

The Solar Polar Field in the Cosmic-Ray Intensity Modulation

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Abstract. In this work the modulation of galactic cosmic-ray intensity based on solar and heliospheric indices for the solar cycle 23 (1996-2008), is studied. In previous works a number of different indices such as the sunspot number, the CME-index, the interplanetary magnetic field and the heliospheric current sheet tilt were selected to be the most appropriate ones in order to describe the cosmic ray intensity of 10 GV observed by the network of neutron monitors. The new approach is an extension of this study to the influence of the solar magnetic field parameters, such as the mean magnetic field and the polar magnetic field, on the cosmic ray (CR) modulations. Using the wavelet analysis method a major periodicity of about 20-21 years was confirmed in the solar magnetic field data, indicating the existence of the solar magnetic cycle in CR variations. The best empirical relation of the cosmic ray modulation taking into account the sunspot number, the CME-index, the mean solar magnetic field and the solar polar field was improved significantly: a relative root mean square deviation (RMSD) between the observed and the calculated cosmic ray intensity values is found to be 8.7% instead to the previous one of about 10%.

1. Introduction

The modulation of galactic cosmic rays has been studied for several decades with both theoretical and empirical work focused on assessing the influence of solar and heliospheric influences on cosmic rays (see [1] and [2] and the references there in). In these empirical models a number of solar and heliospheric parameters, such as the sunspot number, the number of solar flares, the number of CMEs, the geomagnetic index A_p , the interplanetary magnetic field, the heliospheric current sheet tilt etc., have been used. Using solar and heliospheric parameters such as the sunspot number, the geomagnetic index A_p , the number of CMEs per month and the heliospheric current sheet tilt, the cosmic ray intensity through the empirical modulation with the lowest standard deviation of 10.8% between the observed and the calculated values of the cosmic ray intensity for the years 1996-2006 was produced [1].

This study was improved using two contributed factors. The first one was the data of 10 GV cosmic ray intensity instead of the data of separate detectors and the second one was the introduction of a solar activity parameter (P_f -index) based on the CMEs which are important for the cosmic ray modulation. The cosmic ray variations are most accurately measured for the rigidity of 10 GV because data from many neutron monitors can be used. As a result, the study of the cosmic ray long-term modulation at the rigidity of 10 GV is used in this work, as it is independent from the cut-off rigidity phenomena, and we can say that these calculated cosmic ray time series present the cosmic ray



variations at 1 AU outside the magnetosphere and atmosphere. The combination of these improvements led to a new empirical relation with the following parameters of sunspot number, the CME-index, the heliospheric current sheet tilt and the interplanetary magnetic field.

In a recent work [2] two suggestions were underlined as possible improvements. The first one was the examination of the P_i -index data as a function of the angular width of CMEs and the second one was the possible relation of the magnetic fields, such as the solar polar field strength with the galactic cosmic ray modulation. In this work the study of the P_i -index as a function of the angular width presented in section 2.1, was concluded that the best results occurred for data from CMEs with angular width greater than 15 degrees showing that narrow CMEs are less effective for cosmic ray modulation [3]. The wavelet toolkit was applied in section 3 in order to examine further the periodicities of the solar polar field and the cosmic-ray intensity of 10 GV. The magnetic fields taking into account in the section 4 were examined in relation to the cosmic ray modulation giving the best results up to now.

2. Data Collection

In order to study the long-term cosmic-ray modulation for the solar cycle 23 through the years 1996-2008, monthly values of cosmic-rays of 10 GV beyond the magnetosphere were used. These data were kindly provided by IZMIRAN group using the global survey method (GSM). This method uses data from as many ground based detectors (*e.g.* neutron monitors) as possible and it is actually a global method providing useful and reliable information on the conditions of the space environment. It is conceptually a version of spherical analysis [4], [5], [6] and different versions of this method have been evolved and improved at different stages of data processing [7], [8]. The variations of 10 GV cosmic rays with respect to the level of the year 1976 were calculated.

In this study we have also used data of the mean monthly sunspot number (R_z) which have been taken from the National Geophysical Data Center (<ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-indices/>). The intensity of the interplanetary magnetic field (IMF) was obtained from the OMNI database (<http://omniweb.gsfc.nasa.gov/>). The data on the tilt of the heliospheric current sheet (HCS), on the mean magnetic field of the Sun (MF) and on the solar polar field strength (PF) were obtained from the Wilcox Solar Observatory database (<http://wso.stanford.edu/>). The data of CMEs for the formation of the coronal mass ejection index (P_i) were 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. This method based on the polynomial fit uses the monthly number of CMEs and the mean linear plasma speed from January 1998 up to December 1999 as input information.

