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Research Article

Long-Term Cosmic Ray Variability and the CME-Index

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The cosmic ray modulation in relation to solar activity indices and heliospheric parameters during the period January 1996–October 2011, covering the solar cycle 23 and the ascending phase of solar cycle 24, is studied. The new perspective of this contribution is that the CME-index, obtained from only the CMEs with angular width greater than 30 degrees, gives much better results than in previous works. The proposed model for the calculation of the modulated cosmic ray intensity obtained from the combination of solar indices and heliospheric parameters gives a very satisfactory value of the standard deviation. The best reproduction of the cosmic ray intensity is obtained by taking into account solar and interplanetary indices such as sunspot number, interplanetary magnetic field, CME-index, and heliospheric current sheet tilt. The standard deviation between the observed and calculated values is about 6.63% for the solar cycle 23 and 4.13% for the ascending part of solar cycle 24.

1. Introduction

The cosmic ray (*CR*) intensity, as it is observed from Earth and in Earth's orbit, exhibits an approximate 11-year variation anti correlated with solar activity, with perhaps some time lag, firstly studied by Forbush [1]. Many research groups have tried to express this long-term variation of the galactic *CR* intensity through means of appropriate solar indices and geophysical parameters. The modulation of galactic cosmic rays in the heliosphere using theoretical as well as empirical approaches is successful and advanced rapidly [2]. However, an adequate description of the effect of the heliosphere on cosmic rays still does not appear to be a simple task. To be adequate, theoretical models should consider the complex shape and dynamics of the heliospheric current sheet, the heliolatitudinal distribution of the solar wind velocity, boundaries between fast and slow solar wind streams, various sporadic and recurrent structures, and the role of the termination shock and the heliopause. Exarhos and Moussas [3] tried to estimate the magnetic field at the heliospheric termination shock and to study the effects of its temporal variation on the galactic cosmic ray long-term modulation starting from the Parker's model and using in-ecliptic measurements from different Spacecrafts at 1 AU near the Earth. Morishita and Sakukibara [4] tried to estimate the size of the heliosphere derived from the long-term modulation of neutron monitor intensities. Using a construction of the open solar magnetic flux from sunspot data as an input to a spherically symmetric quasisteady state model of the heliosphere, the expected intensity of galactic cosmic rays at the Earth's orbit was calculated in [5]. This calculated cosmic ray intensity is in good agreement with the neutron monitor measurements during the last 50 years. Particular consideration of the cosmic ray modulation is given to the correlation of long-term cosmic ray variations with different solar-heliospheric parameters and to existing empirical models of cosmic ray intensity, as it is described in the review paper by [6]. A method to predict cosmic ray intensity and solar modulation parameters was proposed in [7]. This method gives satisfactory results when applied to prediction of the dose received on-board commercial aeroplane flights. He notes that prediction of the galactic cosmic ray intensity observed at a given station is preferable than prediction of the different potentials such as the modulation potential in terms of sunspot numbers [8]. The importance of this choice is that the cosmic ray intensity is the only variable directly observed. Records of cosmic ray intensity

are available and homogeneous over a long period, while that is not the case for the data obtained from space observations. Two models were proposed in[9], a quasilinear and a model assuming a power-law relation between the modulation potential and the magnetic flux during the neutron monitor area 1951–2005 useful for predictions, if the corresponding global heliospheric variables can be independently estimated.

Recently, an empirical relation based on solar and interplanetary parameters was presented by [10] in order to describe the long-term modulation of cosmic ray intensity during the last solar cycle. Emphasis was given to the different behaviour of the heliospheric parameters compared with the solar ones regarding interesting properties of the cosmic ray intensity modulation. These are the hysteresis phenomenon and the cross-correlation analysis of these parameters with the cosmic ray intensity in the three phases of the solar cycle and according to the solar magnetic field polarity as well. This model has so far been applied to four solar cycles (20, 21, 22, and 23) and can be considered as a useful tool for understanding cosmic ray modulation. The proposed model can be extended backward in time or used for predictions, as it has practical implications for planning solar observations and forecasting space weather phenomena.

