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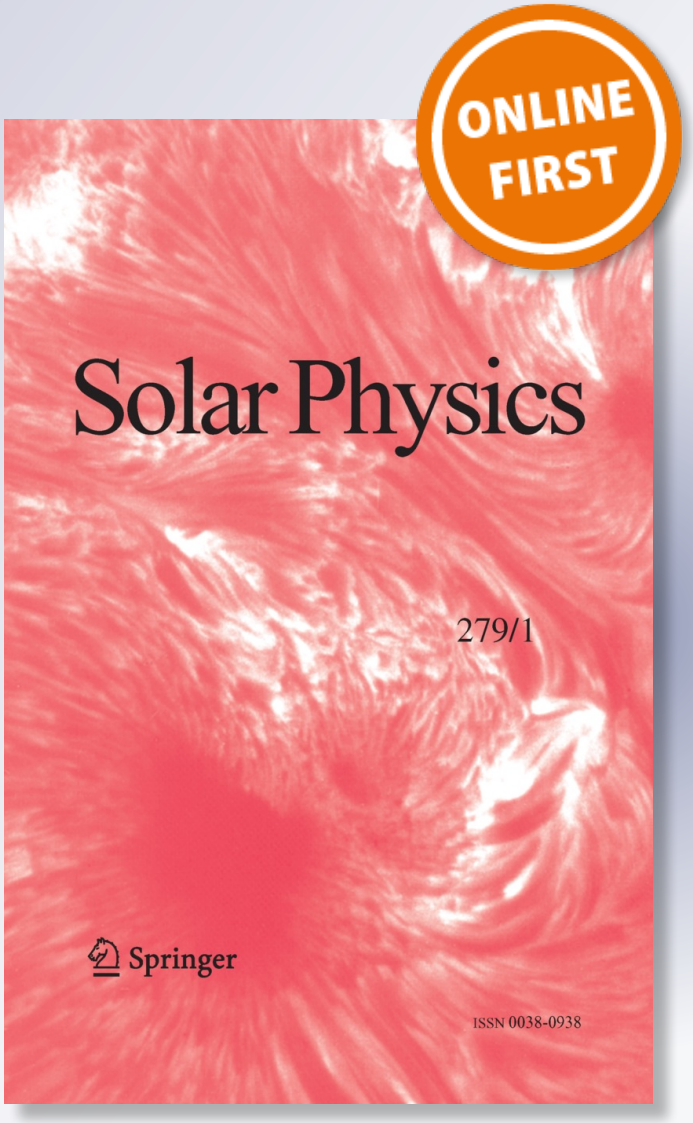

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Abstract In this work the galactic cosmic ray modulation in relation to solar activity indices and heliospheric parameters during the years 1996 – 2010 covering solar cycle 23 and the solar minimum between cycles 23 and 24 is studied. A new perspective of this contribution is that cosmic ray data with a rigidity of 10 GV at the top of the atmosphere obtained from many ground-based neutron monitors were used. The proposed empirical relation gave much better results than those in previous works concerning the hysteresis effect. The proposed models obtained from a combination of solar activity indices and heliospheric parameters give a standard deviation < 10 % for all the cases. The correlation coefficient between the cosmic ray variations of 10 GV and the sunspot number reached a value of $r = -0.89$ with a time lag of 13.6 ± 0.4 months. 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 7.15 % for all of solar cycle 23; it also works very well during the different phases of the cycle. Moreover, the use of the cosmic ray intensity of 10 GV during the long minimum period between cycles 23 and 24 is of special interest and is discussed in terms of cosmic ray intensity modulation.

Keywords Cosmic rays · Long-term modulation · Neutron monitors · Solar cycle · Solar minimum

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1. Introduction

Theoretical as well as empirical studies on the modulation of galactic cosmic rays (CRs) in the heliosphere have advanced rapidly (*e.g.*, Lockwood, 1971, 2001; Webber and Lockwood, 1988, 2004; Potgieter, 1998; Wibberenz and Cane, 2000; Ferreira and Potgieter 2004). However, it is still not simple to adequately describe the effect of the heliosphere on cosmic rays. An adequate theoretical model should consider the complex shape and dynamics of the heliospheric current sheet, the helio-latitudinal 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.

Solar cycle 23 was of great interest mainly for two reasons. First, it was characterized by many violent periods of extreme solar events mainly in the descending phase, such as October – November 2003, January 2005, July 2005, and December 2006. Second, it had an extraordinary and extended minimum with a duration of more than three years. In this solar minimum, the cosmic ray intensity was much higher than in the previous cycles (Kane, 2011). This long, quiet period was characterized by limited magnetic flux emergence at the photosphere, mostly in the southern hemisphere, and low CMEs (coronal mass ejections) and flare activity in the corona. We must go back to the activity minima of 1911 – 1913 or 1901 – 1902 to find solar cycles that had such a deep and long minimum (de Toma, 2011). For these reasons we are trying to investigate in this work the galactic cosmic ray modulation using cosmic ray data of rigidity 10 GV at the top of the atmosphere during solar cycle 23 and the extended minimum between cycles 23 – 24, as a new perspective in contrast to previous work (Xanthakis, Mavromichalaki, and Petropoulos, 1981; Mavromichalaki, Belehaki, and Rafios, 1998; Mavromichalaki, Paouris, and Karalidi, 2007). These data are obtained from all the ground-based neutron monitor stations and not from a single detector (Belov, Gushchina, and Sirotina, 1995; Belov, 2000).

An effort to study the modulation of cosmic rays at 1 – 25 GV during several solar activity cycles using different solar activity parameters such as coronal radiation, total sunspot area, sunspot and flare numbers, and heliospheric current sheet tilt was made by Belov, Gushchina, and Sirotina (1995). The rigidity spectrum of the cosmic ray variations was determined on the basis of cosmic ray observations with different detectors such as neutron monitors (NMs), satellites, ionization chambers, and stratospheric observations. They considered the fact that the long-term cosmic ray variations observed at the Earth at a given moment "remember" the solar activity that was manifested previously. This "memory" might be disentangled by using its different contributions to the integral modulation, because the behavior of a solar activity cycle varies as a function of distance from the Sun up to the heliosphere boundary. They also stressed that cosmic ray variations are most accurately measured for a rigidity of 10 GV because data from many NMs can be used. Thus, a study of the cosmic ray long-term modulation at a rigidity of 10 GV is most appropriate 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 (Caballero and Valdés-Galicia, 2004; Ahluwalia and Ygbuhay, 2011). Lockwood and Webber (1996) noticed significant differences in the rigidity dependence of the 11-year variation of cosmic rays in two solar cycles (20 and 21) with opposite magnetic polarity.