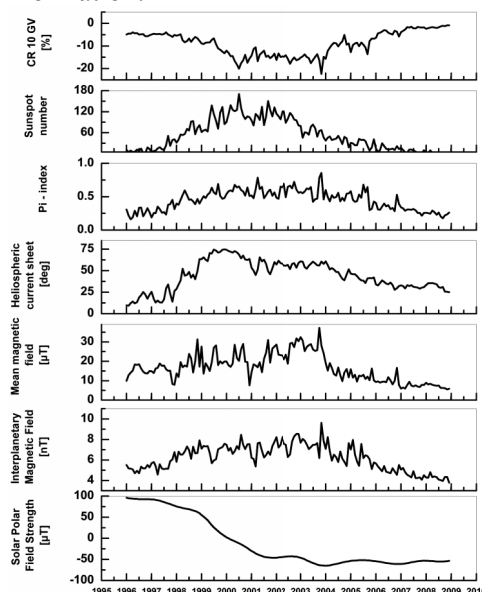


Figure 1. Time profiles of different solar and interplanetary variables used in this study.

The time profiles of solar, interplanetary, and geomagnetic parameters used in this work for all these phases of the interval 1996 to 2008 are presented in Figure 1. It is noted that all the above examined parameters present a clear 11-year variation, except of the solar polar field strength. The sunspot number R_z and the heliospheric current sheet HCS have their maximum values around 2000-2001, while the P_i -index, the mean field MF and the interplanetary magnetic field IMF have their maximum values at the end of 2003. The solar polar field strength has its maximum at the beginning of the solar cycle 23 and the minimum at the end of 2003. It means that this parameter has a different behavior in comparison with the others.

2.1. The CME-index

In a previous work [3] a dimensionless index concerning the properties of CMEs such as the angular width, the monthly number of CMEs and the mean linear speed, named P_i -index, was introduced and a proof of the ineffectiveness of narrow CMEs with angular width less than 30 degrees for cosmic ray modulation was presented. For the examined period of the present work the correlation between this index and the cosmic ray intensity was examined and a step of 5° was applied to the data of the P_i -index starting from the total available data of CMEs (width $> 0^\circ$) up to data of CMEs with angular width greater than 60° . The results from this analysis are presented in Figure 2. From this figure it is obvious that the best cross correlation coefficient ($r = -0.86$) between the P_i -index and cosmic-ray intensity occurred for the set of data with angular width of CMEs greater than 15° . At the same figure the right Y-axis is for the cross correlation coefficient between this index and the sunspot number where it is noticeable the fact that when data based on greater CMEs are used, the coefficient is higher ($r > 0.80$ for CMEs with width $> 50^\circ$). This suggests a possible relation between the angular width of the CMEs and the sunspot numbers which needs a further study.

The values of P_i based on the data of CMEs with angular width greater than 15° are produced by the monthly number of CMEs (N_c) and the mean plasma velocity (V_p) with the following relation:

$$P_i = \alpha \cdot \frac{N_c}{N_{c_{\max}}} + \beta \cdot \frac{V_p}{V_{p_{\max}}} \quad (1)$$

where $N_{c_{\max}} = 173$ and $V_{p_{\max}} = 856.9 \text{ km} \cdot \text{s}^{-1}$. The factors α and β are obtained by seeking for the best cross correlation in a linear fit between the cosmic ray intensity and the CME index P_i , where $\alpha + \beta = 1$, $\alpha, \beta > 0$. This P_i index was applied to the examined time period 1996-2008 and the factors α and β have been found as 0.23 and 0.77, respectively. These values are the best ones which maximize the correlation coefficient (r) between the P_i index and the cosmic-rays of 10 GV ($r = -0.86$) and with the sunspot number as well ($r = 0.78$).

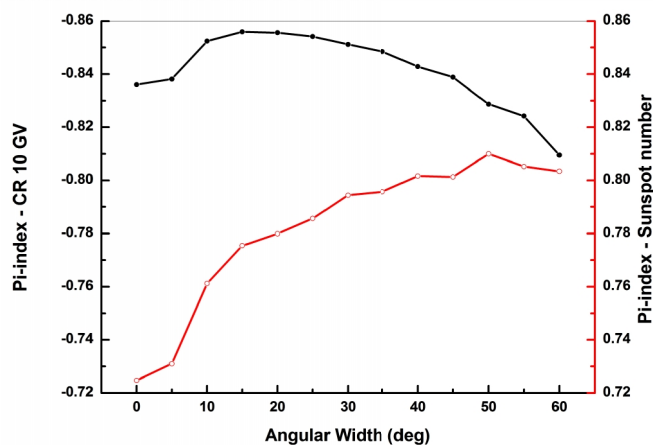


Figure 2. Correlation coefficient of P_i -index with CR intensity (left-y axis) and sunspot number (right-y axis) as a function of the angular width of the CMEs.