Solar cycle 23 was a cycle of great interest firstly, as it was characterized by a lot of violent periods of extreme solar events mainly in the descending phase, such as October-November 2003, January 2005, July 2005, and December 2006 and secondly, it had an extraordinary and extended minimum with duration more than three years. In this solar minimum, the cosmic ray intensity was much higher than in the previous cycles [11]. This long, quiet period was characterized by limited magnetic flux emergence at the photosphere, mostly in the southern hemisphere, and low coronal mass ejections (CMEs) and flare activity in the corona.

In our last work [10], we have shown that the long-term modulation of the intensity of cosmic-rays has reproduced using sunspot number (R_z), CME-index (P_i), interplanetary magnetic field (IMF), and heliospheric current sheet (HCS) tilt. In this work, we are showing the strong connection between the cosmic ray intensity and the CMEs by the use of CME-index, and the main criterion for the form of this index is the angular width of CMEs. According to [12], slow and narrow CMEs are ineffective for modulation, and as a result, we are showing the modulation with the previous form of the index and the new one.

2. Data Collection

In order to study the long-term cosmic ray modulation through the years 1996–2011, monthly values of cosmic rays from Lomnicky Stit neutron monitor (cut-off rigidity 3.84 GV) were used. For the purposes of this study, the time series of cosmic ray variations was normalized taking the cosmic ray intensity maximum (July 2009) equal to 1.00 and the cosmic ray intensity minimum (November 2003) equal to 0.00. We note that the cosmic ray intensity in the period of October-November 2003 during the declining phase of the solar cycle has been used only for normalization reasons and does not coincide with the activity maximum of the solar cycle during the years 2000–2002 [13]. But it is also very important the fact that this minimum of cosmic ray intensity coinciding with the maximum of CME-index shows the strong connection of these two variables.

In this study, we have also used data of the mean monthly sunspot number (R_z), taken from the National Geophysical Data Center (ftp://ftp.ngdc.noaa.gov/index.html), the intensity of the interplanetary magnetic field (IMF) is obtained from the OMNI database (http://omniweb.gsfc.nasa.gov/). The data on the tilt of the heliospheric current sheet using the classic PFSS model [14] (HCS) were obtained from the Wilcox Solar Observatory database (http://wso.stanford.edu/Tilts.html). The CMEs data, for the formation of the coronal mass ejection index (P_i), are taken from the SOHO/LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/). Unfortunately, the SOHO database has no data for CMEs for the months of July, August, and September of 1998 and January of 1999. In order to fill these data gaps, a smoothing method has been used. In Figures 1(a) and 1(b), the time profiles of all the examined parameters are presented.

3. CME-Index

For many years, the sunspot number was the most characteristic index of solar activity. This means that we can determine the phase of the cycle through the sunspot number, and the maximum values mean that we are in the maximum of the solar activity and minimum values that we are in the minimum of the solar cycle, while intermediate values are showing the ascending or descending phase of the cycle. At the maximum phase, we have some periods with very violent activity connected to the CMEs such as July 2000 and April 2001. On the other hand, we had a lot of very violent periods when the sunspot number was at the descending phase of the solar cycle or close to solar minimum, and as a result, we could not take safe results from the sunspot number only for the solar activity. These periods such as October-November 2003, January 2005, November-December 2006, or even February 2010 and August-September 2010 have the characteristic of violent solar activity, and most of them are connected to violent CMEs, X-flares, and finally ground-level enhancements (GLEs). There are CMEs with results on the Earth's magnetosphere causing magnetic storms, SEPs, or even GLEs. These CMEs are the interplanetary coronal mass ejections—ICMEs [15]—and are responsible for temporary disturbances of the Earth's magnetosphere. Now, it is clear that we have two types of CMEs with different characteristics: geoeffective CMEs which can produce geomagnetic storms and the SEP-effective CMEs which can cause SEP events [16, 17]. It is known that SEP events are originating from CME-driven shocks [15, 18, 19]. Based on this issue, a CME-index was introduced in our previous works [20–22].

