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Cosmic-Ray Modulation: An Empirical Relation with Solar and Heliospheric Parameters

H. Mavromichalaki · E. Paouris · T. Karalidi

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Abstract Long-term variations of galactic cosmic rays were compared with the behavior of various solar activity indices and heliospheric parameters during the current solar cycle. This study continues previous works where the cosmic-ray intensity for the solar cycles 20, 21, and 22 was well simulated from the linear combination of the sunspot number, the number of grouped solar flares, and the geomagnetic index A_{p}. The application of this model to the current solar cycle characterized by many peculiarities and extreme solar events led us to study more empirical relations between solar-heliospheric variables, such as the interplanetary magnetic field, coronal mass ejections, and the tilt of the heliospheric current sheet, and cosmic-ray modulation. By analyzing monthly cosmic-ray data from the Neutron Monitor Stations of Oulu (cutoff rigidity 0.81 GV) and Moscow (2.42 GV) the contribution of these parameters in the ascending, maximum, and descending phases of the cycle was investigated and it is shown that a combination of these parameters reproduces the majority of the modulation potential variations during this cycle. The approach applied makes it possible to better describe the behavior of cosmic rays in the epochs of the solar maxima, which could not be done before. An extended study of the time profiles, the correlations, and the time lags of the cosmic-ray intensity against these parameters using the method of minimizing RMS over all the considered period 1996 – 2006 determines characteristic properties of this cycle as being an odd cycle. Moreover, the obtained hysteresis curves and a correlative analysis during the positive polarity ($qA > 0$, where q is the particle charge) and during the negative polarity ($qA < 0$) intervals of the cycle result in significantly different behavior between solar and heliospheric parameters. The time lag and the correlation coefficient of the cosmic-ray intensity are higher for the solar indices in comparison to the heliospheric ones. A similar behavior also appears in the case of the intervals with positive and negative polarity of the solar magnetic field.

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1. Introduction

Cosmic-ray (CR) observations date back to the first half of the 20th century. Together with these observations an effort started to study the CR modulation and define the parameters that affect it (*e.g.*, Forbush, 1958; Nagashima and Morishita, 1980a; Xanthakis, Mavromichalaki, and Petropoulos, 1981). Initially all data were restricted to ground-based measurements, since only after the 1960s were spacecraft able to provide us with data from interplanetary space. With the launch of PAMELA in 2006 and the planned launch of AMS-2 the situation will be greatly improved, as these space-borne detectors will directly and routinely measure the CR spectrum in a wide energy range. However, a major part of the data used in research originates from the worldwide neutron monitor network, since the Earth provides us with the highest accuracy cosmic-ray detector (see Belov, 2000). Only on the Earth have CR observations been carried out at the same distance from the Sun and within a narrow heliolatitude range for more than fifty years, covering six solar activity cycles and three solar magnetic cycles (Belov, 2000).

The cosmic-ray intensity, as is observed from Earth and in Earth's orbit, exhibits an approximate 11-year variation anticorrelated with solar activity, with perhaps some time lag, a fact that was firstly studied by Forbush (1958) and by many subsequent researchers (*e.g.*, Pomerantz and Dugal, 1974; Perko and Fisk, 1983). 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, such as the sunspot number by Nagashima and Morishita (1980a), solar flares by Hatton (1980), and the geomagnetic index by Chirkov and Kuzmin (1979). Other authors such as Xanthakis, Mavromichalaki, and Petropoulos (1981) and Nagashima and Morishita (1980b) took into account the contribution of more than one parameter (solar or geophysical) in the modulation process. Mavromichalaki and Petropoulos (1984) found an empirical relation between the modulated CR intensity during the 20th solar cycle and a combination of the relative sunspot number, the number of proton events, and the geomagnetic index A_p, that was later improved by Mavromichalaki and Petropoulos (1987) by including the number of corotating solar wind streams.

The modulation of galactic cosmic rays in the heliosphere using theoretical as well as empirical approaches is successful and advanced rapidly (Potgieter, 1998). 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 (1999) 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 Parker's model and using in-ecliptic measurements from different spacecraft at 1 AU near the Earth. Morishita and Sakakibara (1999) tried to estimate the size of the heliosphere derived from the long-term modulation of neutron monitor intensities. Usoskin *et al.* (2002), using a reconstruction of the open solar magnetic flux from sunspot data as an input to a spherically symmetric quasi-steady state model of the heliosphere, calculated the expected intensity of galactic cosmic rays at Earth's orbit. This calculated cosmic-ray intensity is in good agreement with the neutron monitor measurements during the past 50 years.

More recently, an effort has begun to find a relation between the CR modulation and the interplanetary magnetic field (IMF), with which it has been suggested to be highly associated (Cane *et al.*, 1999; Belov, 2000). A relationship between cosmic-ray intensity variations and IMF intensity exists for short time intervals during Forbush effects (Cane, 1993) and in the distant heliosphere (Burlaga, McDonald, and Ness, 1993). Kudela *et al.* (2000) distinguish the IMF configurations that can produce Forbush decreases in three categories and show that we cannot ignore the importance of the IMF, as it is also strongly related to cosmic-ray fluctuations. From this point of view we can use the IMF instead of, or coexisting with, geomagnetic index values. Furthermore, the heliospheric current sheet (HCS) results in a drift (mostly in the radial direction), which facilitates CR access to the inner heliosphere. It is of interest the study of the HCS tilt effect on cosmic-ray modulation. Belov *et al.* (2001) have shown that the tilt of the heliospheric current sheet and other solar-heliospheric parameters successfully describe the long-term variations of cosmic rays in the past two solar cycles, especially in the epochs of solar maxima. Additionally, since 1996, with the assistance of the LASCO coronagraphs onboard the SOHO spacecraft, there is a better but still incomplete understanding of and more data concerning coronal mass ejections (CMEs), and many authors have started taking into consideration the possible effect that the CMEs may have on cosmic-ray modulation. Thus, Cane (2000) suggests that CMEs "do not appear to play a major role in long term modulation", whereas others such as Newirk, Hundhausen, and Pizzo (1981) and Cliver and Ling (2001) suggest that CMEs do play a role in long-term cosmic-ray modulation.