Particular consideration for cosmic ray modulation is given to the correlation between the long-term cosmic ray variations and various solar and heliospheric parameters and to existing empirical models of cosmic ray intensity, as is described in a review paper by Belov (2000). Lantos (2005) proposed a method to predict cosmic ray intensity and solar modulation parameters. This method gives satisfactory results when applied to the prediction of cosmic ray doses received onboard passenger airplanes.

In a recent work (Mavromichalaki, Paouris, and Karalidi, 2006) a simulation of the long-term cosmic ray modulation over solar cycle 23 very close to its end (1996 – 2006) was proposed by initially considering the influence of the sunspot number, solar flares with importance $\geq$ 1B, and the geomagnetic index Ap. This model was successfully applied to the previous solar cycles (20, 21, and 22) by considering the time lag of cosmic ray intensity against these parameters (Xanthakis, Mavromichalaki, and Petropoulos, 1981; Mavromichalaki, Belehaki, and Rafios, 1998). Moreover, in our last work we attempted to more extensively apply this empirical model to solar cycle 23 during the ascending, maximum, and descending phases of this cycle by investigating the contribution of the solar and heliospheric variables to the cosmic ray modulation (Mavromichalaki, Paouris, and Karalidi, 2007; hereafter Paper I).

In this paper we have realized a significant improvement to the empirical relations mentioned above for cosmic ray modulation using cosmic ray data of 10 GV at the top of the atmosphere obtained from the worldwide NM network. The effect of hysteresis in the relationship between the cosmic rays of 10 GV and various solar, interplanetary, and geomagnetic indices is investigated in comparison with the previous results. It is shown later that a more satisfactory empirical reproduction of galactic cosmic rays is obtained in the present study. This study has been performed for the entire time period of 1996 – 2010 and separately for the following periods: (a) ascending phase (January 1996 – April 1999), (b) maximum phase (May 1999 – December 2002), (c) descending phase (January 2003 – December 2006), and (d) minimum between solar cycles 23 and 24 (January 2007 – March 2010). The examined indices show contributions which differ in each phase of the solar cycle.

2. Data Collection

In order to study the long-term cosmic ray modulation through the years 1996 – 2010, monthly values of cosmic rays of 10 GV at the top of the atmosphere were used. These data were kindly provided by the IZMIRAN group using the global survey method (GSM). This method uses data from as many ground-based detectors (*e.g.*, NMs) as possible and provides useful and reliable information on the conditions of the space environment. It is conceptually a version of spherical analysis (Krymsky *et al.*, 1966; Dvornikov and Sdobnov, 1997; Belov, Gushchina, and Yanke, 1999), and different versions of this method have been evolved and improved at different stages of the data processing (Baisultanova, Belov, and Yanke, 1995; Belov *et al.*, 2005). The variations of 10 GV cosmic rays with respect to the level of the year 1976 were calculated. For the purposes of this study the time series of cosmic ray variations was normalized, taking the cosmic ray intensity maximum (October 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 (Kane, 2006).

In this study we have also used data of the mean monthly sunspot number (R_Z), the monthly counts of the grouped solar flares (N_f), the monthly geomagnetic index (Ap), and the monthly flare index (FI) taken from the National Geophysical Data Center (ftp://ftp.ngdc.noaa.gov/index.html). The term "grouped solar flares" means that observations of the same event by different sites were combined and counted as one. Moreover, 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 (HCS) were obtained from the Wilcox Solar Observatory database

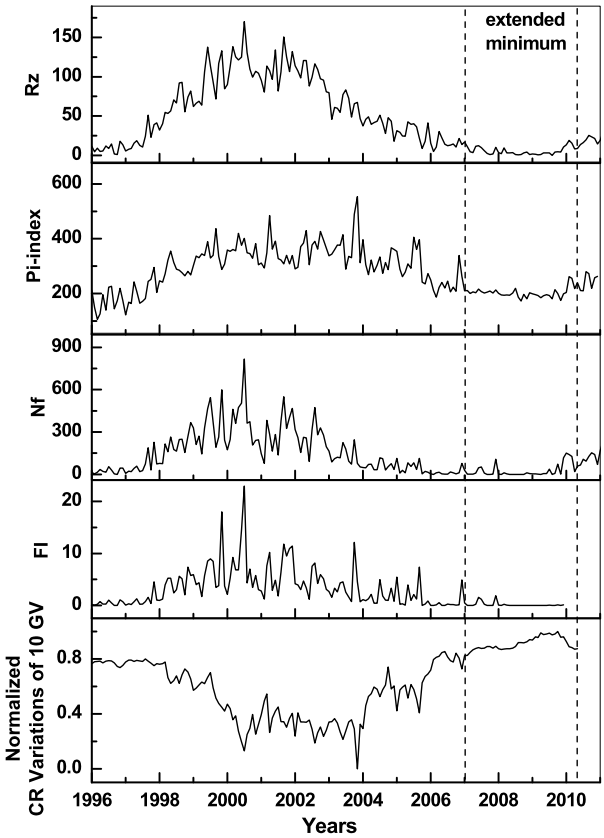

Figure 1a Time profiles, starting from the top, of the sunspot number (R_Z), CME index (P_i), monthly grouped solar flares (N_f), flare index (FI), and the cosmic ray variations of 10 GV for the period of 1996 – 2010. The period of extended minimum is noted between the dashed lines for all the examined parameters.

(http://wso.stanford.edu/Tilts.html). The data on the CME index (P_i) are taken from the Solar and Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronagraph (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; to fill these data gaps, a smoothing method has been used.

Additionally, in Paper I a new index concerning the properties of CMEs, called the P_i index, was introduced. P_i is based on the monthly number of CMEs (N_C) and the mean plasma velocity (V_p) according to the following relation:

$$P_i = \alpha \cdot N_C + \beta \cdot V_p \ (\mathrm{km\,s^{-1}}) \tag{1}$$

The factors α and β are obtained by seeking the best cross-correlation in a linear fit between the monthly number of CMEs (N_C) and the mean plasma velocity (V_p). This P_i index was applied to the examined period of 1996 – 2010, and the factors α and β were found to be equal to 0.37 and 0.63, 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 ($r = -0.84$) and with the sunspot number as well ($r = 0.77$).