In this work, the most extensive number of data as they now covers the whole solar cycle 23 and a part of the ascending phase of the new solar cycle 24 has an advantage for the application of this index. This extraordinary solar

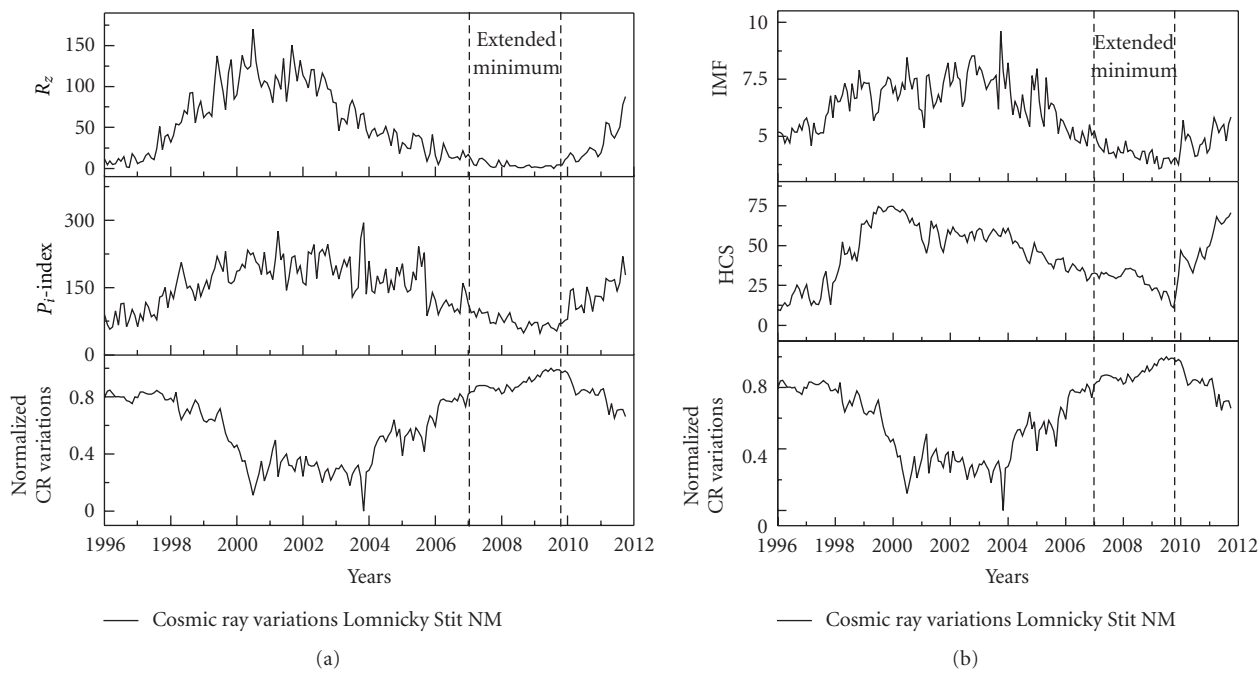

Figure 1: (a) Time profiles, starting from the top, of the sunspot number (R_z), CME-index (P_i), and the cosmic ray variations for the period of 1996–2011. The period of extended minimum is noted between the dashed lines for all the examined parameters. (b) Time profiles, starting from the top, of the interplanetary magnetic field (IMF), the heliospheric current sheet tilt (HCS), and the cosmic ray variations for the period of 1996–2011. The period of extended minimum is noted between the vertical dashed lines.

minimum between the solar cycles 23 and 24 is also very important. Now we have included data for previous periods as mentioned before, and it is clear the weakness of the sunspot number only to explain these periods.

One of the most characteristic parameters of a CME is the linear speed as a factor of the importance of the CME [16, 23], so we are using the mean monthly linear speed (V_p) of the CMEs and their monthly number (N_c) in a new dimensionless relation according to [12] with the form

$$P_i = \alpha \cdot \frac{N_c}{N_{c\max}} + \beta \cdot \frac{V_p}{V_{p_{\max}}}, \tag{1}$$

where the factors α and β are calculated with the best cross-correlation coefficient values, between the values of the index related to the cosmic ray intensity, for α and β factors applies $\alpha+\beta = 1$ and $\alpha, \beta > 0$. The maximum values $N_{c\max}$ and $V_{p_{\max}}$ are the maximum values of the examined period. For the period January 1996–October 2011, we found the relation of the form:

$$P_i = 0.12 \cdot \frac{N_c}{N_{c\max}} + 0.88 \cdot \frac{V_p}{V_{p_{\max}}}, \tag{2}$$

where $N_{c\max} = 178$ and $V_{p_{\max}} = 834$ km/s. The factors 0.12 and 0.88 were the best values which maximize the correlation coefficient of P_i-index between cosmic ray intensity with $r = -0.82$. Between P_i-index and sunspot number, the correlation coefficient is $r = 0.76$.