Particular consideration of 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 is described in the review paper by Belov (2000). Recently, Lantos (2005) proposed a method to predict cosmic-ray intensity and solar modulation parameters. This method gives satisfactory results when applied to prediction of the dose received onboard commercial airplane flights. He notes that prediction of the galactic cosmic-ray intensity observed at a given station is more preferable than prediction of the different potentials such as the modulation potential in terms of sunspot numbers (Badhwar and O'Neil, 1993). 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, but such is not the case for the data obtained from space observations. Alanko-Huotari *et al.* (2006) proposed two models: a quasi-linear model 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.

In this contribution we attempt a simulation of the long-term cosmic-ray modulation for the 23rd solar cycle very close to its end by taking initially into account the influence of the sunspot number, solar flares (≥ 1 B), the interplanetary magnetic field, and the geomagnetic index A_{p}. This model was well applied to the previous solar cycles 20, 21, and 22 by considering the time lag of cosmic-ray intensity against these parameters. Here, we attempt a more extensive study of this empirical modulation to the current cycle 23 in the ascending, maximum, and descending phases of this cycle by investigating the contribution of solar and heliospheric variables to the cosmic-ray modulation. The hysteresis effect and the correlation coefficients between cosmic-ray intensity and different solar and heliospheric parameters obtained by the cross-correlation method is discussed, confirming once again the different characteristics of even and odd solar cycles and differences between solar and heliospheric variables.

2. Data Collection

To study the long-term cosmic-ray modulation in cycle 23, monthly values of cosmic-ray intensity obtained from two neutron monitor stations (super NM-64) with different cut-off rigidities, Moscow (2.42 GV) and Oulu (0.81 GV), have been used. We normalized the pressure-corrected data of each station with an intensity taken equal to 1.00 at cosmic-ray intensity minimum (October 2003) and equal to 0.00 at cosmic-ray maximum (August 1997). We note that cosmic-ray intensity in October 2003 during the declining phase of the solar cycle has been used only for normalization reasons and does not coincide with the maximum of the solar cycle activity during the years 2000 – 2002 (Kane, 2006). We note that the Sun has undergone extremely violent activity during this period (October to November 2003) and we should also mention the extreme magnetospheric activity on 20 November 2003, causing an aurora to be observed even in Athens (latitude 37°58′ N) (Belov *et al.*, 2005). In this study we have also used monthly values of the sunspot number R_z, the number of grouped solar flares with importance ≥ 1 B, N_f and the geomagnetic index A_p taken from the National Geophysical Data Center. The term “grouped solar flares” means that observations of the same event by different sites were lumped together and counted as one (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA). Moreover, monthly IMP values are obtained from the OMNI database (http://omniweb.gsfc.nasa.gov/). Flare index data are calculated by Atac and Ozguc from Bogazici University Kandilli Observatory (http://www.koeri.boun.edu.tr/astronomy/findex.html). Wilcox Solar Observatory data for the heliospheric current sheet tilt were obtained via the Web site http://quake.stanford.edu/~wso. Data for CMEs are taken from the SOHO/LASCO CME catalog (http://lasco-www.nrl.navy.mil/cmelist.html). This CME catalog is generated and maintained at the CDAW Data Center by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory. We should mention that there are no data for CMEs for the months of July, August, and September of 1998 and January of 1999.

A new index, P_i, based on the monthly number of CMEs and the mean plasma velocity of CMEs, during the examined period, is defined in this work according to the following relation:

$$P_i = 0.65 \cdot N_c + 0.35 \cdot V_p \ [\mathrm{km\,s^{-1}}]. \tag{1}$$

The factors 0.65 and 0.35 have been calculated from the best correlation coefficient values in a linear fit between the monthly number of CMEs (N_c) and the mean plasma velocity (V_p). This index can well explain the cosmic-ray intensity fluctuations attributable to solar activity because the main cause of Forbush decreases of cosmic-ray intensity at the Earth are the CMEs traveling in interplanetary space (Kane, 2006). Not only are CMEs themselves (ejecta) important for long-term modulation, but so are CME-driven shocks, as they can form interaction regions (IRs), including MIRs and GMIRs, arising from the interaction and integration of a number of (perhaps, many) ejections of solar material (CMEs), which are considered to be an important factor creating CR modulation at times of high solar activity (Belov, 2000; McDonald, 1998).

The long-term modulation of cosmic rays for the current solar cycle 23 is of special interest, as it is characterized by many peculiarities with double peaks. Many quiet periods, the so-called Gnevyshev gaps (Gnevyshev, 1967), are interrupted by extreme solar activity as for example in April 2001, October to November 2003, January 2005, July 2005, and December 2006. Thus, the differences observed in the modulation of cosmic rays during the current cycle are probably attributable to the solar cycle peculiarities found during this cycle. Time profiles of all solar, interplanetary, and geomagnetic parameters used in this work, as