In the examined time period of 1996 – 2010, the following phases of the solar cycle are included: (a) the ascending phase (from January 1996 to April 1999), characterized by a sharp rise and extreme solar events, (b) the extended maximum phase (from May 1999 to December 2002) with strong double peaks, (c) the descending phase (from January 2003 to

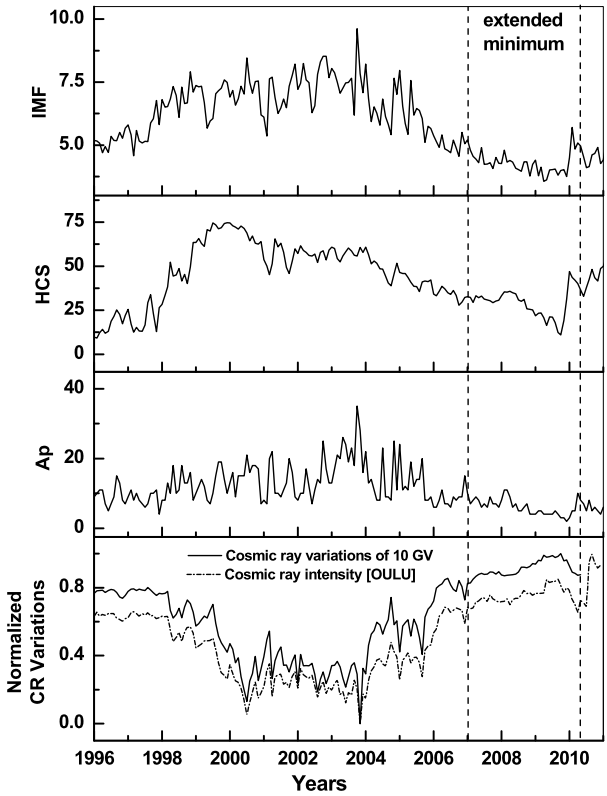

Figure 1b Time profiles, starting from the top, of the interplanetary magnetic field (IMF), the heliospheric current sheet tilt (HCS), the geomagnetic index (Ap), and the cosmic ray variations of 10 GV for the period of 1996 – 2010. The period of extended minimum is noted between the vertical dashed lines.

December 2006) with a slow decline and extreme solar events, and finally (d) the extraordinary and extended solar minimum between solar cycles 23 and 24 (from January 2007 to March 2010). The time profiles of solar, interplanetary, and geomagnetic parameters used in this work for all these phases of the interval 1996 to 2010 are presented in Figures 1a and 1b. The extended minimum indicated by the vertical dashed lines in these figures is obvious in its high counting rates of cosmic ray intensity (Kane, 2011). The cosmic ray variations of 10 GV together with the cosmic ray intensity of Oulu NM station (http://cosmicrays.oulu.fi/) are presented in the lower panel of Figure 1b.

3. Correlations and Time Lags

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 (Moraal, 1976; Usoskin *et al.*, 2002; Kane, 2011; also Paper I). Keeping this in mind, we have analyzed the correlation between the monthly values of the cosmic ray variations at 10 GV and various solar and heliospheric activity parameters (R_Z, IMF, P_i, HCS N_f, Ap, FI, and N_C) for the time period of 1996 – 2010.

To calculate the time lag of each parameter in reference to the cosmic ray intensity (Hatton, 1980; Mavromichalaki and Petropoulos, 1987), we have calculated the cross-correlation coefficients between them with varying time lags from 0 to 30 months for the interval of 1996 – 2010. The maximum cross-correlation coefficients and the corresponding time lags

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

Indices	Correlation coefficients (r) (95 % significance level)		Time lags (months)	
	Paper I	This work	Paper I	This work
Sunspot number, R_Z	-0.87 ± 0.01	-0.89 ± 0.01	+14	+13
Interplanetary magnetic field, IMF	-0.75 ± 0.01	-0.87 ± 0.01	0 – 10 (+10)	+1
Coronal mass ejections index, P_i	-0.82 ± 0.01	-0.84 ± 0.01	0 – 14 (0)	0
Heliospheric current sheet, HCS	-0.79 ± 0.01	-0.80 ± 0.01	−7 – 0 (−7)	+3
Monthly flares number, N_f	-0.70 ± 0.01	-0.77 ± 0.01	+14	+13
Geomagnetic index, Ap	-0.61 ± 0.02	-0.72 ± 0.01	0	0
Flare index, FI	-0.41 ± 0.02	-0.64 ± 0.02	+15	+15
Number of CMEs, N_C	-0.78 ± 0.01	-0.55 ± 0.03	0 – 14 (+14)	+1

are given in Table 1. For comparison the time lags of the cosmic ray intensity measured using data from the Oulu and Moscow NM stations (Paper I) are also given. High correlation values are found between cosmic rays and R_Z (−0.89), IMF (−0.87), P_i (−0.84), and HCS (−0.80), and a good correlation also exists between cosmic rays and N_f (−0.77), Ap (−0.72), and FI (−0.64). Noticeable is the high correlation between the CME index P_i and cosmic rays, but measurements with high accuracy started only in 1996 and cover only one solar cycle. Belov *et al.* (2001) have shown that a good agreement exists between the long-term cosmic ray intensity and HCS in all periods of the same heliospheric polarity, during the whole history of cosmic ray observations with NMs since 1953. It is interesting that the correlation coefficients between the cosmic ray intensity of 10 GV and the solar and heliospheric parameters examined here have significantly increased compared with the results of Paper I, confirming once again the superiority of this time series of cosmic rays. The only parameter which shows a remarkable reduction of the correlation coefficient value (from −0.78 to −0.55) is the number of CMEs (N_C). Possibly it results from the narrow and slow CMEs which are often observed in the period of solar minimum. After the years 2004 – 2005 more narrow CMEs with apparent angular width $< 30°$ were counted, because of changes in the tracking methods (which now use both manual and automated methods) that give a higher mean CME number per month than in the previous periods. Recently, researchers have trusted only CMEs with angular width greater than 30° because the manual detection of such events is highly subjective (Yashiro, Michalek, and Gopalswamy, 2008; Gopalswamy *et al.*, 2010).