We noticed also periods with a lot of CMEs even in minimum as a result of a lot of narrow and slow CMEs. In this work, a new approach is presented using data for CMEs with width >30° for P_i-index for the period January 1996–October 2011. The best relation is

$$P_i = 0.37 \cdot \frac{N_c}{N_{c\max}} + 0.63 \cdot \frac{V_p}{V_{p_{\max}}}, \tag{3}$$

where $N_{c\max} = 152$ and $V_{p_{\max}} = 915.6$ km/s. The correlation coefficient between P_i-index and cosmic rays is found to be $r = -0.84$ and sunspot number $r = 0.82$ respectively, and these are the best cross-correlation values in this work for the examined period (January 1996–October 2011). In Figure 2, it is obvious the increase of narrow CMEs especially after 2005. The number of CMEs using data from CMEs with width >30° follows very well the sunspot number. For the entire examined period, the correlation coefficient between P_i-index from (3) and HCS tilt was $r = 0.76$ and IMF was $r = 0.83$ which is very important proving the strong connection between the index and the heliospheric parameters. We hope that for further studies in space weather and modulation of galactic cosmic rays, the P_i-index could be very helpful and must be a parameter in modulation formulas [10].

4. Cosmic Ray Modulation

It is well known that the 11-year modulation of the cosmic ray intensity shows some time lag behind the solar activity which is a kind of hysteresis effect [1, 10, 21]. Keeping this in mind, we have carried out the analysis of correlation between the monthly values of the cosmic-ray variations and various

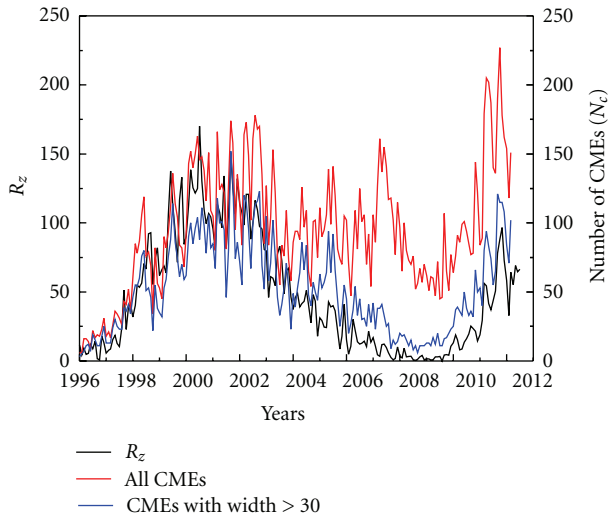

Figure 2: Time profiles of the mean monthly number of CMEs using the total number of CMEs (red line) and those with angular width greater than 30° (blue line). The sunspot numbers are also indicated with the black line.

solar and heliospheric activity parameters (R_z, P_i, IMF, and HCS) for the examined period.

To calculate the time lag of each parameter in reference to the cosmic ray intensity [24, 25], we have calculated the cross-correlation coefficients between them with varying time lags from 0 to 30 months for the interval of the examined period. The maximum cross-correlation coefficients and the corresponding time lags are given in Table 1 for the examined period.

In this work, the same empirical relation of the cosmic ray modulation that was applied in the previous works to solar cycles 20, 21, 22, and 23 is adopted [21, 26]. This is derived by a generalization of Simpson's solar wind model using the diffusion-convection drift model [27], and it is expressed by the following relation:

$$I(t) = I - \int f(r)S(t-r)dr, \tag{4}$$

where I and $I(t)$ are the galactic (unmodulated) and modulated cosmic ray intensities, respectively, $S(t-r)$ is the source function representing some proper solar activity indices at a time $t-r$ ($r \geq 0$), and $f(r)$ is the characteristic function that expresses the time dependence of solar disturbances represented by $S(t-r)$ [28, 29]. According to the previous model, the modulated cosmic ray intensity $I(t)$ is expressed by a constant C and the sum of a few source functions appropriately selected from the solar and interplanetary indices that affect cosmic ray modulation. This relation is given by the following expression:

$$I(t) = C - 10^{-3}(a_1X + a_2Y + a_3Z + a_4W), \tag{5}$$

where C is a constant, X, Y, Z, and W are the selected time-lagged solar-heliospheric parameters, and α_i ($i = 1$ to 4) are coefficients calculated by the RMS-minimization method.