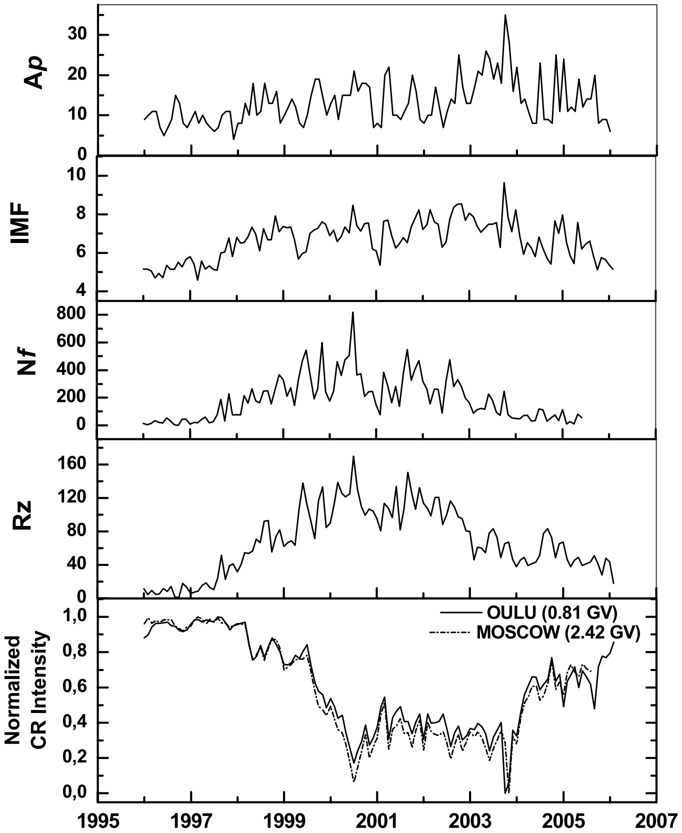

Figure 1a Time profiles of the geomagnetic index A_p, the interplanetary magnetic field IMF, the number of grouped solar flares, N_f, the sunspot number R_z, and the cosmic-ray intensity from Oulu and Moscow neutron monitor stations for the time period 1996 – 2006.

a function of time for the years 1996 to 2006 for the current solar cycle 23, are given in Figures 1a and 1b. It is noted that this cycle presents the main features of an odd solar cycle, as they are described in previous works (Mavromichalaki, Marmatsouri, and Vassilaki, 1988; Mavromichalaki *et al.*, 1997). As far as the solar activity is concerned, there are symmetrical and asymmetrical cycles where generally the rise is faster and decline lasts longer. The odd cycles are characterized by a simple and relatively smooth increase to the maximum of about 3 – 4 years, whereas the even cycles on average are characterized by two maxima. At this point we should mention that the asymmetry of a solar cycle is related not only to the odd – even number resulting from solar magnetic field reversals but also to its magnitude, the so-called Waldmeier's rule. That means the duration of the rise phase is anticorrelated with the height of the maximum, so higher cycles are more asymmetric and the recovery phase is of long duration, about 6 – 8 years. As is seen in Figures 1a and 1b, the solar parameters sunspot number, number of solar flares, and flare index present one maximum in the year 2000 together with the first minimum of cosmic-ray intensity. The geomagnetic index A_p, the interplanetary parameter IMF, the coronal mass ejections index, and the cosmic-ray intensity present a secondary maximum in the year 2003, consistent with the second great burst of solar activity in the declining phase of the current solar cycle. The first burst was in April

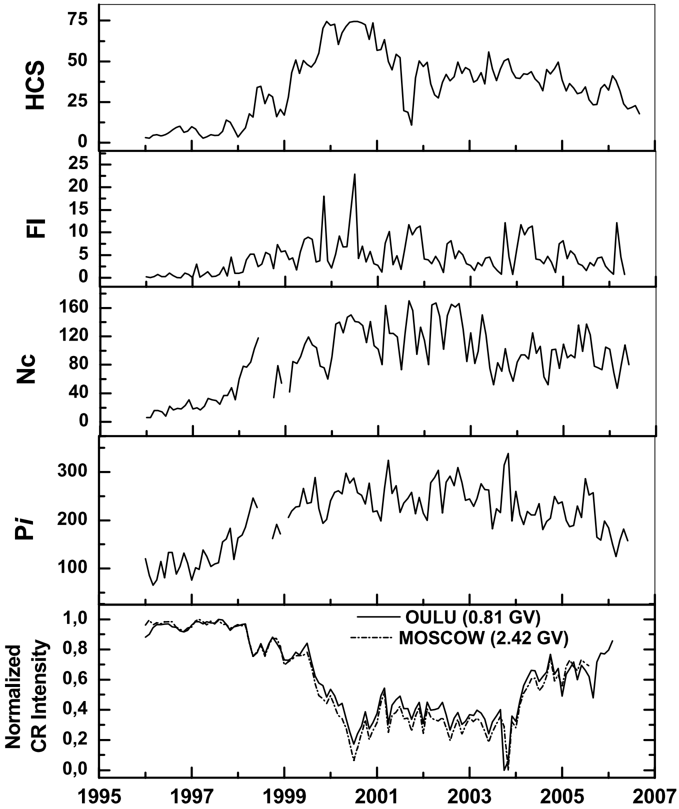

Figure 1b Time profiles of the heliospheric current sheet HCS, the flare index FI, the number of coronal mass ejections N_c, the index P_i, and the cosmic-ray intensity from Oulu and Moscow neutron monitor stations for the period 1996 – 2006.

2001 (Eroshenko *et al.*, 2004). In the declining phase of the current solar cycle a large number of major flares were produced. During four epochs since 2002, flare activity became very high. Compared to this, each of the cycles 21 and 22 produced only one epoch of high activity in the declining phase (Bai, 2006). It is remarkable that the time behavior of the defined coronal mass ejections index P_i follows the cosmic-ray intensity, indicating the close relationship of these two parameters. Because coronal mass ejections are recorded at Earth's orbit, this means that it is an important index to the cosmic-ray modulation recorded at ground-based neutron monitors.

3. Effect of Hysteresis

The 11-year modulation of the cosmic-ray intensity shows some time lag behind the solar activity that is a kind of hysteresis effect against the activity (Moraal, 1976; Mavromichalaki, Marmatsouri, and Vassilaki, 1990). A correlation analysis between the monthly values of the cosmic-ray intensity at neutron monitor energies for the 23rd solar cycle and different solar and heliospheric activity parameters as indicated by the sunspot number R_z, the number of

Table 1 Cross-correlation coefficients and the corresponding time lags for the 23rd solar cycle.