The correlation coefficients between the cosmic ray intensity and solar/heliospheric parameters over solar cycle 23 as a function of time lag are presented in Figure 2 with their statistical errors. It is noteworthy that the time lag between the cosmic ray intensity and the solar variables, such as R_Z, N_f, and FI, is remarkably large, reaching a value of 13 – 14 months. The time lag of the cosmic ray intensity with respect to R_Z was estimated to be two – four months for the previous even cycles 20 and 22, while it was 16 months for cycle 21 (Paper I). This gives further evidence concerning the distinction between even and odd solar cycles resulting from the hysteresis phenomenon and the polarity reversal of solar magnetic fields (Nagashima and Morishita, 1980; Mavromichalaki and Petropoulos, 1987; Mavromichalaki, Belehaki, and Rafios, 1998). It is expected that particles reach the Earth more easily when their access route is through the heliospheric polar regions than along the current sheet. In the latter case, as the route of access becomes longer because of the waviness of the current sheet (Kota and Jokipii, 1991), the time lag is also longer than one would

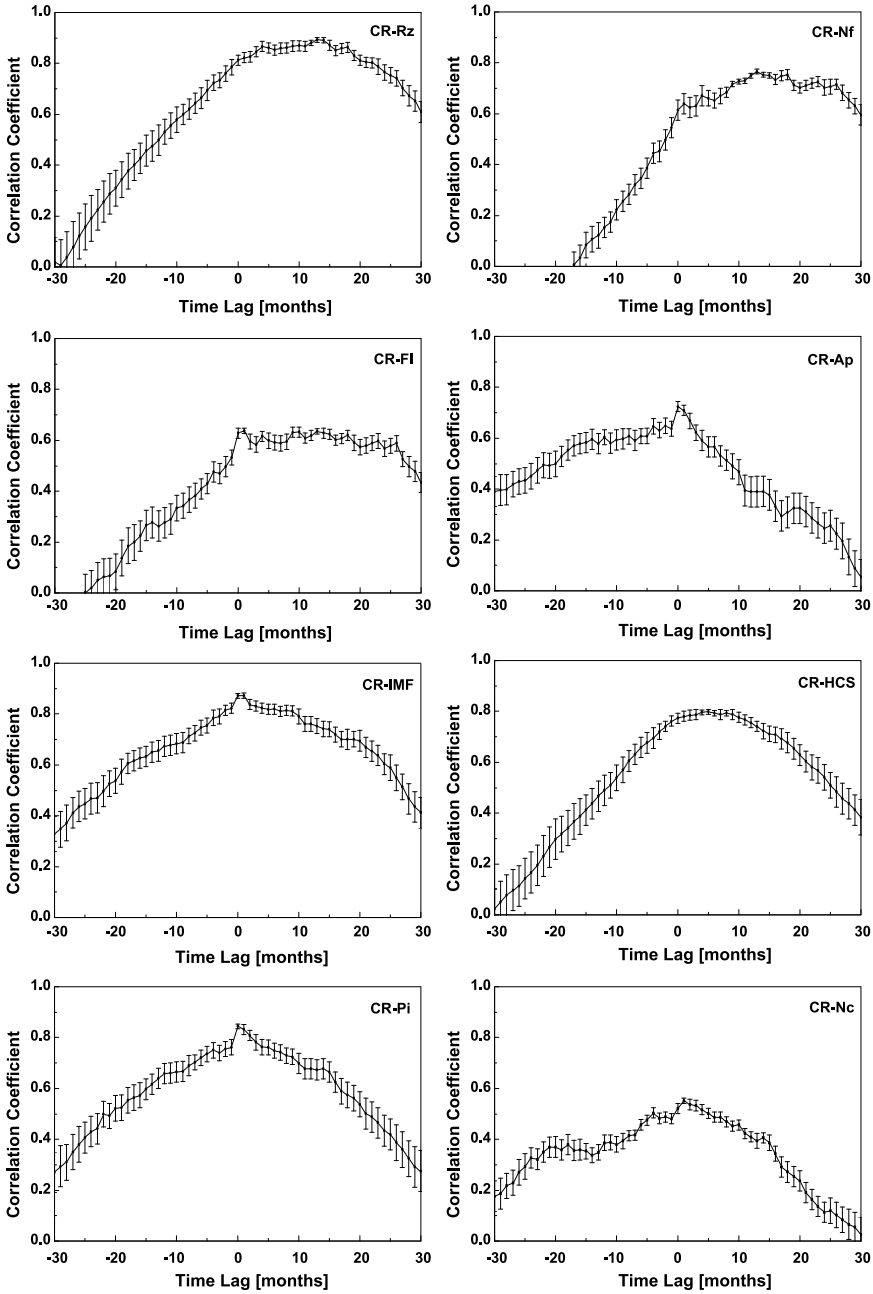

Figure 2 Correlation coefficients with error bars as a function of time lag of the monthly cosmic ray variations of 10 GV with respect to the sunspot number R_Z, number of grouped solar flares N_f, flare index FI, geomagnetic index Ap, interplanetary magnetic field IMF, tilt angle of the heliospheric current sheet HCS, coronal mass ejection index P_i, and number of CMEs N_C.

expect. N_f and FI show a broad maximum from 0 to 13 months and from 0 to 15 months, respectively, following in some way the time lag results of Paper I. The heliospheric variables IMF and HCS show a broad maximum with a pronounced peak at zero and three months, respectively. CME-related N_C and P_i, as well as the geomagnetic index Ap, show the maximum correlation at zero month. These results are consistent with the results for the earlier cycles (Mavromichalaki, Belehaki, and Rafios, 1998; Belov *et al.*, 2001).

In summary, the time lag of the cosmic ray intensity with respect to the solar parameters ranged from 0 to 14 months for the last solar cycle, whereas for most heliospheric parameters no significant time lag was found. This result was expected, as we have used data of the cosmic ray intensity of 10 GV from the magnetosphere and the atmosphere. We also note that some differences between the previous results and the current work are strongly connected with the interval of the extended solar minimum, which was characterized by zero solar activity.

