Journal of Atmospheric and Solar–Terrestrial Physics 247 (2023) 106068

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Research Paper

Observation of large scale precursor correlations between cosmic rays and earthquakes with a periodicity similar to the solar cycle

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ARTICLE INFO

Handling Editor: Dora Pancheva

ABSTRACT

The search for correlations between secondary cosmic ray detection rates and seismic effects has long been a subject of investigation motivated by the hope of identifying a new precursor type that could feed a global early warning system against earthquakes. Here we show for the first time that the average variation of the cosmic ray detection rates correlates with the global seismic activity to be observed with a time lag of approximately two weeks, and that the significance of the effect varies with a periodicity resembling the undecenal solar cycle, with a shift in phase of around three years, exceeding 6 σ at local maxima. The precursor characteristics of the observed correlations point to a pioneer perspective of an early warning system against earthquakes.

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https://doi.org/10.1016/j.jastp.2023.106068
Received 12 September 2022; Received in revised form 24 February 2023; Accepted 6 April 2023
Available online 13 April 2023
1364-6826/

One-sentence summary: Variations of secondary cosmic ray detection rates are *periodically* correlated with *future* global earthquake magnitude sum.

1. Introduction

Despite decades of research, the mechanisms initiating large earthquakes remain enigmatic (Kato and Ben-Zion, 2020) which leaves room for testing novel ideas. We propose focusing on the effects that might be triggered by reconfiguration of the planetary dynamo whose mechanisms are associated with the physical processes occurring in the very interior of the Earth. Mass movements inside the Earth could lead to earthquakes (EQ), causing temporary changes in both the gravitational and geomagnetic fields simultaneously. If the changes in the latter propagate relatively fast, they can probably be observed on the surface of the planet earlier than the corresponding seismic activity possibly triggered by gravitational changes. A detection of such precursor effects can be possible, for example, by registering changes in the frequency of detection of secondary cosmic radiation (CR), which is very sensitive to geomagnetic conditions. The existing literature documents the efforts towards identifying transient features of cosmic radiation, solar activity, ionospheric conditions, and the geomagnetic field, that could serve as precursors of seismic effects (Morozova et al., 2000; Foppiano et al., 2008; L'Huissier et al., 2012; Romanova et al., 2015; Cordaro et al., 2018; He and Heki, 2018; Ikuta et al., 2020; Marchitelli et al., 2020; Yanchukovsky, 2021), however, none of *cosmo-seismic* or *solar-seismic* correlations have been demonstrated on a global scale so far in a statistically convincing and model independent way (i.e. on a discovery level, see e.g. the criticism concerning the total electron content ionospheric monitoring (Eisenbeis and Occhipinti, 2021)), and in particular no hypotheses concerning an earthquake precursor effect observable in CR data have been verified. Here we report on an observation of the correlations between variation of the average rates of secondary cosmic ray fluxes measured locally and global seismic activity, and we also point to the periodicity of these correlations (or their observability) which corresponds to sunspot number observations back to the 1960s.

The inspiration for the investigation on the possible earthquake precursor effects in cosmic ray data that precedes this article originates in the research undertaken after the devastating M 8.8 earthquake in Chile, in 2010. The most intriguing results concerning only this particular earthquake include ionospheric anomalies above the earthquake region (Píša et al., 2010), geomagnetic fluctuations at a distant location (Romanova et al., 2015), and unusual variations of secondary cosmic radiation detection rates (Space Weather public web page of the Pierre Auger Observatory), all preceding the earthquake by different time periods: 15 days, 3 days, and $^1/_3$ day, respectively. The latter result, i.e. the unusual secondary cosmic ray rate, was recorded by the Pierre Auger Observatory (Auger), the largest cosmic ray infrastructure, dedicated mostly to research related to ultra-high energy cosmic rays, but also offering interdisciplinary opportunities such as space weather studies with their scaler data (Space Weather public web page of the Pierre Auger Observatory; The Pierre Auger collaboration, 2011). The Auger site is located in Argentina, ~500 km away from the Chilean earthquake epicenter, thus a good candidate location to probe the possible connection between the secondary cosmic ray fluxes and this particular seismic event. While the Auger studies concerning the big Chilean earthquake were not published, they triggered a longer term interest diffused within the cosmic ray community, resulting in reviving the related research under the scientific agenda of the Cosmic Ray Extremely Distributed Observatory (CREDO) (Homola et al., 2020) - a recent cosmic ray initiative dedicated mostly to the global search for large scale cosmic ray correlations and associated inter-domain efforts, e.g. those related to the joint research program of the astroparticle physics and geophysics communities (Workshop on Observatory Synergies for, 2019). The first extensive *cosmo-seismic* studies of the CREDO programme concerned the public Auger scaler data set, and they were focused on short term scale (up to few days) correlations of secondary cosmic ray detection rates and precursor effect searches using the major (magnitude ≥4) earthquakes with epicenters located at different distances (up to 7000 km) from the Pierre Auger Observatory. The apparent inconclusiveness of these still-ongoing studies triggered an alternative, novel approach on which we report here: comparing the absolute average variabilities of secondary cosmic radiation to the average global sum of earthquake magnitudes.

Since we consider seismogenic processes occurring very deeply under the Earth's surface it is justified to widen the search for manifestations of *cosmo-seismic* correlations on the surface of the Earth to global phenomena - just because one can attribute no "locality" to deep interior processes. A consequence of this approach is that instead of individual major earthquakes and the corresponding before- and after-shocks, one has to pay attention to the earthquake events occurring globally within a specific time window. Both of these consequences have been adopted in the analysis presented here.

2. The cosmo-seismic correlations

To look for the correlations between the detection rates of secondary cosmic rays and seismic activity we explored the Pierre Auger Observatory scaler data (Space Weather public web page of the Pierre Auger Observatory) compared to selected stations of the Neutron Monitor Database (NMDB) (Real-Time Database for high), and to the earthquake data from the U.S. Geological Survey (USGS) database (U.S. Geological Survey Search Earthquake Catalog). In addition, as a reference for the space weather situation, solar activity data were taken into account, available from the Solar Influences Data analysis Center (SIDC) (SILSO data/image). All the data sets used within this study are illustrated in Fig. 1 using a binning relevant for the analysis to be presented subsequently.

The hypothesized complexity of the physical connection between magnetohydrodynamics of the interior of the Earth and the subsequent variations of the secondary cosmic ray detection rates justifies no *a priori* expectations concerning the proportionality between cosmic and seismic data. It is not even clear which kind of cosmic ray response to seismicity should be expected: a specific strength of a transient magnetohydrodynamic instability of the planetary dynamo might result in different seismic effects, depending on the location of the instability with respect to the seismically sensitive regions, and could give a complex picture of the corresponding geomagnetic fluctuations. The subsequent variations of the cosmic ray detection rates might then in principle possess characteristics which are different from those of the corresponding seismic activity, while the two effects might still remain correlated or even causally connected. In particular, neither the direction of changes of the cosmic ray rates nor the direction of their changes can *a priori* be expected to reflect the corresponding behavior of the seismic data. On the other hand, within the planetary dynamo mechanism, one can expect a *change* in the *variations* of the cosmic ray data to be caused by some mass reconfiguration in the Earth's interior. One also considers the inertia of the planetary dynamo system: slow movement of the liquid iron in the Earth interior (reflected in the variation of the cosmic ray rates) might trigger a seismic effect only after some threshold of resistance of the adjoining matter (rocks) is exceeded. It then motivates the search for transient changes of the geomagnetic field and, consequently, of the CR flux before a rapid increase of the global earthquake number. In consequence, an adequate and sufficiently general approach for checking whether there is any correlation between seismic activity and cosmic radiation seems to be a dichotomization of the data (MacCallum et al., 2002) which would turn the analysis into a simple *yes/no* study by allowing the application of binomial distribution in order to assess the statistical significance of the possible effects. In addition, one is inclined to introduce a time-dependent parameter which could reflect the potential precursor character of the expected correlations. We define the expression