Indices	Correlation coefficient (r) (s.l. 95%)	Time lag (months)
Sunspot number R_z	-0.87 ± 0.01	14
Heliospheric current sheet HCS	-0.79 ± 0.01	−7 – 0 (−7)
Grouped solar flares N_f	-0.70 ± 0.01	14
Geomagnetic index A_p	-0.61 ± 0.02	0
Interplanetary magnetic field IMF	-0.75 ± 0.01	0 – 10 (10)
Flare index FI	-0.41 ± 0.02	15
Coronal mass ejections index P_i	-0.82 ± 0.01	0 – 14 (0)
Number of CMEs N_c	-0.78 ± 0.01	0 – 14 (14)

grouped solar flares, N_f, the geomagnetic index A_p, the interplanetary magnetic field IMF, the flare index FI, the HCS tilt, and the coronal mass ejections index P_i for the time period 1996 – 2006 was carried out. 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 coefficient between cosmic-ray intensity and solar activity parameters with time lags from 0 to 30 months and the probable error for each value of the correlation coefficient for the interval 1996 – 2006. The maximum anti-cross-correlation coefficient between cosmic-ray intensity and different parameters with corresponding time lags are given in Table 1. The variation of the correlation coefficients of the parameters R_z, N_f, IMF, HCS, P_i, N_c, and A_p to the cosmic-ray intensity with their statistical errors and 95% significance level for different time lags calculated over the 23rd solar cycle is presented in Figure 2.

The high correlation values between cosmic rays and sunspot number ($r = 0.87$), coronal mass ejections number ($r = 0.78$), and coronal mass ejections index P_i ($r = 0.82$) as well are indicated. Mavromichalaki, Belehaki, and Rafios (1998) have reported the same values concerning the sunspot number for the odd 21st solar cycle whereas values were smaller in even cycles 20 and 22. Noticeable is the high correlation of the coronal mass ejections with cosmic rays, but such measurements only started in 1996 and cover only one solar cycle. A good correlation seems also to exist between cosmic-ray intensity and number of solar flares and HCS as well. Belov *et al.* (2001) have shown that a good agreement between long-term cosmic-ray intensity and the tilt of the heliospheric current sheet exists in all periods of the same heliomagnetospheric polarity, during the whole history of cosmic-ray observations with neutron monitors since 1953.

However, it is noteworthy that the phase lag of the cosmic-ray intensity and the solar variables such as sunspot number, the number of solar flares, and the flare index for the 23rd solar cycle is remarkably large, reaching the value of 13.5 ± 0.6 months, whereas it was at values of 2 months and 4 months in the previous even cycles 20 and 22, respectively (Mavromichalaki, Belehaki, and Rafios, 1998). This gives us more evidence concerning the existing distinction between even and odd solar cycles resulting from the hysteresis phenomenon (Nagashima and Morishita, 1980b; Mavromichalaki, Belehaki, and Rafios, 1998). To clarify this distinction, we present the time lag of sunspot number with respect to cosmic-ray intensity for the last seven solar cycles in Table 2. The results for the first three solar cycles have been adopted from Nagashima and Morishita (1980b), and the hysteresis for the next three cycles has been computed for the purposes of a previous work by Mavromichalaki, Belehaki, and Rafios (1998).