To confirm these results, the hysteresis curves between the observed cosmic ray intensity of 10 GV and each one of the parameters studied in this work are plotted in the left-hand panels of Figure 3. The cosmic-ray intensities calculated by Equation (5) are given in the right-hand panels of the same figure. Note that the hysteresis loops for the solar parameters R_Z and N_f are wider than the others. This supports our previous results from the correlative analysis that these variables present high values of the hysteresis effect. These curves also confirm the even–odd asymmetry of the solar cycles, as they are generally wider for this odd-numbered cycle 23 (Mavromichalaki, Belehaki, and Rafios, 1998). As shown by Nagashima and Morishita (1980), if the effect of the polarity reversal is superposed on the hysteresis effect, the hysteresis curve would split into two loops that correspond, respectively, to parallel and antiparallel states of the Sun's magnetic polarity with respect to the galactic magnetic field. Because the polarity reversal occurs a few years after a solar maximum, the transition from the upper to the lower loop and back can be expected alternately every eleven years (Otaola, Perez-Enriquez, and Valdes-Galicia, 1985). Each hysteresis curve presented in Figure 3 consists of two parts corresponding to the parallel state occurring in the years 1996 – 2000 (from left to right on the panels) and to the antiparallel one occurring in the years 2002 – 2008 (from right to left) according to the dates indicated in the HCS diagram of Figure 3. The transition from the parallel to the antiparallel state of the solar magnetic field took place in 2000 – 2002, which is when the solar polar magnetic field reversed (Kane, 2006). More specifically, the transition took place in June 2001, which coincided with the middle of the time interval when the magnetic field reversal occurred. The extended solar minimum from 2007 to 2010 is also indicated in these diagrams.

4. Galactic Cosmic Ray Modulation

In this work the same empirical relation of cosmic ray modulation that was applied in previous works to solar cycles 20, 21, 22, and 23 is adopted (Mavromichalaki, Belehaki, and Rafios, 1998; Paper I). This relation is derived by a generalization of Simpson's solar wind model using the diffusion–convection drift model (Nagashima and Morishita, 1980) and is expressed by the following relation:

$$I(t) = I - \int f(r) S(t-r)\,\mathrm{d}r \tag{2}$$

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

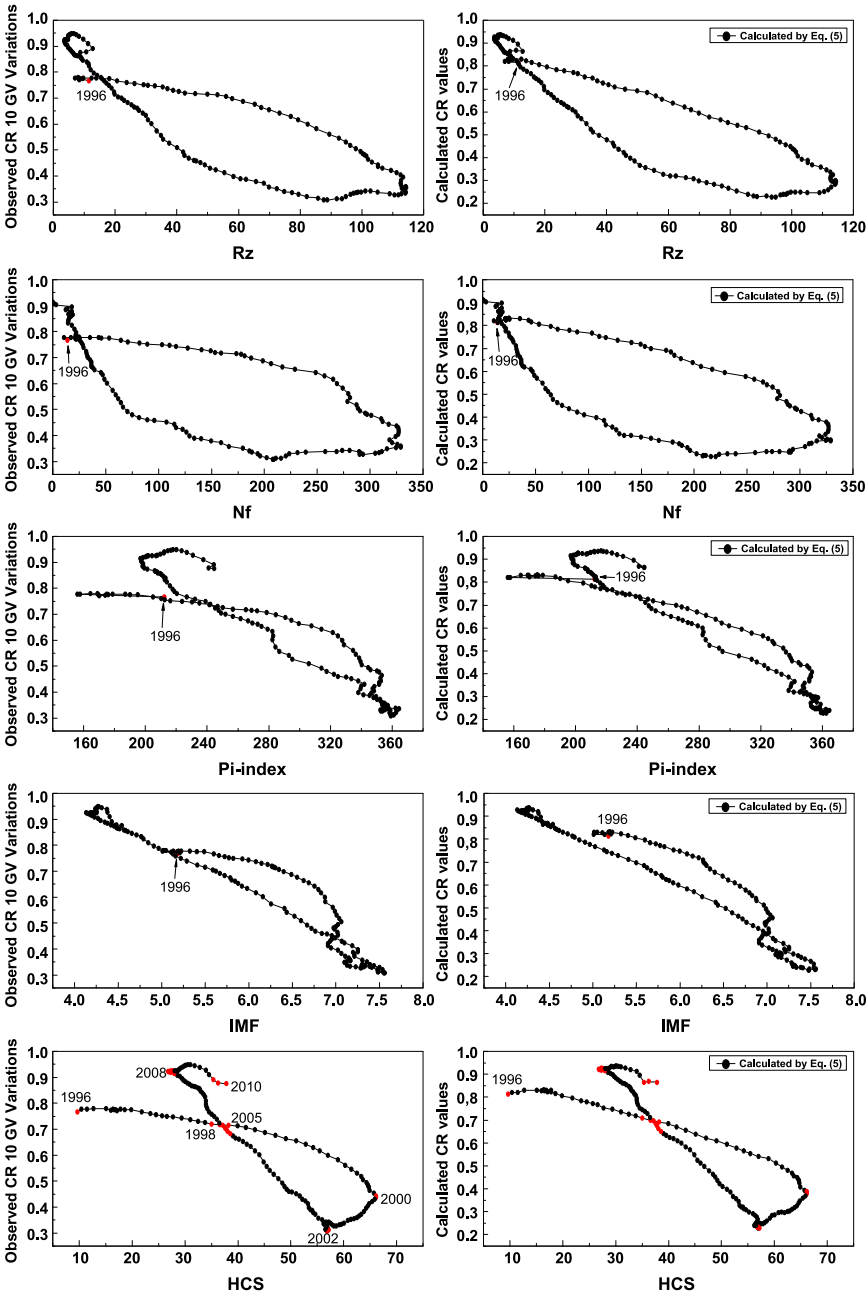

Figure 3 Hysteresis curves of the observed cosmic ray variations of 10 GV (left panels) and of those calculated by Equation (5) (right panels) with respect to the sunspot number R_Z, grouped solar flares N_f, CME index P_i, interplanetary magnetic field IMF, and heliospheric current sheet tilt HCS.

time $t-r$ ($r \geq 0$), and $f(r)$ is the characteristic function that expresses the time dependence of solar disturbances represented by $S(t-r)$ (Xanthakis, Mavromichalaki, and Petropoulos, 1981; Ferreira and Potgieter, 2004). The contribution of this work is the use of a cosmic ray intensity of 10 GV, as the rigidity of 10 GV in the evaluation of the cosmic ray variations is the most accurate. 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:

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

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. The constant C is linearly correlated to the cut-off rigidity of each station according to the relation

$$C = 0.95 + 0.005P \text{ [GV]} \tag{4}$$

where P is the cut-off rigidity for each NM station (Mavromichalaki, Marmatsouri, and Vassilaki, 1990). In this work, using the data for cosmic ray variations of 10 GV obtained from the worldwide NM network, the constant C is equal to 1, which means it is rigidity independent.