$$c_i(d, m, t_0, t_i, \Delta t, P) = A_i(d, m, t_0, t_i, \Delta t, P) \times B_i(d, t_0, t_i, P) \quad (1)$$

where

$$A_i(d, m, t_0, t_i, \Delta t, P) = \frac{S_m(d, m, t_0, t_i + \Delta t)}{M(S_m(d, m, t_0, t_i + \Delta t), P)} - 1, \text{ and}$$
$$B_i(d, t_0, t_i, P) = \frac{|\Delta n_{CR}(t_0, t_{i,i-1})|}{M(|\Delta n_{CR}(t_0, t_{i,i-1})|, P)} - 1$$

where $\Delta n_{CR}(t_0, t_{i,i-1}) = n_{CR}(t_i) - n_{CR}(t_{i-1})$ is the difference in the average cosmic ray detection rates between the two neighbor intervals ending at t_i and t_{i-1}, $S_m(d, m, t_0, t_i + \Delta t)$ is the global sum of the earthquake magnitudes larger than or equal to m during the corresponding interval ending at $t_i + \Delta t$ with Δt being the time shift of the earthquake data set with respect to the cosmic ray data, $M(S_m, P)$ and $M(|\Delta n_{CR}|, P)$ are the medians of the corresponding quantities over the period of length P within which the search for the correlations is being checked, t_0 determines the starting time of the period P, and $d = t_i - t_{i-1}$ specifies the length of the time interval over which the cosmic ray rates are averaged and the sums of magnitudes S_m are calculated. Then for a given set of free parameters: $P, t_0, d, m,$ and Δt, one defines variables $N_{+/-}$ as sums of positive/negative signs of expression (1) to obtain the binomial probability density function (PDF) describing the probability of getting exactly k positive signs for n intervals of length d, over the period P:

$$P_{PDF}(N_{+/-} = k) = \left(\frac{n!}{k!(n-k)!}\right) p_{+/-}{}^{k} \left(1 - p_{+/-}\right)^{n-k} \quad (2)$$

with $p_{+/-}$ being the probability of a "success": getting the positive/negative sign of expression (1). One expects the following five situations that determine the sign of expression (1):

I. $sign(c) = (+) \times (+) > 0$

II. $sign(c) = (-) \times (-) > 0$

III. $sign(c) = (+) \times (-) < 0$

IV. $sign(c) = (-) \times (+) < 0$

V. $sign(c) = 0$

The situation V can occur if one or more data values are equal to the median value, e.g. in case of odd n. If we require that

$$(A_i \neq 0) \text{ and } (B_i \neq 0) \text{ and } (n_{CR}(t_i) > 0) \text{ and } (n_{CR}(t_{i-1}) > 0) \text{ and } (S_m(t_i + \Delta t) > 0) \quad (3)$$

and that in addition the numbers of positive and negative values of A_i and B_i are the same, i.e.:

$$n_{A_i>0} = n_{A_i<0} = n_{B_i>0} = n_{B_i<0}, \quad (4)$$

then the null hypothesis, defined as independence of the two considered data sets containing the EQ and CR data implies that $p_{+/-} = 0.5$, as the situations *I*, *II*, *III*, and *IV* might occur with the same probabilities of 25%. Thus the probability P_{PDF} from Eq. (2). and the corresponding cumulative distribution function (CDF) $P_{CDF}(N_{+/-} \geq k)$ can

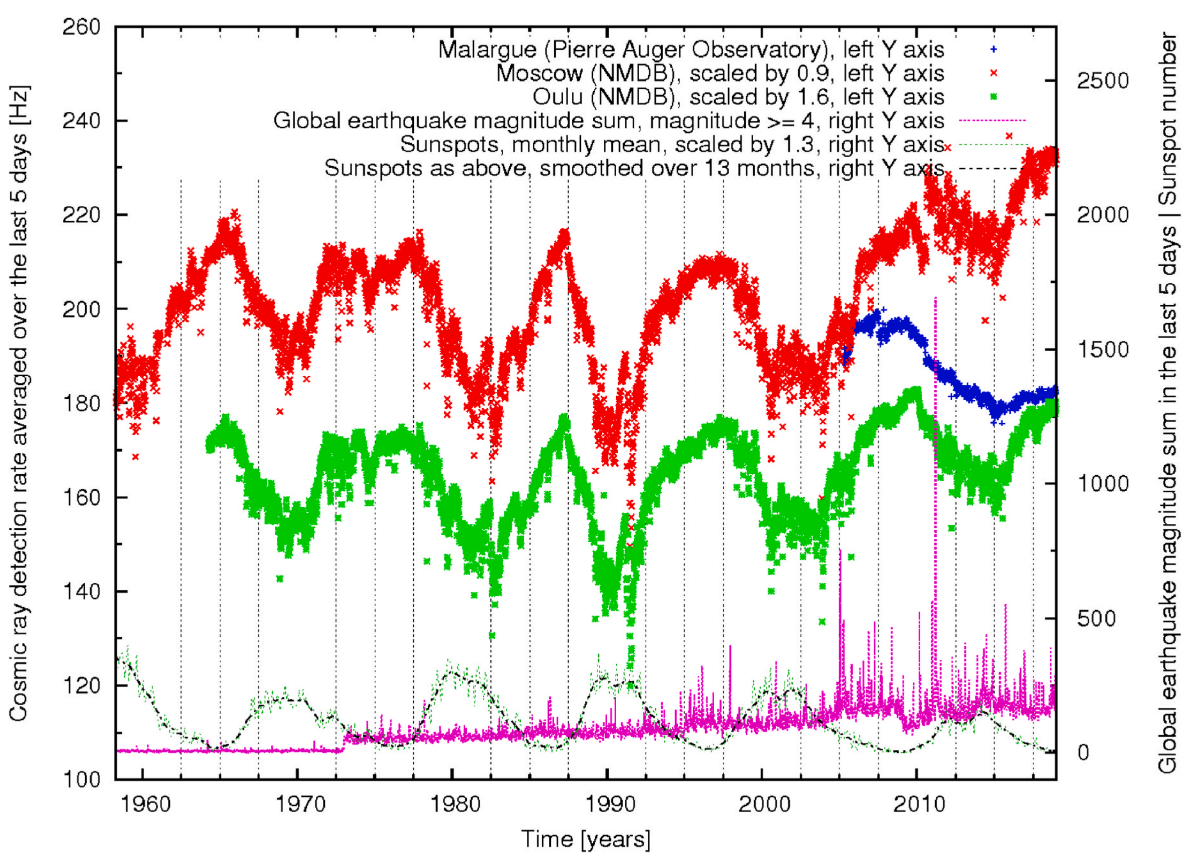

Fig. 1. The data sets analyzed in this study. The points in the earthquake and cosmic ray data sets correspond to values averaged over the previous 5 days. Solar activity is visualized with monthly averages of sunspot numbers, and with monthly averages smoothed over the period of 13 months.

serve as measures to test the null hypothesis.

3. The precursor effect

The search for the *cosmo-seismic* correlations reported here was performed in three stages: at first the Auger data was examined to optimize the search strategy with post-trial checks, then the optimum correlation prescription was fine-tuned using technically independent data sets from the Moscow and Oulu NMDB stations within the time period corresponding to the Auger data taking time. Finally, we applied the prescription to the earlier periods of time available in case of the Moscow and Oulu data.