Table 1: Cross-correlation coefficients and the corresponding time lags for the entire period (1996–2011).

Indices	Correlation coefficients (r) (95% significance level)	Time lags (months)
Sunspot number R_z	-0.91 ± 0.01	+14
Coronal mass ejections index P_i	-0.84 ± 0.01	0
Interplanetary magnetic field IMF	-0.86 ± 0.01	+1
Heliospheric current sheet HCS	-0.82 ± 0.01	+8

Constant C is linearly correlated to the cut-off rigidity of each station according to the following relation:

$$C = 0.95 + 0.005P[\text{GV}], \tag{6}$$

where P is the cut-off rigidity for each neutron monitor station [30]. In this work, using data of the cosmic ray variations obtained from the Lomnicky Stit neutron monitor with cut-off rigidity of 3.84 GV, constant C is found to be equal to 0.9692.

We will investigate the entire period of 1996–2011 and separately the period of 23rd solar cycle (May 1996–December 2008) and the ascending part of 24th solar cycle (January 2009–October 2011). The model parameters, the standard deviation for each case, and coefficients α_i calculated by the RMS-minimization method are presented in Table 2. It is remarkable that the standard deviations for all cases are smaller than 7%. Comparing with the results of our last work [10], they have been improved for the entire period.

The best relation reproducing the cosmic ray variations is the combination of R_z, P_i, IMF, and HCS [10]. This is expressed by the following relation:

$$I(t) = C - 10^{-3}(a_1R_z + a_2P_i + a_3\text{IMF} + a_4\text{HCS}), \tag{7}$$

where constant C was found equal to 0.9692, and R_z, P_i, IMF, and HCS are the solar-interplanetary parameters incorporating the time lag. Coefficients α_i were found equal to 2.42, 0.54, 54.08, and 2.02, respectively. The standard deviation for this relation is found to be 6.69% which is a very good approximation. It is noticed that the maximum phase of solar cycle 23 was very complicated including double peaks and the reversal of the solar magnetic field as well. It is interesting that there is a good agreement in the maximum and descending phases due to the use of P_i and IMF, mainly in the solar extreme period of October-November 2003, while the contributions of IMF and HCS complement each other and improve the agreement in the ascending and descending phases that are characterized by strong solar events.

As we mentioned earlier, the use of CMEs with angular width greater than 30° shows a very good behavior for the entire solar cycle, and as a result, we have the best cross-correlation values between the cosmic ray intensity and P_i-index [12]. If we use the P_i-index data which occurs from

Table 2: Standard deviation for different models during the solar cycles 23 and 24 and in total examined period. Coefficients α_i factors are also given in the first column, respectively, for each variable.

Model parameters	Solar cycle 23 (May 1996–Dec 2008)	Solar cycle 24 (Jan 2009–Oct 2011)	Total (Jan 1996–Oct 2011)
R_z, P_i, IMF, HCS (2.42, 0.54, 54.08, 2.02)	6.98%	4.79%	6.69%
R_z, P_i (width >30°), IMF, HCS (2.36, 0.91, 52.51, 2.12)	6.63%	4.13%	6.27%

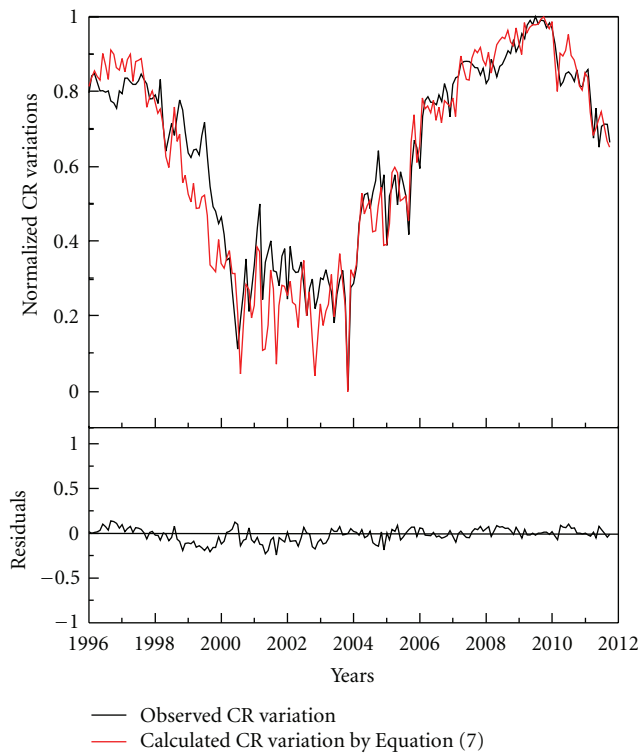

Figure 3: The observed values of cosmic ray intensity (black line) and those calculated by (7) (red line). The residuals are indicated in the lower panel. This modulation has a standard deviation of about 6.27%.