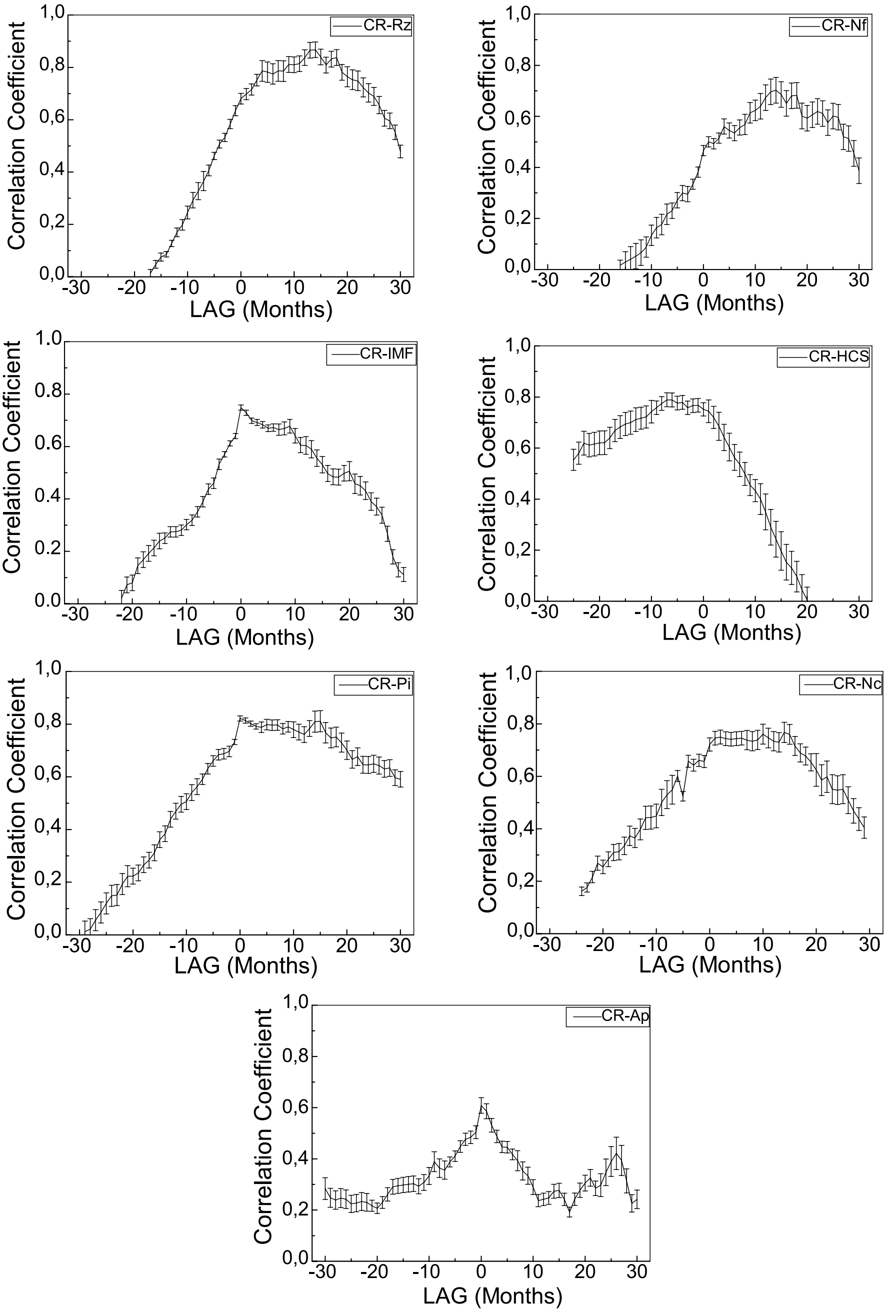

Figure 2 Correlation diagrams of the monthly cosmic-ray intensity with respect to sunspot number, number of solar flares, interplanetary magnetic field, heliospheric current sheet, coronal mass ejections, and geomagnetic index for the 23rd solar cycle.

Table 2 Solar cycle dependence of the cosmic-ray intensity time lag behind the sunspot number.

Solar cycle	17	18	19	20	21	22	***23***
Time lag (months)	9	1	10–11	2	16	4	***14***

Inspecting the whole set of results, we can clearly distinguish between even and odd solar cycles as far as the sunspot number time lag is concerned. This is due to the 22-year variation in the time lag, as already found by Nagashima and Morishita (1980b), Otaola, Perez-Enriquez, and Valdes-Galicia (1985), and Mavromichalaki, Belehaki, and Rafios (1998). Indeed, particles reach the Earth more easily when their access route is through the heliospheric polar regions than when they gain access along the current sheet. In this case, as the route of access becomes longer because of the waviness of the neutral sheet (Kota and Jokipii, 1991), the time lag is also longer than one would expect from theoretical considerations.

For the correlation coefficient diagrams of the heliospheric variables IMF, N_c, and P_i with respect to the cosmic-ray intensity time lag it seems that the first parameter presents a broad maximum from 0 to 10 months, whereas the other two present a maximum level from 0 to 14 months. The P_i index presents the maximum value of the correlation coefficient ($r = -0.82$) at zero months but a secondary maximum at 14 months is also obvious, as well as the number of coronal mass ejections (Figure 2). The HCS has the maximum correlation coefficient from -7 to 0 months and the geomagnetic index A_p is presented with no pronounced time lag. These results are consistent with results in earlier cycles (Mavromichalaki, Belehaki, and Rafios, 1998; Belov *et al.*, 2001). In any case the maximum time lag of the solar parameters with respect to the cosmic-ray intensity seems to be 14 months for the last solar cycle, whereas for the most heliospheric parameters range from 0 to 14 months.

To support the time-lag findings, we have plotted the hysteresis curves between the observed cosmic-ray intensity and each parameter studied in this work shown in the left panels of the Figures 3a and 3b. It has been observed that the hysteresis loops for the solar parameters R_z and N_f in Figure 3a are wider than the other ones in Figure 3b. 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 wide during this odd cycle (Mavromichalaki, Belehaki, and Rafios, 1998). As has been shown by Nagashima and Morishita (1980b) if the effect of the polarity reversal is superposed on the hysteresis effect, the hysteresis curves split into two loops that correspond, respectively, to parallel and antiparallel states of the polarity to the galactic magnetic field. These states refer to the state of the magnetic dipole moment with respect to the radial corotating velocity of the Sun. Because the polarity reversal occurs a few years after solar maxima, 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 Figures 3a and 3b consists of two parts corresponding to the parallel state occurring in the years 1996 – 2000 (right part) and to the antiparallel one occurring in the years 2002 – 2006 (left part). It denotes the transition from the parallel to the antiparallel state of the solar magnetic field within the time interval 2000 – 2002, which is the time interval when the solar polar magnetic field reversal took place (Kane, 2006). More specifically, it is noted that the transition took place in June 2001, which coincided with the middle of the time interval when the magnetic field reversal happened.

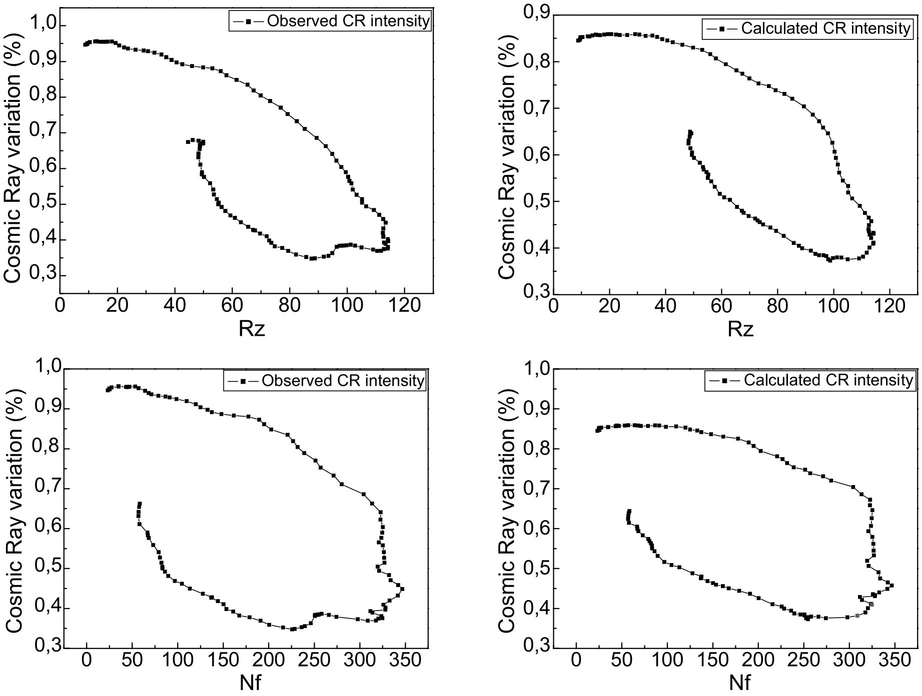

Figure 3a Hysteresis curves of the observed cosmic-ray intensity (left panel) and of that calculated by Equation (7) (right panels) with respect to the solar parameters sunspot number R_{Z} and number of solar flares N_{f}.

