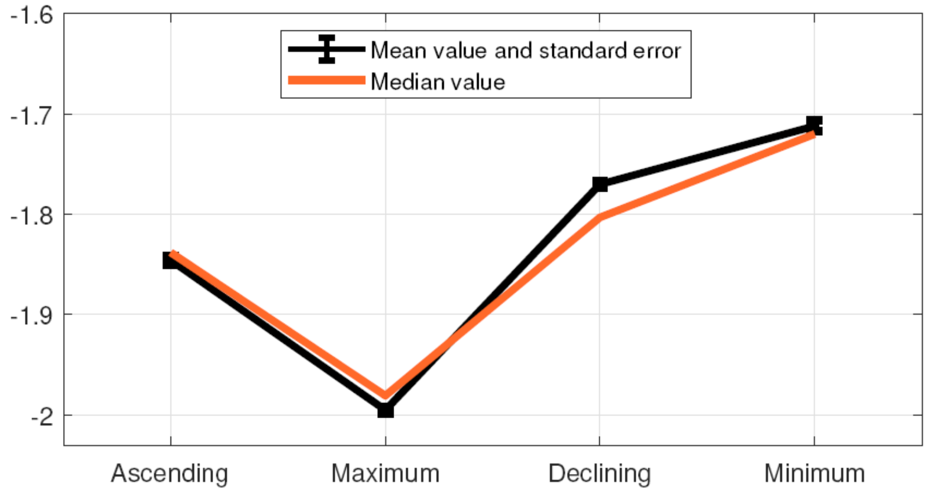

Figure 3: [Average (with the standard error of the mean) and median slope values for different solar cycle phases.

phases are between these values, suggesting a mixture of different processes Such a pattern can be understood via the dominance of different processes at different phases of the solar cycle (see, e.g., [3]). While the modulation of GCR is "diffusion-dominated" and strongly affected by drifts, during solar minimum conditions [5], the modulation is defined mostly by propagating barriers (CME-driven shocks, merged interaction regions, corotating regions, etc) leading to step-like modulations and Forbush decreases during the maximum phase of a cycle [3]. This processes naturally have different spatial and temporal scalings, with the regular diffusion around solar minima being close to the typical Kolmogorov-type turbulence, and fully developed propagation barriers are ordered to strongly affect larger spatial, and hence temporal scales.

These results emphasize the need of having a vast, long-term global NM network with the stable-quality measurements, which provide a full 3D probing of the heliosphere not limited to the Earth's very location.

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