An examination of the Auger data gives a stable and significant correlation result already after a coarse variation of the key parameters, with an example local optimum for: $P = 1675\ days, t_0 = 2\ Apr\ 2014\ 22:07:12\ GMT$ (apart from the large scale time dependence we have also found a sensitivity to small shifts of the data bins in time, of the lengths less than the individual bin size), $d = 5\ days$, $m = 4.0$, and $\Delta t = 15\ days$. Out of the $N = P/d = 335$ intervals 294 fulfilled the requirements (3) and (4) to give $N_+ = 202$ and $N_- = 92$ (the sum of N_+ and N_- is less than N because of a number of empty intervals in the Pierre Auger Observatory data - such intervals were excluded from the analysis), with the corresponding medians $M(S_m, P) = 859.55$ and $M(|\Delta n_{CR}|, P) = 0.48$, with $P_{PDF}\ (N_+ = 202, N = 294) = 3.5 \times 10^{-11}$ and $P_{CDF}(N_+ \geq 202, N = 294) = 6.3 \times 10^{-11}$. The latter value corresponds to the significance of more than 6.5 σ.

The prescription found for the Auger data was then applied to other cosmic ray data sets, recorded by the aforementioned Moscow and Oulu NMDB stations. In the Moscow case, when applying all the free parameter values exactly as in the prescription, one receives the CDF significance at the level of $\sim 3.5\ \sigma\ (N_+ = 199, N_- = 132)$, and when we allow a role of the local properties of the Moscow site manifesting in the change of the starting time t_0, a scan of this parameter beginning from March 30, 2005 (the data of the first record in the Auger database) with a step of 6 h (the data bin width in the Moscow database), i.e. checking 13,400 partly overlapping periods, reveals again an effect at the level of $\sim 6\ \sigma\ (P_{CDF} = 4.1 \times 10^{-9};\ N_+ = 218, N_- = 113)$ for $t_0 = 14\ Nov\ 2013\ 07:00:00\ GMT$, i.e. ~4 months earlier and with borders of five-day intervals on a different time of the day compared to the effect observed for the Pierre Auger Observatory site (morning in Moscow vs. evening at the Auger site). Similarly, the Oulu NMDB data reveal a sharp minimum chance probability of $(P_{CDF} = 1.6 \times 10^{-9};\ N_+ = 220, N_- = 112)$ at $t_0 = 4\ Jan\ 2014\ 23:37:12$, yet another value of the starting time, more or less in the middle between the values found in the Auger and Moscow data. The comparison between the Auger, Moscow and Oulu results with the corresponding sunspot numbers is presented in Fig. 2.

An important feature of the apparent *cosmo-seismic* correlations is a sensitivity of the significance of the effect on the time shift between the CR and EQ data sets. The strongest correlations are found for $\Delta t = \sim 2\ weeks\ (15\ days)$, which points to the precursor character of the CR data behavior with respect to the seismic data changes, as illustrated in Fig. 3 using the Auger data.

While the apparent chance probabilities of the correlation effect are very low in all the three CR data sets, the statistical significance of the result has an uncertainty due to fine tuning of the free parameters needed to find the lowest $P_{PDF/CDF}$, and related to the physical correlations between the CR data sets introduced by the solar activity. However, a simple verification of the significance of the demonstrated relation between the CR and EQ data can be performed by “looking elsewhere”, i.e. by considering earlier periods of data taking in the available detectors.

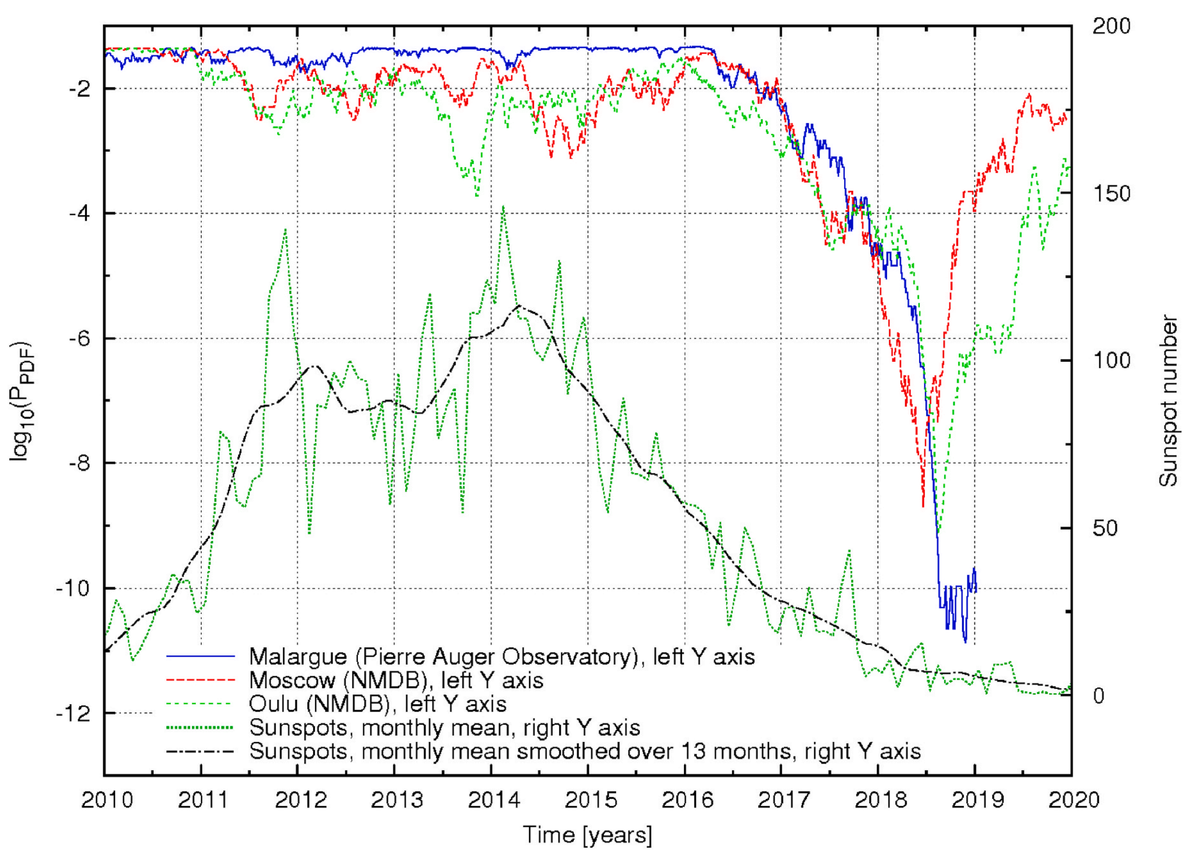

Fig. 2. $\sim 6\ \sigma$ significance of the effect in three technically independent CR data sets collected by the Moscow and Oulu NMDB stations, and by the Pierre Auger Observatory, compared to sunspot numbers. Each point illustrates the correlation effect during the last ~4.5 years (335 five-day intervals). All the significance curves were obtained after fine tuning of the parameter t_0 performed by applying 20 small shifts in time between 0 and 5 days.