In Paper I the relation that best reproduced the cosmic ray intensity was the one using the sunspot number R_Z, the geomagnetic index Ap, the monthly number of CMEs N_C, and the heliospheric current sheet tilt HCS, giving a standard deviation 10.76 % for the years 1996 – 2006. This relation gave the best standard deviation of 4.52 % for the ascending phase (1996 – 1999). However, it was 11.85 % for the maximum phase (2000 – 2003) and 11.47 % for the descending phase (2004 – 2006). The best results for the standard deviation of the descending phase (8.22 %) were given by replacing HCS with IMF. From this cosmic ray modulation study it was confirmed that a strong connection exists not only between the cosmic ray intensity variations and well-known parameters such as R_Z, HCS, IMF, and Ap (see, *e.g.*, Chirkov and Kuzmin, 1979; Nagashima and Morishita, 1980; Cane *et al.*, 1999; Belov, 2000; Belov *et al.*, 2001), but also with N_C and the newly introduced CME index P_i, and the mean linear plasma speed V_p (Paper I; Paouris, 2007).

Here, adopting the same technique, we will try to reproduce the cosmic ray intensity of 10 GV by the joint use of the variables R_Z, N_f, IMF, P_i, HCS, and Ap. We will investigate the entire period of 1996 – 2010 and separately the periods of ascending, maximum, and descending phases and the minimum between solar cycles 23 and 24 as well. The model parameters, the standard deviation for each case, and coefficients a_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 10 %. Compared with the results of Paper I, they have improved by at least 32 % concerning the entire period.

The best relation reproducing the cosmic ray variations of 10 GV is obtained from the last case of Table 2, taking into account the combination of R_Z, P_i, IMF, and HCS. This is expressed by the following relation:

$$I = C - 10^{-3}(a_1 R_Z + a_2 P_i + a_3 \text{IMF} + a_4 \text{HCS}) \tag{5}$$

where the constant C is equal to 1, and R_Z, P_i, IMF, and HCS are the solar–interplanetary parameters incorporating the time lag. Coefficients a_i were found to be equal to 2.7, 0.41, 71.8, and 0.24, respectively. The standard deviation for this relation is 7.15 %, which is much

Table 2 Standard deviation for different models during the three phases of solar cycle 23 and the period of minimum between cycles 23 and 24. Coefficients a_i are also given in the last column.

Model parameters	Ascending phase (Jan 1996 – Apr 1999)	Maximum (May 1999 – Dec 2002)	Descending phase (Jan 2003 – Dec 2006)	Minimum (Jan 2007 – Mar 2010)	Total (1996 – 2010)
R_Z, N_f, Ap	6.32 %	11.65 %	10.14 %	4.75 %	9.77 % (3.3, 0.5, 6.6)
R_Z, IMF, N_f, Ap	5.59 %	10.81 %	9.65 %	3.19 %	8.73 % (3.2, 38, 0.1, 1.2)
R_Z, IMF, P_i, Ap	5.42 %	10.85 %	8.48 %	2.87 %	8.28 % (2.6, 22.1, 0.47, 3.9)
R_Z, HCS, N_f, Ap	5.95 %	11.68 %	8.71 %	4.13 %	8.94 % (3.2, 1.6, 0.25, 11.4)
R_Z, P_i, HCS, Ap	**5.07 %**	11.07 %	8.08 %	**2.72 %**	7.96 % (2.5, 1.05, 0.65, 6.2)
R_Z, P_i, IMF, HCS	5.17 %	**9.53 %**	**7.61 %**	2.88 %	**7.15 %** (2.7, 0.41, 71.8, 0.24)

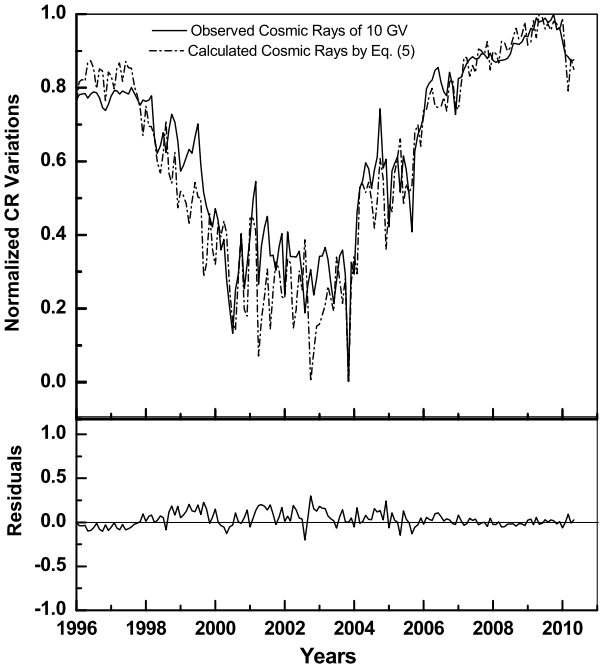

Figure 4 The observed values of cosmic ray intensity of 10 GV (solid line) and those calculated by Equation (5) (dashed line). The residuals are indicated in the lower panel. This modulation has a standard deviation of about 7.15 %.

better than the value in Paper I. The ascending and the descending phases gave standard deviations of 5.17 % and 7.61 %, respectively, while the maximum phase gave a greater value of 9.53 %. The maximum phase of solar cycle 23 was very complicated, including double peaks and a reversal of the solar magnetic field. Possibly the use of the polar magnetic field of the Sun in a solar model would improve the simulation of this phase. The observed values of cosmic rays at 10 GV together with the calculated ones from Equation (5) (upper

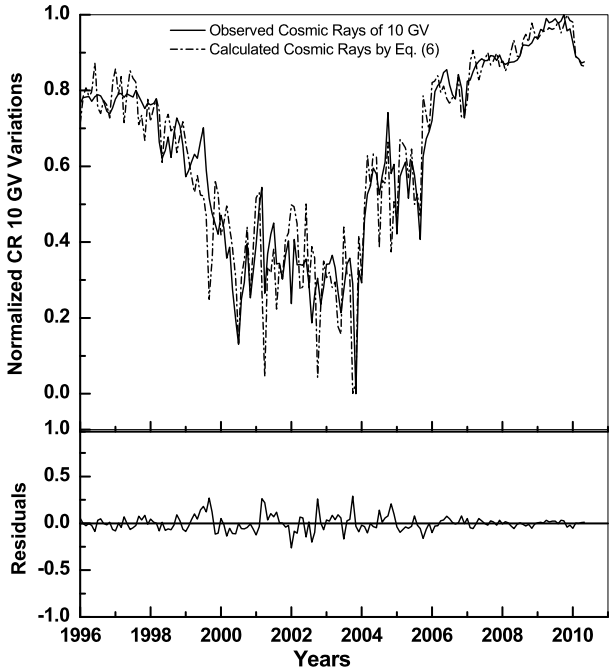

Figure 5 The observed values of cosmic ray intensity of 10 GV (solid line) and those calculated by Equation (6) (dashed line). The residuals are indicated in the lower panel. This modulation has a standard deviation of about 7.96 %.

panel) as well as the residuals between them (lower panel) are illustrated in Figure 4. The good agreement between the observed and calculated values of the cosmic ray intensity of 10 GV at the top of the atmosphere is remarkable. 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, which are characterized by strong solar events.