3. Time lag and Wavelet Analysis

The 11-year modulation of the cosmic-ray intensity shows some time lag behind the solar activity which is a kind of hysteresis effect [9], [10], [11] and also in [1].

In our previous work [2] the time lag of the cosmic-ray intensity behind various solar and heliospheric activity parameters concerning the period of 1996-2010, was investigated. In this work an analysis of the correlation between the monthly values of the cosmic-ray variations at 10 GV and the parameters R_z , P_i , IMF, HCS, and the MF, PF as well studied for the first time, has been carried out for the solar cycle 23 (1996-2008).

3.1. Correlation coefficients and Time Lags

In order to calculate the time lag of each parameter in reference to the cosmic-ray intensity [1], [2], the cross-correlation coefficients between these parameters with varying time lags from 0 to ± 120 months for the time interval 1996 – 2008 have been calculated. The maximum cross-correlation coefficients and the corresponding time lags are given in table 1.

Table 1. Cross-correlation coefficients and the corresponding time lags of the examined parameters

Indices	Correlation coefficients (r) (95% significance level)	Time lags (months)
Sunspot number R_z	-0.87 ± 0.01	+13
Coronal mass ejections index P_i	-0.86 ± 0.01	0
Heliospheric current sheet HCS	-0.77 ± 0.01	+4
Mean Magnetic Field MF	-0.78 ± 0.01	+1
Interplanetary magnetic field IMF	-0.85 ± 0.01	0
Solar Polar Field Strength PF	-0.93 ± 0.01	+67

High correlation values are found between cosmic rays and R_z (-0.87), P_i index (-0.86), IMF (-0.85), and HCS (-0.77) which are in accordance with our previous work [2]. The correlation value of the mean magnetic field MF is $r = -0.78$ with a time lag of one month. The most interesting results are the very high correlation value of the strength of the solar polar field PF with $r = -0.93$ and the extremely large time lag of 67 months (~ 5.58 years). As it is obvious in Figure 1 the maximum of PF coincides with the minimum of solar activity and/or the maximum of cosmic ray intensity at the beginning of the cycle 23 at the year 1996. The minimum of PF is at the end of the cycle at the year 2008 implying that the PF has a cycle of around 22 years that means two solar cycles. This is a result which is in accordance with the periodicity of 22 years of the solar magnetic field (Hale cycle) [12], [13].

The obtained results for sunspot number, CME-index and HCS are in accordance with our previous works. The MF is close to our previous results for IMF, so the time lag of one month is acceptable. The PF shows the most interesting result as it has a time lag of 67 months with the best value of $r = -0.93$ among the examined variables.

3.2. Wavelet Analysis

In order to study further the periodicities firstly of the solar polar field and secondly of the other parameters, the wavelet toolkit was applied. Non-stationary time series were expanded in terms of

time-localized waves, or wavelets. We obtained a compact two dimensional representation (see [14] and [15]):

$$y(t, t', f) = \exp(2i\pi ft) \exp\left(-f^2 \frac{(t-t')^2}{2}\right), \quad (2)$$

where f is the frequency, t' the time delay and

$$\exp\left(-f^2 \frac{(t-t')^2}{2}\right), \quad (3)$$

is the Gaussian support.

The Morlet wavelet is the most common function used in astrophysical signals expansions; this makes easier the comparison with previously published work. Furthermore, due to its Gaussian support, the Morlet wavelet expansion inherits optimality as regards the uncertainty principle [14]. The global wavelet spectrum [15], which is the time-averaged wavelet spectrum over all the local wavelet spectra, is given by

$$\overline{W}^2(s) = \frac{1}{N} \sum_{n=0}^{N-1} |W_n(s)|^2 \quad (4)$$

where $W_n(s)$ is the wavelet power and N the number of local wavelet spectra. From this, we obtained an unbiased and consistent estimation of the true power spectrum of a time series.