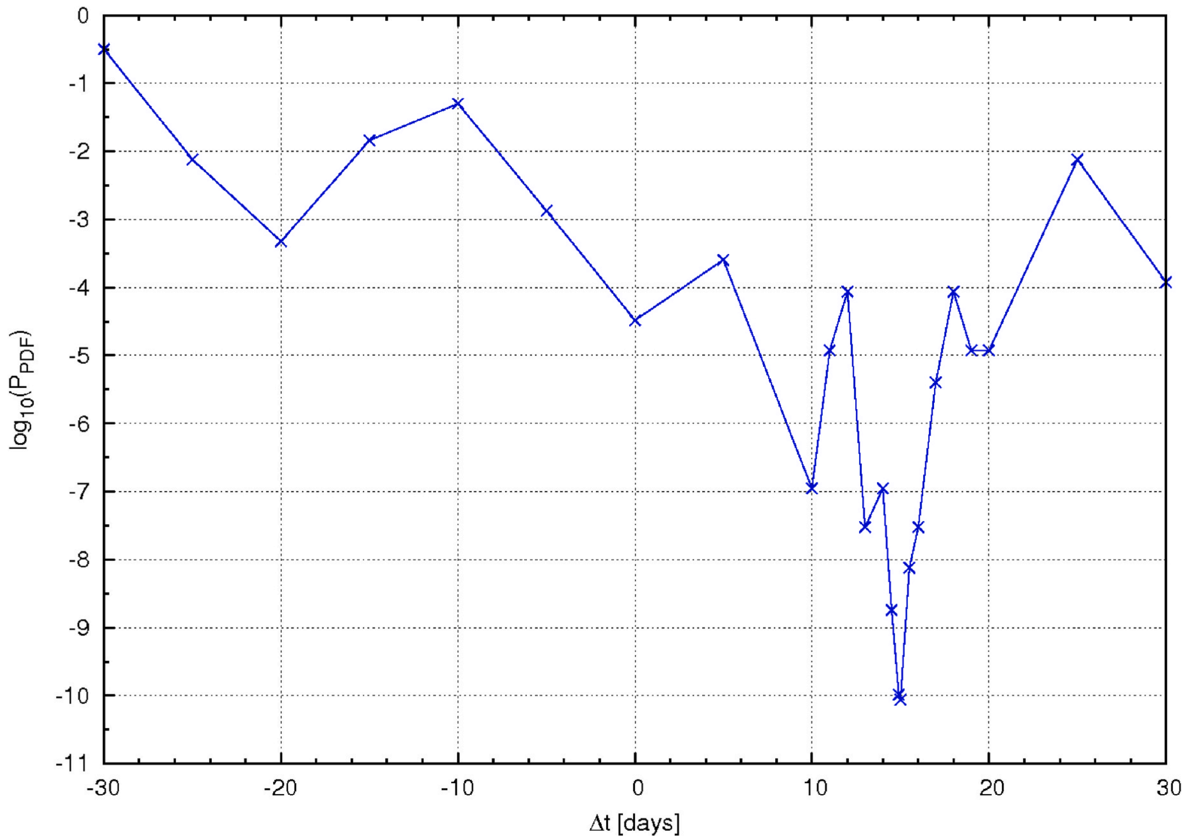

Fig. 3. The dependence of the significance of the *cosmo-seismic* correlations on the time shift Δt of the EQ data with respect to the Auger CR data, for the optimum free parameter set defined in Eq. (1). The positive or negative values of Δt correspond to the situations in which one compares the secondary cosmic ray data in a given time interval to the seismic data recorded in time intervals in the future or in the past, respectively.

4. The statistical significance and the role of the SUN

The large-scale time dependence and the aforementioned uncertainty of the apparent *cosmo-seismic* correlation seen in Fig. 2 motivates a check with an independent data set extending over another period of time, and also using different time windows. Interestingly, such a study including older data reveals excesses of both N_+ and N- varying regularly over time which justifies using the P_{PDF} (Eq. 2) as an indicator of the binomial distribution anomaly, instead of focusing on an excess of a certain type. As illustrated in Fig. 4, applying smoothing windows of two different lengths (~4.5 and ~9 years) to the Moscow data set indicates a connection with the activity of the Sun: between 1965 and 2015 five distinct and significant minima of P_{PDF} are visible when a wider (~9 years) smoothing window is used, all follow sunspot number maxima after ~3 years.

Considering earlier time periods, we scanned over the available t_0 range excluding the previously studied period (cf. Fig. 2), and keeping the other free parameters unchanged, i.e. with the same values which gave the results presented in Fig. 2. The procedure gave 3430 new partly overlapping data sets, each of them independent of the excluded "burning sample" data plotted in Fig. 2. Using the wider smoothing window of ~9 years results in four new distinct anomalous values of $P_{PDF}: 3.3 \times 10^{-8}, 3.0 \times 10^{-6}, 3.6 \times 10^{-5}$, and 2.9×10^{-6} corresponding to t_0 values (GMT) of:

1. 12 *Jul* 1969 07 : 37 : 12,
2. 11 *Jul* 1978 07 : 37 : 12,
3. 21 *Sep* 1988 07 : 37 : 12,
4. 23 *Dec* 1999 07 : 37 : 12,

respectively. For completeness we also list the local minimum $P_{PDF} = 8.1 \times 10^{-9}$, occurring for $t_0 = 23$ *Feb* 2009 07 : 37 : 12. As explained in the previous section, the specific fraction of the five-days period at which we begin the scanning procedure is an effect of the optimization applied already to the "burning sample" of the data, so in the other data set the only factor that penalizes a specific probability value is related to the number of steps in t_0 available as new trials. All the four minima occur in non-overlapping periods of 3350 days, so they can be considered as independent events. The overall probability of occurring of all of these minima within the time period checked can then be described by the product of the individual probabilities, with the corresponding penalization factors. To apply these penalization factors to the four minima listed above we use the penalizing factor of 3430 for the first minimum, then for the second minimum the available number of new trials is only 2682 (the scan of the new sets can be continued only beginning from the first t_0 value after the previous minimum), for the third minimum it is 1952, and for the fourth one - 1207. Collectively, the probability of an accidental appearance of the four minima to occur during the available data taking time period that precedes the "burning sample" is no greater than

$$3.34 \times 10^{-8} \times 3430 \times 3.0 \times 10^{-6} \times 2682 \times 3.58 \times 10^{-5} \times 1952 \times$$

$$\times 2.92 \times 10^{-6} \times 1207 = 2.3 \times 10^{-10}$$

which corresponds to $\sim 6.3\,\sigma$.

While the recipe we apply does not point to a specific t_0 at which an anomalous P_{PDF} should occur, applying a simple scanning rule and the related penalization to compute the chance probability of the *cosmo-seismic* correlation effect to occur many times over decades, confirms that the effect observed is statistically significant. Moreover, the temporal distances between the observed P_{PDF} minima: 10.2, 10.0, 10.2,