4. Empirical Modulation Modeling

An empirical model to describe the long-term cosmic-ray modulation in the heliosphere during solar cycles 20, 21, and 22 was presented in an earlier work by Mavromichalaki, Belehaki, and Rafios (1998). This model was derived by a generalization of Simpson's solar wind model using the diffusion-convection-drift model (Nagashima and Morishita, 1980a) and it was 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, respectively, the galactic (unmodulated) and modulated cosmic-ray intensities, $S(t-r)$ 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 $S(t-r)$ (Xanthakis, Mavromichalaki, and Petropoulos, 1981).

Recently, in a preliminary study of cosmic-ray modulation over the current solar cycle, this empirical model was applied by using the parameters sunspot number, number of solar flares, and geomagnetic index, and a good approximation between observed and calculated values was shown (Mavromichalaki, Paouris, and Karalidi, 2006). This model simulated fairly well the cosmic-ray intensity observed at the Earth during the onset and the declining phase of the solar cycle, whereas our results were not so satisfactory during the maximum phase of the solar cycle. This poor performance was expected, because during this phase

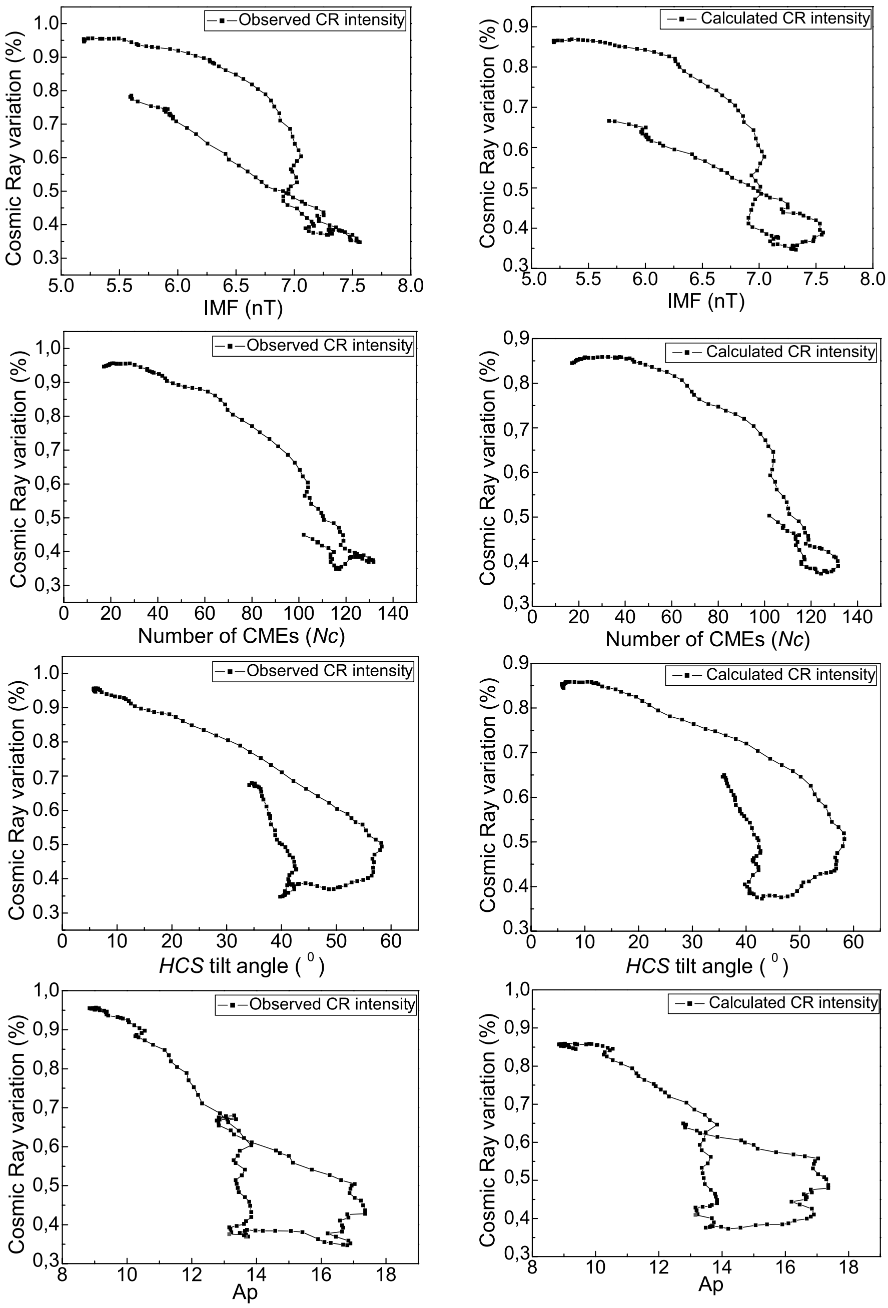

Figure 3b Hysteresis curves of the observed cosmic-ray intensity (left panels) and of that calculated by Equation (7) (right panels) with respect to the heliospheric parameters IMF, CMEs, HCS, and A_p index.

Table 3 Standard deviation for different models during the three phases of the solar cycle. The a_i factors are also given.