Another very good approach to cosmic ray modulation involves combining the variables R_{Z}, IMF, P_{i}, and Ap, as expressed by the following equation:

$$I = C - 10^{-3}(a_1 R_{\mathrm{Z}} + a_2 P_{\mathrm{i}} + a_3 \mathrm{HCS} + a_4 \mathrm{Ap}) \tag{6}$$

where $C = 1$, and coefficients a_i ($i = 1$ to 4) were found equal to 2.5, 1.05, 0.65, and 6.2, respectively. This relation uses the geomagnetic index Ap instead of IMF, while the use of CME-related indices (mainly the CME index P_{i}) and not the solar flare parameters is obvious in both cases. As shown in Table 2, a standard deviation of about 7.96 % is obtained for the entire period. The ascending and descending phases give very significant standard deviations among all the models, 5.07 % and 8.08 %, respectively, due to the use of the heliospheric current sheet tilt HCS and the geomagnetic index Ap, in contrast to the maximum phase, which presents significant differences between the observed and calculated values (11.07 %). The observed values of cosmic rays of 10 GV and the calculated ones from Equation (6) (upper panel) together with the residuals (lower panel) are presented in Figure 5. It is remarkable to find a very good agreement in the year 2003, which was characterized by extreme solar events, in Figures 4 and 5. This is due to the use of the CME index P_{i} containing the mean plasma velocity.

This model seems to be similar with the best one of Paper I. The significant improvement of this empirical model results from the use of the cosmic ray variations of 10 GV data and the CME index P_{i}, which is highly correlated with the cosmic ray intensity variations ($r = 0.84$) in contrast to the number of CMEs ($r = 0.55$). The previous value of the correlation coefficient of the CME number N_{C} was 0.78, 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; in this period many narrow and slow CMEs were recorded without any effect on the long-term modulation.

5. Solar Minimum Between Cycles 23 and 24

As mentioned above, the slow decline of solar cycle 23 and the slow rise of solar 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, in contrast to the previous solar minima, the solar minimum between cycles 23 and 24 was very extended and deep, with a duration of tens of months instead of a few months as in the earlier cycles. In Paper I 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 (Nagashima and Morishita, 1980; also Paper I).

During the last solar cycle (cycle 23) the minimum of the monthly mean sunspot number occurred on August 2009. According to Ahluwalia and Ygbuhay (2011) the maximum cosmic ray intensity was observed on October 2009, and the onset of the current solar cycle (cycle 24) of galactic cosmic rays was noted on January 2010. Kane (2011) noticed that the cosmic ray intensity decreased only after March 2010.

In this section the period of solar minimum from January 2007 to March 2010 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 $r = -0.59$ with a corresponding time lag of two months was found. As we can see in Figure 6, a maximum of the correlation coefficient appears between two – three months, a small plateau between five – seven months, and a secondary maximum at 10 months, confirming the hysteresis effect of the solar parameters. Kane (2011) found a time lag for this minimum of about six – seven months. Ahluwalia and Ygbuhay (2011) also calculated a time lag of about three months between a large, sharp increase of the HCS tilt angle and the onset of cosmic ray modulation, in agreement with our calculations where a time lag of about one – two months (1.4 ± 0.3 months) with respect to HCS is found with a very high correlation coefficient of $r = -0.80$. The time lag between the cosmic ray intensity and the solar activity from the best nonlinear fitting is 2.3 ± 0.4 months. This value coincides – up to now – with the expected value for even cycles as mentioned in Paper I.

If we consider the cosmic ray modulation from Table 2, the best approximation for the period of solar minimum (January 2007 – March 2010) is given by Equation (6) with a standard deviation of 2.72 %. It is also noteworthy that Equation (5) is a very good approximation for the solar minimum with a standard deviation of 2.88 %.

It is remarkable that the extended minimum between solar cycles 23 and 24 is obvious in all parameters presented in Figures 1a and 1b, while the very good approximation of the proposed models during this time interval is also confirmed in Figures 4 and 5. Moreover, this period of minimum is also indicated very well in the hysteresis curve of the HCS tilt of Figure 3. Finally, the small time lags of the cosmic ray intensity of 10 GV against the

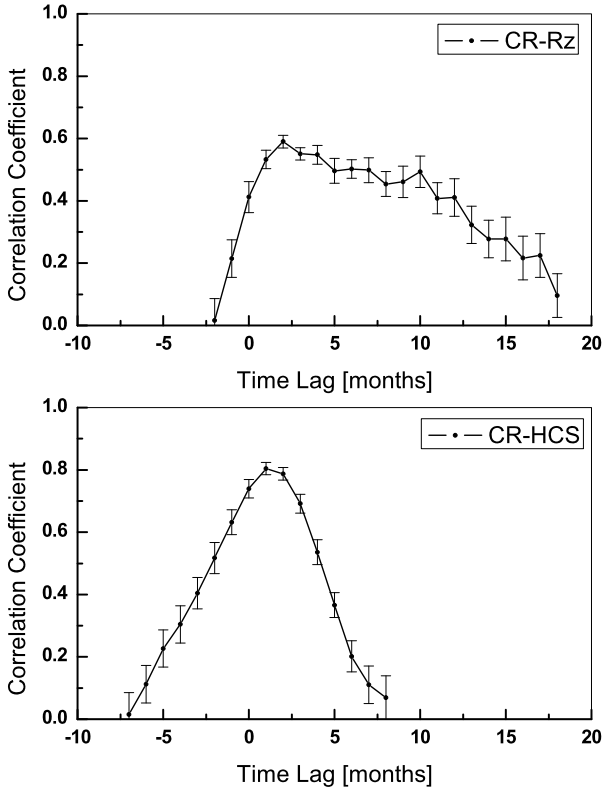

Figure 6 Correlation coefficients with error bars as a function of time lag of the monthly cosmic ray intensity of 10 GV with respect to the sunspot number R_Z and heliospheric current sheet tilt HCS for the period of the solar minimum between cycles 23 and 24 (January 2007 – March 2010).

solar activity expressed by the sunspot number R_Z is confirmed in Figure 6 (upper panel). Many theoretical researchers have tried to determine the connection between the HCS tilt and cosmic ray modulation (*e.g.*, Jokipii and Thomas, 1981), which seems to be clearer, from an observational point of view, near the minimum phases of solar activity (Lockwood, Webber, and Hoeksema, 1988).