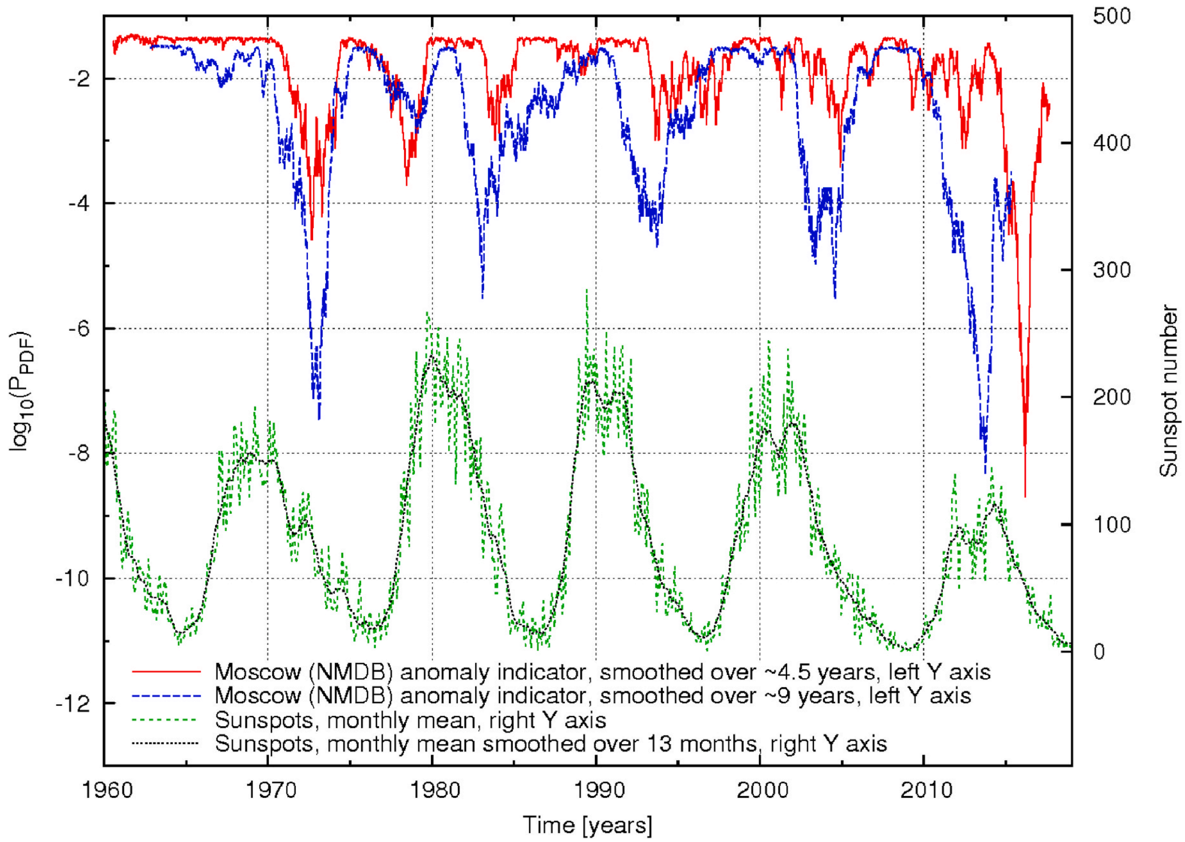

Fig. 4. The anomaly indicator in the Moscow NMDB data set compared to the sunspot number. Each point on the correlation significance curves corresponds to the effect found over the smoothing window length of ~4.5 years (1675 days, in red) and ~9 years (3350 days, in blue), with the curve points located at the centers of the windows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

11.3, and 9.2 years, as well as the occurrence of the minima ~3 years after the maxima of the solar activity, seem to indicate to a role or even an impact of the Sun that should be studied more deeply in follow up analyses.

5. Validation with cyclostationarity-based methods

Aimed at corroborating the results presented above, statistical dependence or correlation are analyzed by studying the joint cyclostationarity properties of pairs of the following time series: cosmic ray detection rate, earthquake sum magnitude, and sunspots.

The cyclostationary model is appropriate when signals are created by the interaction of periodic and random phenomena. In such a case, the signal itself is not periodic, but the periodicity is hidden and is present in its statistical functions (Gardner, 1987; Napolitano, 2019, chaps. 1-2). Data originated by geophysical phenomena exhibit cyclostationarity due to, for example, Earth revolution and rotation (Javors'kyj et al., 2015; Napolitano, 2019, sec. 10.9). Data originated by astrophysical phenomena exhibit cyclostationarity due to revolution and rotation of stars and planets and periodicities in Sun and star pulsation and activity (Demorest, 2011; Napolitano, 2019, sec. 10.9).

Cyclostationary feature measurements show that pairs of the considered time series can be suitably modeled as jointly cyclostationary. The estimated Fourier coefficients of the periodically time-varying joint distribution function or of the joint cross-correlation function are different from zero in correspondence of frequencies related to characteristic periods of the time series.

5.1. Cyclostationarity analysis

In the considered problem, the signals $y_1(n)$ and $y_2(n)$ are single time series, that is, for each of them an ensemble of realizations, namely a stochastic process, does not exist. In such a case, the statistical characterization is more suitably made in the functional of fraction-of-time (FOT) approach (Gardner, 1987; Leśkow and Napolitano, 2006; Napolitano, 2019, chap. 2). In the FOT approach, starting from a single time series, all familiar probabilistic parameters such as mean, autocorrelation, distribution, moments, and cumulants, are constructed starting from the unique available time series.

In the FOT approach, the joint cumulative distribution function (CDF) of $y_1(n+m)$ and $y_2(n)$ is defined as

$$F_{y_1y_2}(n,m;\xi_1\xi_2) \triangleq P\,[y_1(n+m) \le \xi_1, y_2(n) \le \xi_2] = E^{\{\alpha\}}\{u(\xi_1 - y_1(n+m))\, u(\xi_2 - y_2(n))\}$$

where $P[\cdot]$ denotes FOT probability (Gardner, 1987; Napolitano, 2019), $u(\xi) = 1$ for $\xi \ge 0$ and $u(\xi) = 0$ for $\xi < 0$, and $E^{\{\alpha\}}\{\cdot\}$ is the almost-periodic component extraction operator, that is, the operator that extracts all the finite-strength additive sine-wave components of its argument. It is the expectation operator in the FOT approach.

All the results can be interpreted in the classical stochastic approach by interpreting $P[\cdot]$ as classical probability and $E^{\{\alpha\}}\{\cdot\}$ as the ensemble average $E\{\cdot\}$, provided that appropriate ergodicity conditions (called cycloergodicity conditions) are satisfied by the stochastic processes (Gardner, 1987; Napolitano, 2019, chapt. 5).

The function $F_{y_1y_2}(n,m;\xi_1\xi_2)$ is almost-periodic in n by construction. For jointly stationary time-series it does not depend on n. We have (Napolitano, 2019, sec. 2.3.1.5)

$$F_{y_1y_2}(n,m;\xi_1\xi_2) = \sum_{\alpha\in\Gamma_2} F^{\alpha}_{y_1y_2}(m;\xi_1,\xi_2)\, e^{j2\pi\alpha n}$$

where Γ_2 is a countable set of possibly incommensurate cycle frequencies $\alpha \in [-1/2, 1/2)$ and

$$F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2) \triangleq \lim_{N\to\infty} \frac{1}{2N+1} \sum_{n=-N}^{N} u(\xi_1 - y_1(n+m))\, u(\xi_2 - y_2(n))\, e^{-j2\pi\alpha n}$$

are the Fourier coefficients which are referred to as cyclic joint CDFs. The function $F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$ is not identically zero for $\alpha \in \Gamma_2$. For jointly stationary time-series, $F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$ is non zero only for $\alpha = 0$.

The cross-correlation function of $y_1(n)$ and $y_2(n)$ is given by

$$E^{\{\alpha\}}\{y_1(n+m)\, y_2(n)\} = \int_{R^2} \xi_1\, \xi_2\, dF_{y_1 y_2}(n, m; \xi_1 \xi_2)$$

$$= \sum_{\alpha \in \Gamma_2} \int_{R^2} \xi_1\, \xi_2\, dF^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)\, e^{j2\pi\alpha n}$$

$$= \sum_{\alpha \in A_2} R^{\alpha}_{y_1 y_2}(m)\, e^{j2\pi\alpha n}$$

where $A_2 \subseteq \Gamma_2$ is a countable set of possibly incommensurate cycle frequencies $\alpha \in [-1/2, 1/2)$ and

$$R^{\alpha}_{y_1 y_2}(m) \triangleq \lim_{N\to\infty} \frac{1}{2N+1} \sum_{n=-N}^{N} y_1(n+m)\, y_2(n) e^{-j2\pi\alpha n}$$

$$= \int_{R^2} \xi_1\, \xi_2\, dF^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$$

are the Fourier coefficients which are referred to as cyclic cross-correlation functions. The function $R^{\alpha}_{y_1 y_2}(m)$ is not identically zero for $\alpha \in A_2$.

5.2. Measurement results

The Fourier coefficients $F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$ and $R^{\alpha}_{y_1 y_2}(m)$ of the periodically time-varying cross statistical functions of pairs of time series $y_1(n)$ and $y_2(n)$ are estimated over the available finite observation intervals (N finite in the above expressions) (Napolitano, 2012 chap. 2, 2019 chap. 5). The energies of the estimates, for each α, are the sum over the lag parameter m of the squared magnitudes of the estimates.

Missing values in the data files are reconstructed by linear interpolation. Then, time series are dichotomized. In the joint CDF, the temporal median values ξ_1 and ξ_2 of $y_1(n)$ and $y_2(n)$ are considered.