Model parameters	Ascending phase (1996 – 1999)	Maximum (2000 – 2003)	Descending phase (2004 – 2006)	Total (1996 – 2006)
A_p, R_z, N_f	9.39%	18%	13.17%	12.2% (0.1, 5.1, 0.5)
A_p, R_z, N_f, IMF	7.70%	12.88%	10.35%	11.65% (1.23, 5.43, −0.23, 0.30)
A_p, R_z, N_c, IMF	7.02%	12.67%	**8.22**%	11.01% (1.16, 3.99, 1.06, 0.32)
A_p, R_z, N_f, HCS	5.29%	12.19%	11.80%	10.97% (1.19, 4.09, −0.23, 3.29)
A_p, R_z, N_c, HCS	**4.52**%	**11.85**%	11.47%	**10.76**% (1.19, 3.13, 0.80, 2.88)

of the cycle the solar magnetic field polarity changed configuration over a period of several months. However, solar activity was high during the declining phase of this cycle, as considerable extra violent activity occurred. For these purposes the need for a better understanding of the cosmic-ray modulation led us to further improvements of this simulation. Applying our model to the ascending, maximum, and descending phases of the cycle separately and on the overall the cycle we have obtained interesting results for the contribution of each parameter to the phases of the current solar cycle.

According to this model, the modulated cosmic-ray intensity 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. An empirical relation is given by the following expression:

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

where C is a constant, X, Ψ, Z, and W are the selected time-lagged solar-heliospheric parameters and α_i ($i = 1$ to 4) are factors calculated by the RMS-minimization method. The constant C is linearly correlated to the cutoff rigidity of each station according to the relation

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

where P is the cutoff rigidity for each neutron monitor station (Mavromichalaki, Marmatsouri, and Vassilaki, 1990). The observed and calculated [by Equation (3)] values of the cosmic-ray intensity for Oulu neutron monitor station for the 23rd solar cycle are presented in Figure 4a for the parameters A_p, R_z, and N_f and in Figure 4b for the parameters A_p, R_z, N_f, and IMF. The residuals between observed and calculated values are indicated in the lower panels of these figures. The improvement of this simulation in the maximum phase of the cycle owing to the IMF is obvious. The standard deviation for this model for the first case was 12.2% and in the second case it was 11.65%. The improvement during the maximum phase ranged from 18.00% to 12.88%. Results of these simulations in the three parts of the solar cycle are given in Table 3.

It is noteworthy from Figures 4a and 4b that relation (3) simulates fairly well the cosmic-ray intensity observed at the Earth during the onset and the declining phase of the solar

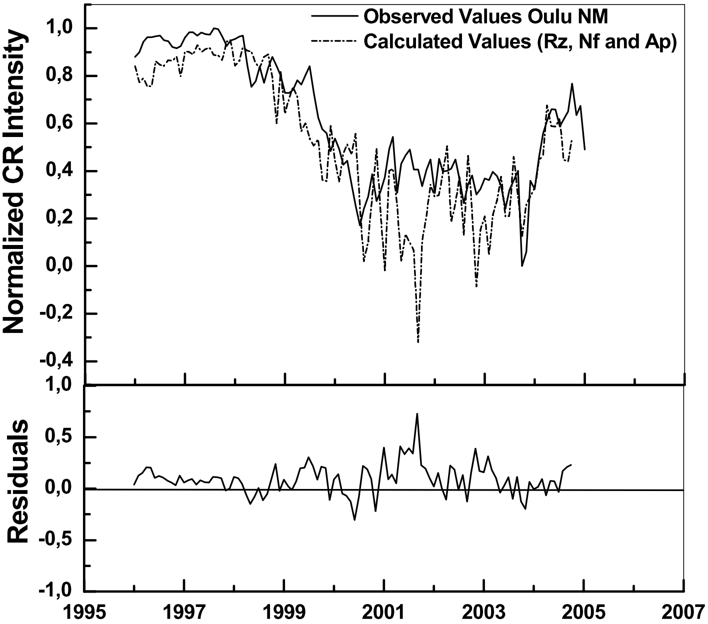

Figure 4a Observed and calculated values of the cosmic-ray intensity using R_{Z}, A_{p}, and N_{f} indices for Oulu for the 23rd solar cycle.

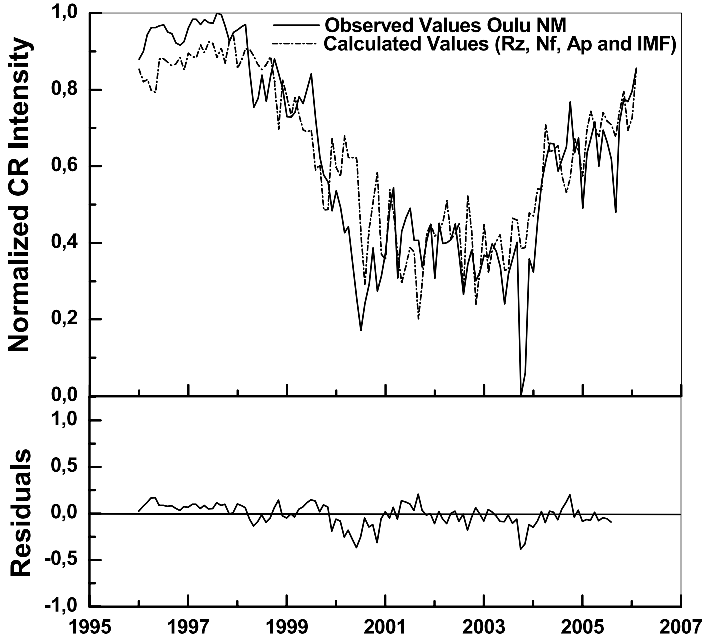

Figure 4b Observed and calculated values of the cosmic-ray intensity using A_{p}, R_{Z}, N_{f}, and IMF for Oulu Neutron Monitor station for the 23rd solar cycle.