data of CMEs with width >30° using the same modulation as in (7), the results are much better with a standard deviation of 6.27%. The coefficients α_i were found equal to 2.36, 0.91, 52.51, and 2.12, respectively. These values of CME-index give much better results also between cosmic ray intensity and the number of CMEs (N_c), with $r = -0.72$, and the mean linear speed (V_p), with $r = -0.79$. In Figure 3, the observed and calculated cosmic ray variations by (7) using P_i-index from CMEs with width >30° are presented.

The significant improvement of this empirical model is resulted from the use of the CME-index P_i, using only CMEs with angular width >30°, which is highly correlated with the cosmic ray intensity variations ($r = -0.84$). Between the monthly number of CMEs (N_c), using CMEs with angular width >30°, and *CR* intensity, we found $r = -0.72$, in opposition with the total number of CMEs per month and *CR* intensity with correlation coefficient $r = -0.44$. The previous value of the correlation coefficient of the total number of CMEs was −0.78 [22], which was obtained over a shorter time period, up to the beginning of 2006 (February 2006), without the period of the solar minimum which was examined here, where a lot of narrow and slow CMEs were recorded without any effect on the long-term modulation [12].

5. Ascending Part of Solar Cycle 24

As it was mentioned earlier, the slow decline of solar cycle 23 and the slow rise of cycle 24 resulted in a very long period of low solar activity which lasted from about 2006 to the end of 2009, with 2008 and 2009 being particularly quiet years. Therefore, the solar minimum between cycles 23 and 24 was very extended and deep in contrast to the previous solar minima with duration of tens of months instead of few months as in earlier cycles. In [21], the solar cycle dependence of the cosmic ray intensity time lag behind the sunspot number was studied extensively. For cycles 17–23, the mean value of this time lag is 2.4 ± 1.9 months for even cycles and 12.4 ± 7.2 for odd cycles [21, 27].

During the last solar cycle 23, the minimum of the monthly mean sunspot number occurred on August 2009. According to [31], the maximum of cosmic ray intensity was observed in October 2009, and the onset of the current solar cycle 24 of galactic cosmic rays was noted in January 2010. Kane [11] noticed that the cosmic ray intensity decreased only after March 2010.

In this section, the period of the ascending part of solar cycle 24 from January 2009 to October 2011 is studied separately from the whole time interval. The cross-correlation coefficients for this period between the cosmic ray intensity and the sunspot number were calculated, and a maximum coefficient $r = -0.90$ with a corresponding time lag of 2 months was found. Kane [11] found a time lag for this minimum about 6-7 months. Ahluwalia and Ygbuhay [31] also calculated a time lag of about 3 months between a large, sharp increase of the HCS tilt angle and the onset of cosmic ray modulation, in agreement to our calculations where a time lag of about 2-3 months (2.3 ± 0.3 months), with respect to HCS, is found, with a very high correlation coefficient of $r = -0.96$. The time lag between the cosmic ray intensity and the sunspot number from the best nonlinear fitting is calculated to the value of 1.9 ± 0.3 months. This value coincides—up to now—with the expected value for even cycles as mentioned in a previous work [10]. Between the cosmic ray intensity and the IMF, a time lag of about 1

Table 3: Cross-correlation coefficients and the corresponding time lags for the ascending part of 24th solar cycle.

Indices	Correlation coefficients (r) (95% significance level)	Time lags (months)
Sunspot number R_z	-0.90 ± 0.02	+2
Coronal mass ejections index P_i	-0.85 ± 0.02	0
Interplanetary magnetic field IMF	-0.84 ± 0.02	+1
Heliospheric current sheet HCS	-0.96 ± 0.02	+2

month was found, with $r = -0.84$. The maximum cross-correlation coefficients and the corresponding time lags for this period are given in Table 3.