The analyzed time series have been obtained with sampling periods of 5 days or 1 month. Each sample of a time series sampled with sampling period 1 month is replicated 6 times in order to obtain a new time series with sampling period 5 days (1 month = 30 days = 6 × 5 days). Thus, all processed time series have the same sampling period of 5 days. The sampling period is denoted by T_s and the sampling frequency by $f_s = 1/T_s$. When time series have different lengths, the shortest is zero-filled.

5.3. Statistical Dependence Between Cosmic Rays and Earthquakes (experiment 1)

In the first experiment,

- Time series $y_1(n)$ is the average variation of the cosmic ray detection rate taken from Moscow (NMDB), (original sampling period = 5 days);
- Time series $y_2(n)$ is log_{10} of earthquake (EQ) sum magnitude taken from Moscow (NMDB), (original sampling period = 5 days).

Results for the estimated cyclic joint CDF $F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$ are reported in Fig. 5.

Significant cyclostationary features are found at cycle frequencies $\alpha = \pm 0.001288 f_s$. The cycle frequency $\alpha_0 = 0.001288 f_s$ corresponds to the period $T_0 = 776.02\, T_s = 3880.1$ days = 10.63 years.

5.4. Cyclic Cross-Correlation Between Cosmic Rays and Sunspots (experiment 2)

In the second experiment,

- Time series $y_1(n)$ is the average variation of the cosmic ray detection rate taken from Moscow (NMDB), (original sampling period = 5 days);
- Time series $y_2(n)$ is the Sunspot monthly mean (original sampling period = 1 month).

Results for the estimated cyclic cross-correlation function $R^{\alpha}_{y_1 y_2}(m)$ are reported in Fig. 6.

Significant cyclostationary features are found at cycle frequency $\alpha = \pm 0.00130 f_s$. A more detailed analysis shows features at cycle frequencies $\alpha = \pm 0.001101 f_s$ and $\alpha = \pm 0.001466 f_s$. These cycle frequencies merge into $\alpha = \pm 0.00130 f_s$ in the shown graphs. The cycle frequency $\alpha_0 = 0.00130 f_s$ corresponds to the period $T_0 = 769.2\, T_s = 3846.2$ days = 10.53 years.

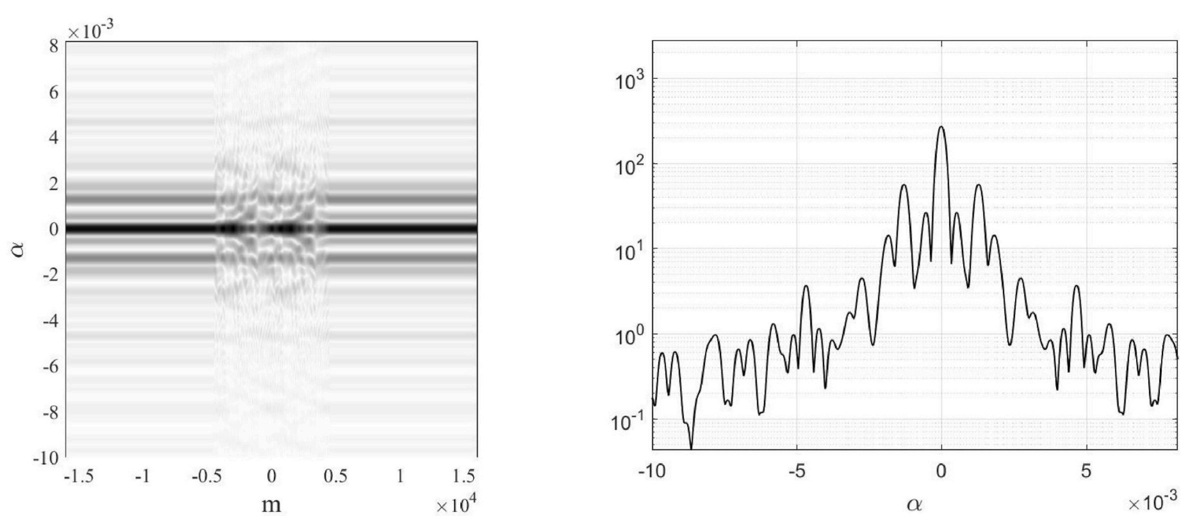

Fig. 5. Statistical Dependence between Cosmic Rays and Earthquakes. (Left) magnitude of the estimated cyclic joint CDF $F^{\alpha}_{y_1 y_2}(m; \xi_1, \xi_2)$ as a function of α and m (2-dimensional grayscale elevation map); (Right) energy of the estimated cyclic joint CDF as a function of α.

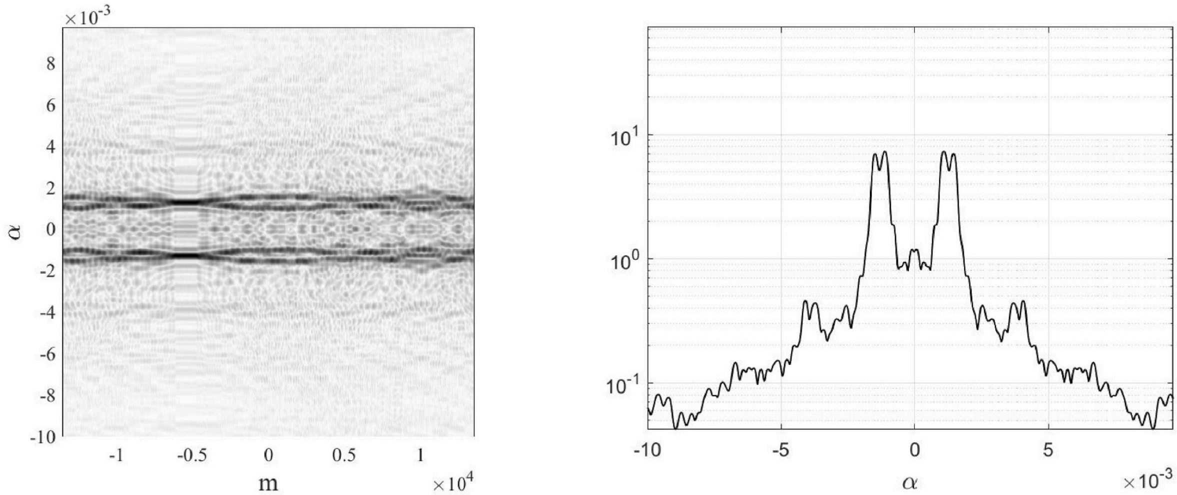

Fig. 6. Cyclic Cross-Correlation between Cosmic Rays and Sunspots. (Left) magnitude of the estimated cyclic cross-correlation function $R^{\alpha}_{y_1y_2}(m)$ as a function of α and m (2-dimensional grayscale elevation map); (Right) energy of the estimated cyclic cross-correlation as a function of α.

5.5. Cyclic Cross-Correlation Between Earthquakes and Sunspots (experiment 3)

In the third experiment,

- Time series $y_1(n)$ is log_{10} of earthquake (EQ) sum magnitude taken from Moscow (NMDB), (original sampling period = 5 days);
- Time series $y_2(n)$ is the Sunspot monthly mean (original sampling period = 1 month);

Results for the estimated cyclic cross-correlation function $R^{\alpha}_{y_1y_2}(m)$ are reported in Fig. 7.

Significant cyclostationary features are found at cycle frequency $\alpha = \pm 0.001279\, f_s$. The cycle frequency $\alpha_0 = 0.001279\, f_s$ corresponds to the period $T_0 = 781.5\ T_s = 3907.5$ days = 10.71 years.

5.6. Discussion

Measurements of joint cyclic statistical functions show the existence of statistical dependence or correlation between the pairs of analyzed signals. In particular, the dark lines in Fig. 6 left and Fig. 7 left is the evidence of joint cyclostationarity between the analyzed pairs of signals. The cycle frequencies obtained from the analysis correspond to periods of almost 11 years.