6. Discussion and Conclusions

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 have proposed empirical relations describing the long-term cosmic ray variations based on the joint use of solar and/or heliospheric indices. At first, solar indices such as sunspot number and solar flares were used (Mavromichalaki, Belehaki, and Rafios, 1998). Later Belov, Gushchina, and Yanke (1999) proposed a multiparametric description of long-term cosmic ray 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 (*e.g.*, Parker, 1963), an increase of H should lead to a decrease of transport path and the diffusion coefficient and, consequently, to an increase in cosmic ray modulation. The relationship between the IMF strength

and long-period cosmic ray variations was corroborated experimentally (Cane *et al.*, 1999; Belov, Gushchina, and Yanke, 1999) when long data series of solar wind measurements were developed, and 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 quantitatively characterizes its effect on cosmic rays. In Paper I the solar indices (R_Z, N_C) together with the heliospheric variables IMF, HCS, and Ap were found to better explain 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 significantly improved the relation between the observed and the calculated values of the cosmic ray intensity measured by a single NM station. In this work the use of the cosmic ray variations at 10 GV at the top of the atmosphere obtained from the worldwide NM network has yielded essentially better results than those of the separate detectors.

The global survey method (GSM) used for these data is a technique for investigating the spatial distribution of primary cosmic rays outside the magnetosphere in interplanetary space; it was first introduced by Krymsky *et al.* (1966). Because this method uses data from as many ground-based detectors (*e.g.*, NMs) as possible, it allows a set of parameters defining the galactic cosmic ray density and anisotropy to be derived from the ground-level NM network (Belov *et al.*, 2005). The method takes into account cosmic ray transport in the magnetosphere and atmosphere and uses trajectory calculations in the Earth's magnetic field and the NM response functions (Dorman, 1963). A time series of these cosmic ray data of 10 GV for the period until the end of the year 2010 has not yet been presented in another work.

This work has attempted a comparative study of the long-term modulation of these accurate cosmic ray data equivalent to the cosmic ray intensity as it is recorded in the Earth's orbit at 1 AU, with the cosmic ray intensity modulation of a single detector. By applying a similar correlative analysis and the same empirical relation as used in the previous work, the following conclusions have been outlined.

- The correlation analysis of the cosmic ray data at 10 GV with each one of the solar and heliospheric parameters examined here gave much better correlation coefficients in contrast to the previous work (Paper I), as shown in Table 1. An exception is the case of CME number N_C due to changes in the tracking methods used for the narrow CMEs, especially after the year 2004. Moreover, as concerns the solar indices R_Z and the grouped solar flares N_f, the time lags were around 13 – 14 months as in the previous work, while the time lags of the heliospheric variables were shifted to zero month. This is expected, as we use the cosmic ray data of 10 GV equivalents with cosmic ray intensity at the top of the atmosphere and not on the ground.
- Concerning the modulation effect, in all the proposed models the standard deviation is smaller than 10 %. The best one obtained from Equation (5) using the parameters R_Z, P_i, IMF, and HCS gives a standard deviation of 7.15 % for the total time period. The total improvement between the previous and current empirical models for the cosmic ray modulation is about 32 %.
- It is noteworthy to look at the improvement for each case of examined models separately. Interestingly, the estimated cosmic ray values from Equation (6) using the R_Z, P_i, HCS, and Ap indices are similar to the best empirical model from the previous work, giving a very good fit for the ascending phase (5.07 %) and the solar minimum (2.72 %).
- Applying our model to the ascending, maximum, and descending phases of the cycle separately and to the overall cycle, we have obtained interesting results for each parameter's contribution to the phases of the current solar cycle. The contribution of the CME index and IMF during the maximum and descending phases is important, while the contribution

of the HCS tilt during the ascending phase improves our results. A poor performance in the solar maximum was expected, because during this phase of the cycle the solar magnetic field polarity changed configuration over a period of several months.

- By examining the period of solar minimum separately, a small time lag between cosmic ray intensity and solar activity of about two – three months was underlined, as was expected for the even solar cycles (Nagashima and Morishita, 1980; Mavromichalaki and Petropoulos, 1987). Cosmic ray intensity and heliospheric current sheet present a time lag of one – two months.

Examining the entire current solar cycle, 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, when only two at a time are included in the model. The addition of all parameters together gives unsatisfactory results, as is expected from the integral Equation (3), where the selected source functions represent appropriate selected solar, interplanetary, and geomagnetic activity (Xanthakis, Mavromichalaki, and Petropoulos, 1981). 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, V_p and Ap, are limited to the ecliptic plane. According to Usoskin *et al.* (1998) 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.

It was also shown here that the combined use of the heliospheric current sheet tilt and magnetic field mean intensity in describing cosmic ray modulation allows us to improve semiempirical models of long-term cosmic ray variations, particularly during periods of high solar activity. However, a question under investigation is whether the IMF parameters measured in the Earth's environment are able to fully characterize the magnetic fields all over the heliosphere, which are responsible for cosmic ray modulation. This compels us to search for a different parameter, which would supplement the HCS tilt well enough, but unlike the IMF intensity, would be more global. This solar index might be the magnetic field of the Sun as a star or, more logically, it should be sought at the source surface, where the properties of the HCS are determined (Belov *et al.*, 2001).

Summarizing, we can say that the empirical model proposed in the previous works and here with significant improvements has been studied for many solar cycles (19, 20, 21, 22, and 23), and the obtained results confirm its reliability. In a future work we hope that the consideration of an updated CME index (P_i), obtained from CME data with angular width greater than 30° as mentioned above, and of another solar parameter such as the Sun's polar magnetic field will be able to provide more insight into the investigation of long-term cosmic ray modulation. All these studies will be useful in solar cycle prediction and space weather applications.

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