6. Discussion and Conclusions

The cosmic ray modulation is a complex phenomenon which occurs all over the heliosphere and depends on many factors. No single solar index, however sophisticated, can account for cosmic ray variations. Different scientists proposed empirical relations describing the long-term cosmic ray variations based on the joint use of solar and/or heliospheric indices. At first, the solar indices such as sunspot number and solar flares were used [26]. Later, Belov et al. [32] proposed a multiparametric description of long-term *CR* variations, based on a joint use of the HCS tilt and intensity variations of the IMF. The effect of IMF intensity variations on cosmic ray modulation is even easier to substantiate theoretically than the effect of the HCS tilt. The main determining parameter of particle transport—gyroradius—is inversely proportional to the IMF strength (H). According to theory [32], an increase of H should lead to a decrease of transport path and the diffusion coefficient and, consequently, to an increase of the *CR* modulation. The relationship between the IMF strength and long-period variations of *CR* was corroborated experimentally [32, 33] when long data series of solar wind measurements were built up. Indeed, these parameters—the HCS tilt and the IMF intensity—successfully supplement each other. The point is that the HCS tilt manifests the structure of the heliosphere, while the IMF intensity characterizes quantitatively its effect on cosmic rays. In our previous work [21], the solar indices (R_z, N_c) together with the heliospheric variables IMF, HCS, and Ap were found to explain better the cosmic ray modulation. In this approach, the use of the CME parameters represented by the CME-index P_i based on the number of CMEs and the mean plasma velocity taking account only CMEs with width >30° improved significantly the relation between the observed and the calculated values of the cosmic ray intensity measured by a single neutron monitor station. By applying a similar correlative analysis and the same empirical relation of the previous work [10], the following conclusions were outlined.

(i) As concerns the modulation effect, in the proposed model, the standard deviation is smaller than 7%. The best one obtained from (7) using the parameters R_z, P_i, IMF, and HCS gives a standard deviation of 6.63% for the 23rd solar cycle, 4.13% for the 24th solar cycle, and 6.27% for the total time period. The total improvement between the previous [10] and current empirical models for the cosmic ray modulation is significant.

(ii) This significant improvement of this empirical model is resulted from the use of the CME-index P_i, using CMEs with angular width >30°, which is highly correlated with the cosmic ray intensity variations ($r = -0.84$) which confirm our results according the correlation coefficient factors in our previous work [12].

(iii) Between the monthly number of CMEs (N_c), using CMEs with angular width >30°, and *CR* intensity, we found $r = -0.72$, in opposition with the total number of CMEs per month, and *CR* with correlation coefficient $r = -0.44$. The previous value of the correlation coefficient between the total number of CMEs and *CR* was -0.78 [22], which was obtained over a shorter time period, up to the beginning of 2006 (February 2006), without the period of the solar minimum which was examined here, where a lot of narrow and slow CMEs were recorded without any effect on the long-term modulation [12].

(iv) Examining the period of solar minimum and the ascending part of the solar cycle 24, a small time lag between cosmic ray intensity and solar activity of about 2 months with $r = -0.90$ was underlined, as it was expected for the even solar cycles [24, 27]. Cosmic ray intensity and heliospheric current sheet present a time lag of ~2 months with a very significant correlation coefficient $r = -0.96$. Between *CR* intensity and IMF, a time lag of about 1 month was noticed with $r = -0.84$.

Examining the entire period, we can conclude that all the selected heliospheric parameters (P_i, IMF, and HCS) can give a very good approximation to the modulated cosmic ray intensity. Moreover, we note that some of the indices used, such as R_z, P_i, and HCS, are global indices, whereas others, such as IMF, are limited to the ecliptic plane. According to [34], the cosmic ray modulation is defined mainly by the global indices because of their complicated transport in the heliosphere, consistent with our results in this work.

Summarizing, we can say that the empirical model proposed in the previous works and also in this work with significant improvements has been studied finally for a lot of solar cycles 19, 20, 21, 22, and 23, and the obtained results are a confirmation of the reliability of this. In a future work, we hope that the consideration of another solar parameter such as the polar magnetic field of the Sun will be able to throw more light to the investigation of the long-term cosmic ray modulation. All these studies will be a useful tool for solar cycle prediction and space weather applications.

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