6. Validation with randomized data sets

In order to validate the significance of cosmo-seismic correlations that was obtained after applying "local optima" of the parameters to each data set, we have conducted additional validation using the randomized data sets. For such a purpose the cosmic ray (CR) and earthquake (EQ) data were downloaded and binned independently according to the prescription given earlier.

Following the approach described in the previous sections we introduce the additional parameter.

$X_{CR/EQ}$ for CR and EQ data in order to characterize their simultaneous behavior. Namely, using the variables defined in equation (1) we can write

$$X_{EQ} = A_i(d, m, t_0, t_i, \Delta t, P) + 1, X_{CR} = B_i(d, t_0, t_i, P) + 1$$

In order to study the simultaneous variations of EQ and CR data above their median values, we construct new parameter $X^{'}_{CR/EQ}$ for CR and EQ

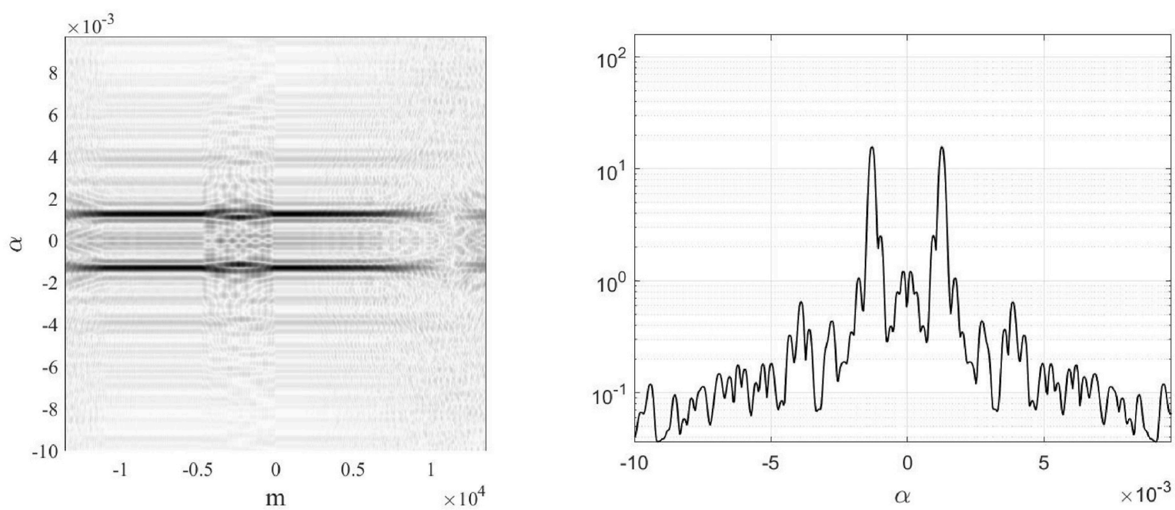

Fig. 7. Cyclic Cross-Correlation between Earthquakes and Sunspots. (Left) magnitude of the estimated cyclic cross-correlation function $R^{\alpha}_{y_1y_2}(m)$ as a function of α and m (2-dimensional grayscale elevation map); (Right) energy of the estimated cyclic cross-correlation as a function of α.

data by assigning X' to "+ 1" if its value at a given time step is above its median value ($X_{CR/EQ} > 1$), and to "− 1" if the value is below the median value ($X_{CR/EQ} < 1$)

$$X'_{CR/EQ} = \begin{cases} +1, if X_{CR/EQ} > 1 \\ -1, if X_{CR/EQ} < 1 \end{cases}$$

The variable N_+ that was defined earlier and shows the sum of positive signs of expression (1) can be written in terms of $X'_{CR/EQ}$ as

$$N_+ \ (lag) = \frac{1}{2}\sum |X'_{CR} + X'_{EQ}|$$

where the sum of arrays $X'_{CR} and X'_{EQ}$ is calculated element-by-element and then the sum of its absolute values is calculated for various lags. The non-zero values of this parameter show how many cases we have the situation when CR and EQ behave in a similar way, i.e. both simultaneously go below or above their median values.

We have estimated the uncertainties by random shuffling the original EQ and CR time series, where we have performed $N = 10^7$ random realizations and have calculated the correspondent percentiles and moments of obtained distributions of N_+^{rand}. The results are shown on Fig. 8.

From obtained results we conclude that for each original data set the value of N_+ is larger than the highest N_+ value in 10^7 randomized data sets, which is consistent with the main result reported here.

7. Summary, discussion, and outlook

We have demonstrated for the first time that the variation of the absolute average detection rates of secondary cosmic radiation correlates with the global seismic situation (sum of the magnitudes of earthquakes with magnitudes greater-than or equal to 4, occurring at all locations) that takes place approximately two weeks later than the relevant cosmic ray data. The size of the shift in time between the cosmic and seismic data sets reveals the precursor character of the correlation effect, coinciding with the time of occurrence of ionospheric anomalies preceding the 2010 8.8-M earthquake in Chile (Píša et al., 2010). The observed correlation effect was validated by independent analyses using cyclostationarity-based methods and randomized data sets, its significance exceeds 6 σ, it varies with time with a periodicity resembling the undecenal solar cycle, and it also depends on tiny (less than 5 days), geographically varying shifts of the data bins in time. The latter dependence, although presently not understood, should be investigated interdisciplinarily to search for some lower-level periodicity in the data which might be related e.g. with the rotational period of the Sun, which is approximately 25.6 days at the equator and 33.5 days at the poles, or with tides occurring at maximal strengths twice a month, when the Moon is approximately along the Earth - Sun line. The main limitations of the study are mostly related to the purely phenomenological value of the outcome, and to the unknown nature of a number of specific parameters which had to be implemented in the analysis, like e.g. the required time lag between the cosmic ray and earthquake data sets. On the other hand, given the unquestioned statistical significance of the effect, these obvious limitations define a bunch of potentially valuable new research directions which might help getting a deeper insight into the physics underlying the reported observation. In fact such analyses are already in progress.

The 6σ effect described in this report was found after considering a search for global manifestations of *cosmo-seismic* correlations, without restricting the earthquake data set to the locations of the cosmic ray data used in the analysis. While it has to be emphasized that the nature of the demonstrated correlations between cosmic rays and earthquakes remains unknown, one may suppose that such a result could be the signature of a possible connection between physical mechanisms responsible for changes in the Earth's dynamo and seismic activity. In such a scenario, variations of the geomagnetic field generated by the movements of the liquid core of the Earth could have a direct impact on cosmic-ray detections and would justify the widening of the consideration of *cosmo-seismic* correlations as a global phenomenon observable on the surface of the Earth. However, despite an apparent consistency between the properties of the observed phenomenon, and the geophysical assumptions which motivated the study, at the present stage of the investigation one cannot exclude also non-geophysical interpretations of the periodic *cosmo-seismic* correlations which are demonstrated in this report. For an example, if the solar activity was to induce large scale and energetic transient atmospheric changes which in turn could trigger seismic activity in regions already close to an earthquake due to some other processes, as proposed e.g. in Refs (Marchitelli et al., 2020; Yanchukovsky, 2021). (see also the references therein), the resultant relation between variations of secondary cosmic ray intensities and global seismic activity could look similarly to the effect described here. In any case our observation should be considered as a significant step towards understanding the physics of big earthquakes and to developing an efficient earthquake early warning system.

We expect that the correlations demonstrated here with three arbitrarily chosen independent cosmic ray observation sites should be essentially visible in all the other cosmic ray data sets of comparable quality and volumes, and, possibly, even in smaller sets that extend over a sufficiently long period of time. While precise predictions of seismic activity currently seem unachievable, the fine structure of the observed dependencies, including site-to-site and technique-to-technique differences, creates a perspective of the application of cutting-edge data processing and analysis techniques, including the latest achievements in artificial intelligence and big data, to assess the future earthquake risk at least globally, in a continuous way, and broadcast the information widely, leaving precaution-related decisions to the most exposed governments, organizations, or even individuals. With this starting point concerning the early warning system against earthquakes, the further accumulation of secondary cosmic ray data, together with other *inward* multimessenger channels of physics information, and with continuously improved modeling and methodology of the analyses, the precision of the warnings will only increase and save lives of many throughout the world, wherever the seismic activity is an everyday threat.