The new perspective in this work is the wavelet analysis of the cosmic-ray intensity of 10 GV, the heliospheric current sheet and the polar field strength. The wavelet analysis of the sunspot number has been presented also by previous researchers [16], [17]. For this wavelet study data for four solar cycles were obtained for cosmic-ray intensity of 10 GV, of sunspot numbers, of polar field strength and heliospheric current sheet tilt angle.

- For the data of cosmic-ray intensity of 10 GV the most important periodicity is that one of 128 m (10.67y). Minor periodicities are spotted around 32 m (2.67 y), 16 m (1.33y), 12 m (1y) and 8 m (0.67 y).
- For the sunspot number it is obvious that the most important periodicity is the one of 128 m (10.67 y). Minor periodicities are noticed around 32 m (2.67 y), 16 m (1.33y) and 8 m (0.67 y).
- For the polar field strength the most important periodicity is spotted around the 245 m (20.42 y). Minor periodicities are visible around 16 m (1.33 y).
- For the heliospheric current sheet tilt angle, it has almost the same periodicities with the R_z . The most important seems to be the one of 128 m (10.67 y). Then other periodicities are present also around 50 months = 4.17 y and 16 m (1.33 y).

It is interesting that all parameters present the 11-year variation as well as the 1.33 year one. These periodicities for sunspot number and for the cosmic ray intensity have also been spotted in previous works [18], [19], [20]. The new point is that only the solar polar field presents the periodicity of 20.47 y that corresponds to the 22-y variation which is the magnetic cycle periodicity. The comparison of the wavelet figures with the periodicities are presented in Figure 3. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively.

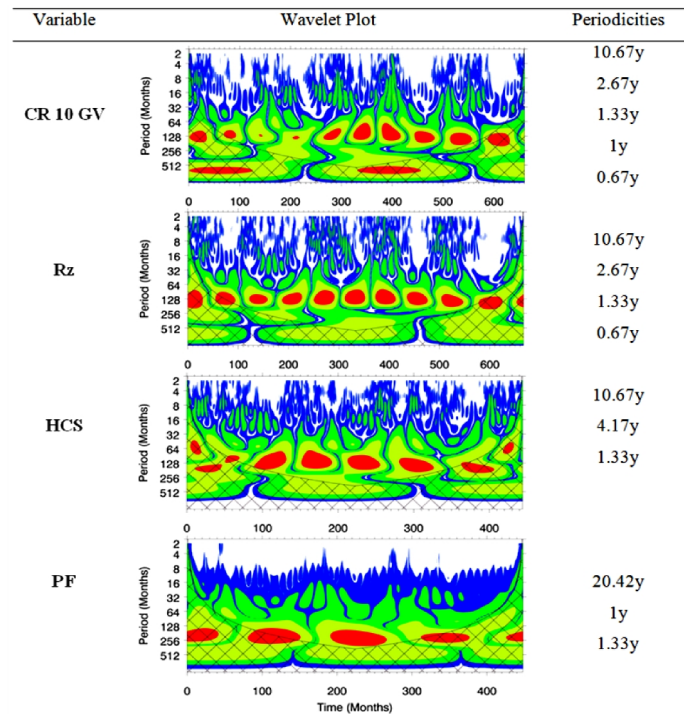


Figure 3. Wavelet analysis diagrams and list of the determined periodicities

4. Galactic Cosmic Ray Modulation

In a previous work [2] an empirical relation of the cosmic ray modulation for the time period from January 1996 up to December 2009, covering the solar cycle 23 and the extended minimum between solar cycles 23 and 24 was applied with very good results.

According to the previous model, the modulated cosmic-ray intensity I 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:

$$I = C - 10^{-3} (a_1 X + a_2 Y + a_3 Z + a_4 W) \quad (5)$$

where C is a constant, X , Y , Z and W are the selected time-lagged solar-heliospheric parameters, and a_i ($i=1$ to 4) are coefficients calculated by the RMS-minimization method. Constant C is linearly correlated to the cut-off rigidity of each station according to the relation:

$$C = 0.95 + 0.005P \text{ [GV]} \quad (6)$$

where P is the cut-off rigidity for each neutron monitor station [20]. In this work, using data of the cosmic ray variations of 10 GV obtained from the network of all neutron monitors around the world, constant C is found to be equal to 1 that means rigidity independent.

This model was derived by a combination of solar and heliospheric parameters such as the sunspot number (Rz), the CME-index (Pi), the heliospheric current sheet tilt angle (HCS), and the interplanetary magnetic field (IMF). This work suggested two possible improvements for future studies. The first one is the data which are used for the formation of the CME-index taking into account only the wider CMEs except the narrow ones, which are studied in the present work in section

2.1. The second one is the use of another solar parameter such as the Sun's polar magnetic field which is implemented in the present work.

The previous empirical modulation with the minimum root mean square deviation (RMSD) of 9.96% was expressed by the following relation:

$$I = C - 10^{-3} (a_1 R_z + a_2 P_i + a_3 \text{IMF} + a_4 \text{HCS}) \quad (7)$$

where constant C was found equal to 1, R_z , P_i , IMF (in μT) and HCS (in deg) are the solar-interplanetary parameters incorporating the time lag. Coefficients a_i , were found equal to 3.5, 395.5, 2.5, and 0.5, respectively.

The next model which examined in the present work took in to account the CME-index (P_i), the heliospheric current sheet (HCS) tilt angle, the mean magnetic field (MF) and the polar field (PF) strength by the equation:

$$I = C - 10^{-3} (a_1 P_i + a_2 \text{HCS} + a_3 \text{MF} + a_4 \text{PF}) \quad (8)$$

where constant C was found equal to 1, P_i , HCS (in deg), MF (in μT) and PF (in μT) are the solar-interplanetary parameters incorporating the time lag. Coefficients a_i equal to 227.75, 2.75, 5.50 and 1.50 respectively, were found. This version gave a RMSD of 11.81%, the most important result was that the minimum of the modulated cosmic-ray intensity coincides with the observed one and this contribution is due to the CME-index which is a more reliable solar activity index especially for the periods of solar extreme events [3] than sunspot number, where the sunspot number is reliable for the overall solar cycle. Set of similar parameters as in equation (8) demonstrated the best results on the long period 1976-2007 [21].

However in solar cycle 23 the best approximation of modulation produced by the equation:

$$I = C - 10^{-3} (a_1 R_z + a_2 P_i + a_3 \text{MF} + a_4 \text{PF}) \quad (9)$$

where constant C was found equal to 1, R_z , P_i , MF (in μT) and PF (in μT) are the solar-interplanetary parameters incorporating the time lag. Coefficients a_i equal to 3.00, 268.60, 3.40, and 0.80, respectively, were found. This modulation gave a RMSD of 8.72%, which is a better result than the results from (7) or (8). In future works this simulation in order to determine the possible extension of this modulation in other periods such as in the solar cycle 24, will be applied. The observed (red line) and the modulated cosmic-ray intensity values (black line) are presented in Figure 4.

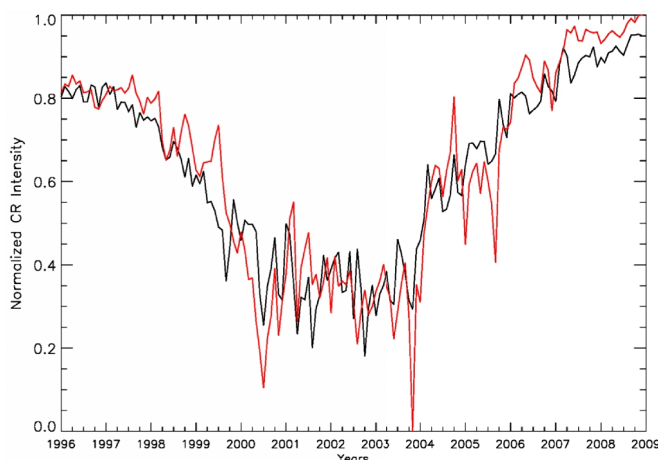


Figure 4. The observed values of cosmic ray intensity of 10 GV (red line) and those calculated by (9) (black line).

5. Conclusions

The cosmic ray modulation is a complex phenomenon, which occurs all over the heliosphere and depends on many factors, so it is important to study as many as possible solar and heliospheric variables. In this work new variables, such as the mean magnetic field and the polar field strength of the Sun, have been studied in relation to the long-term modulation. The solar polar field as a solar parameter has also been presented in previous works, such as in [21].

The CME-index as one of the most important indices for the solar activity formatted using only the wider CMEs except the narrow ones with angular width $w < 15^\circ$.

Applying a wavelet analysis for first time to the cosmic ray data of 10 GV, the well known periodicities of the 11-year as well as the one of 1.33-year, were presented in all examined here variables. It is interesting to note that the solar polar field presents a variation of 20.47 y that seems to be corresponded to the 22-years solar magnetic cycle.

Moreover, the contribution of the solar magnetic fields to the cosmic ray modulation was also outlined from the fact that the best modulation was obtained using the including these variables equation (9) giving a RMSD of 8.72% improving all the previous suggested models.

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