We expect that the apparent similarity of the periodical changes of the *cosmo-seismic* correlation effect to the undecenal solar cycle will be a starting point for a new kind of interdisciplinary analyses concerning the yet unconfirmed though possible physical connections (e.g. of magnetic or gravitational origin) between the Sun and the Earth. The subsequent studies should also include, in particular, investigations on shorter time scale precursors, correlations with other known earthquake precursors or precursor candidates (e.g. radon emission and/or particle densities in the ionosphere), and potential connections with the planned technological efforts (e.g. using tiltmeters to obtain the information on gravitational changes that precede seismic effects).

The character and the scope of the potential impact of this study, but also its ultimate relevance, warrant efforts for spreading the presented results as widely as possible so that a collective and well-coordinated interdisciplinary research dedicated to an earthquake early warning system can be pursued efficiently.

Funding

Visegrad Fund, Grant No. 21920298 (PH, AT); King Abdullah University of Science and Technology (KAUST) Office of Sponsored Research (OSR), Award OSR-2019-CRG8-4057 (AN); National Science-Center, Grant No. 2016/22/E/ST9/00061 (VM); National Science Center, Grant No. 2018/29/B/ST2/02576 (RK, ŁB, DAC); Foundation for Polish Science (FNP), International Research Agenda Programme AstroCeNT (MAB/2018/7), funded from the European Regional Development Fund (TB); ANID-Millennium Science Initiative Program - ICN2019 044 (JZS); AGH University of Krakow, Grant No. 16.16.120.773 for 2023 (KR, TS).

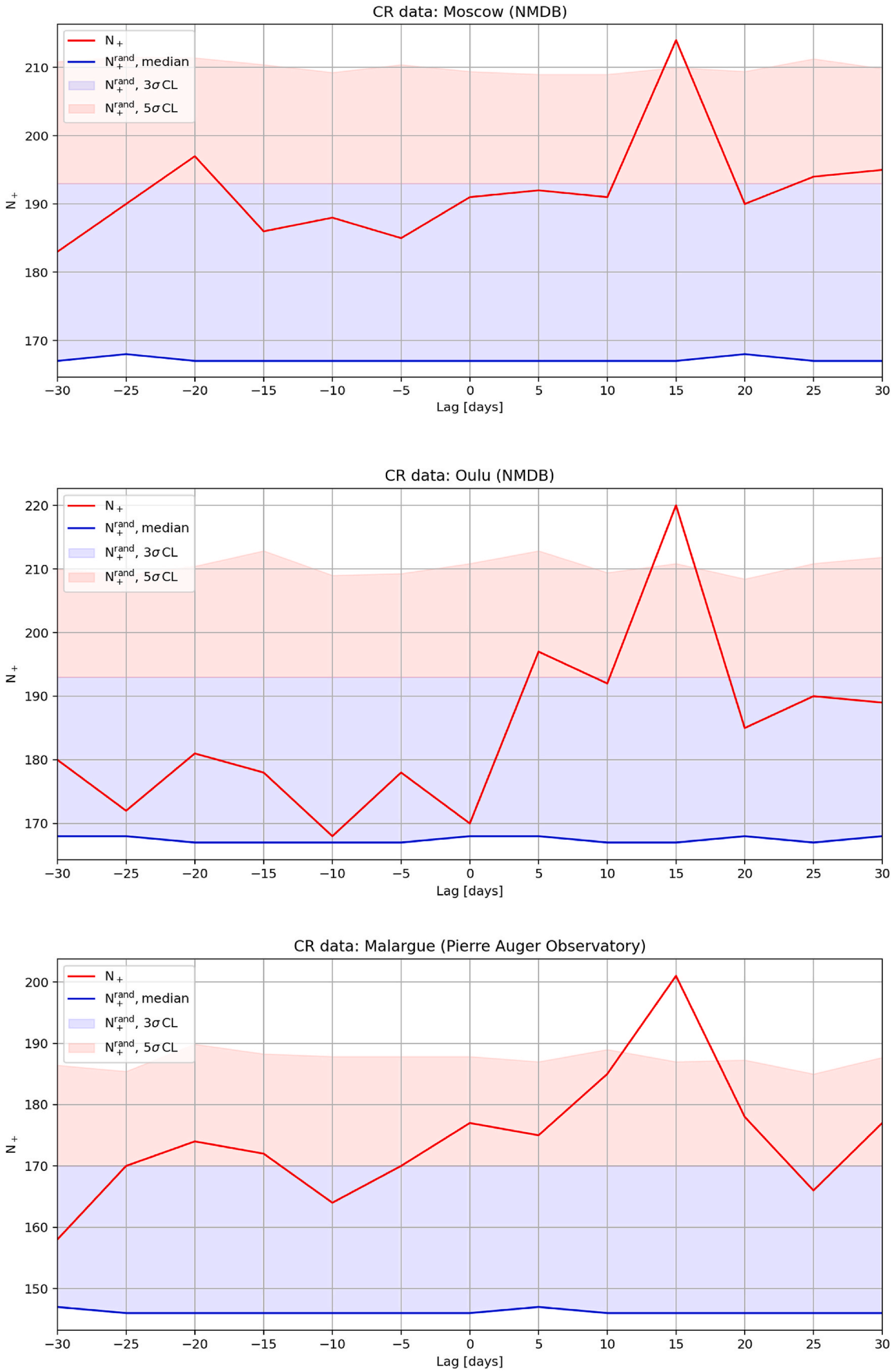

Fig. 8. The parameter N_+ for different time lags for various cosmic ray data. The median level and $3\sigma, 5\sigma$ confidence levels from random simulations are shown.

Author contributions

Conceptualization: PH, VM, AN, DAC, JZS, JWM, NB; Methodology: PH, VM, AN; Resources: PH, MK, BI; Investigation: PH, VM, AN, RD, RG, SS, OR, OSk, KD, MK, OSu, KG; Visualization: PH, SS, MK; Project administration: PHSupervision: PH, JWM, DAC; Writing – original draft: PH, VM, AN, JZS; Writing – review & editing: PH, DAC, SS, JZS, JMV, TW, NZ, KAC, BI, TB, GB, NB, RK, MVM, KK, OB, ŁB, MB, MDRF, MF, PK, BŁ, JM, MN, LP, MP, KR, KS, TS, JS, AAT.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in our analysis is publicly available under the links provided in the References.

Acknowledgments

We acknowledge the leading role in the CREDO Collaboration and the commitments to this research made by the Institute of Nuclear Physics, Polish Academy of Science. We acknowledge the Pierre Auger Observatory for providing the scaler data (The Pierre Auger collaboration, 2011), the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007), and the PIs of individual neutron monitors at Moscow (Pushkov Institute of Terrestrial Magnetism, Ionosphere and radio wave propagation IZMIRAN, Troitsk, Russia) (MOSCOW Neutron Monitor and Russia (MOSC) and Oulu (Sodankyla Geophysical Observatory of the University of Oulu, Finland) (Kananen et al., 1991; NMDB Oulu) for providing data. This research has been supported in part by the PLGrid Infrastructure - we warmly thank the staff at ACC Cyfronet AGH-UST for their always helpful supercomputing support. We thank Roger Clay, Dariusz Góra, Bohdan Hnatyk, Michał Ostrowski, Leszek Roszkowski, and Henryk Wilczyński for critical reading of the manuscript, and for their useful remarks and valuable discussions.

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