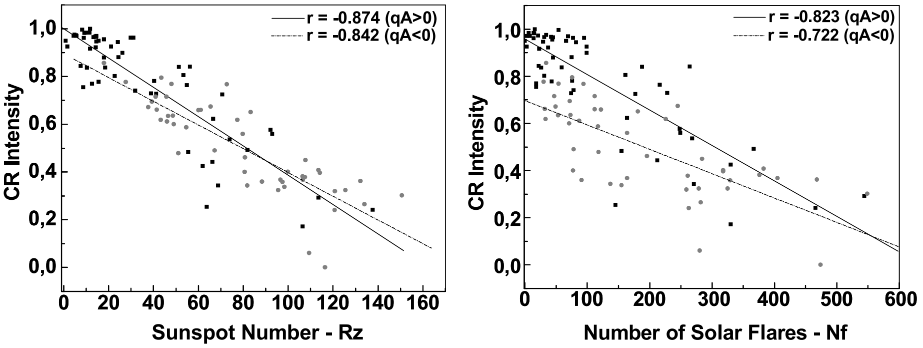

Figure 5a Correlative diagrams of R_Z and N_f with respect to cosmic-ray intensity for positive polarity ($qA > 0$) and for negative polarity ($qA < 0$) intervals. These solar parameters seem to undergo no remarkable change between the two time intervals with different polarity.

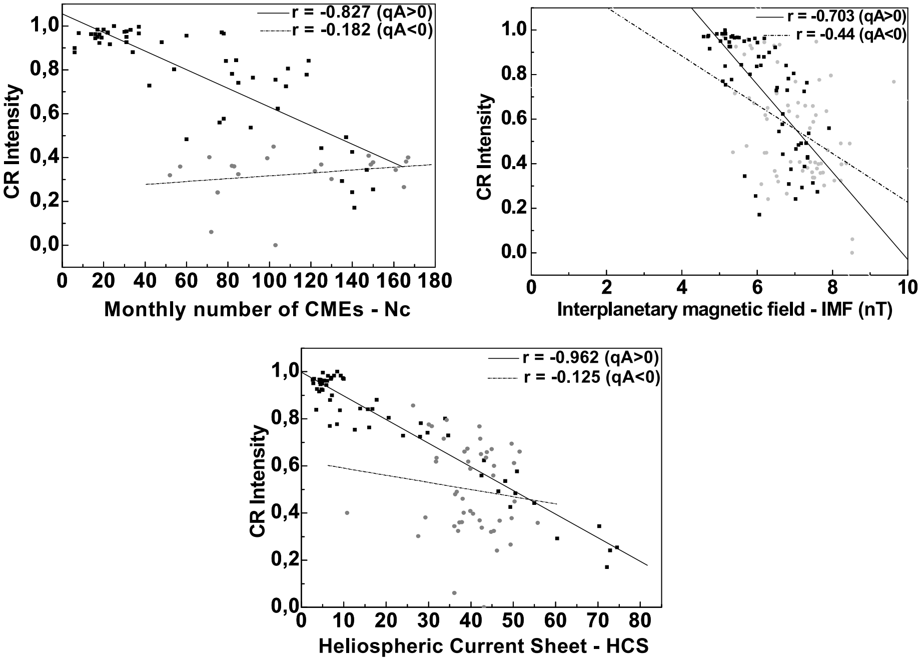

Figure 5b Correlative diagrams of CMEs, IMF, and HCS with respect to cosmic-ray intensity for positive ($qA > 0$) and for negative ($qA < 0$) polarity intervals. In all cases there is a significant difference between the correlation coefficients in the two intervals with different polarity.

cycle. Some significant discrepancies appear in the maximum phase of cosmic-ray intensity (inversely to solar activity), as was already mentioned. It is known that the change of the magnetic field polarity took place over a period of several months. According to Lantos (2005) using cosmic-ray intensity and sunspot number data in the current solar cycle this period was estimated from 1999.84 to 2001.99 years (about two years). Kane (2006), studying solar magnetic flux data, reported that the reversal took place from the last quarter of 2000 for the north pole to the first quarter of 2002 for the south pole. Indeed, during this

Table 4 Correlation coefficient of the cosmic-ray intensity with respect to the different indices for positive polarity (1996 – 2000) and for negative polarity (2001 – 2006). The significant level is 95%.

Indices	1996 – 2000 $qA > 0$	2001 – 2006 $qA < 0$
Sunspot number R_z	−0.874	−0.842
Flare index FI	−0.425	−0.385
Grouped Solar Flares N_f	−0.823	−0.722
Geomagnetic index A_p	−0.646	−0.691
Interplanetary magnetic field IMF	−0.703	−0.440
Heliospheric current sheet HCS	−0.962	−0.125
Coronal mass ejections index P_i	−0.800	−0.722
Number of CMEs N_c	−0.827	−0.182

time interval the differences between observed and calculated values of the cosmic-ray intensity seem to be high. Thus, we tried calculating the cross-correlation coefficient of each one of the parameters considered here in comparison to the CR intensity, before and after the reversal of the magnetic field. Correlative diagrams with respect to cosmic-ray intensity for positive-polarity ($qA > 0$) and for negative-polarity ($qA < 0$) intervals are given in Figure 5a for the solar variables R_z and N_f and in Figure 5b for the heliospheric variables CMEs, IMF, and HCS. The solar parameters seem to undergo no remarkable change between the two time intervals with different polarity, whereas the heliospheric ones present a significant difference. The correlation coefficient for each case is indicated in the diagrams, and results for all parameters are given in Table 4.

As we can clearly see, the correlation of each parameter to the CR intensity is indeed higher during the period with positive polarity ($qA > 0$) of the solar magnetic field from 1996 till the third quarter of 2000 than during the period with negative polarity ($qA < 0$) from the second quarter of 2001 till today. It is remarkable that the polarity reversal does not appear to make much difference in the two periods in the case of solar parameters (Figure 5a), whereas it is very significant in the case of heliospheric ones (Figure 5b). This means that this correlation is good during the ascending phase of the solar cycle, but it is not for the heliospheric variables during the declining phase.

Generally, it is clear that the correlation of the solar and heliospheric parameters with cosmic rays is better during negative polarity than positive polarity of the solar magnetic cycle. Gupta, Mishra, and Mishra (2006) have shown the same results for the correlation of cosmic-ray intensity with the sunspot number and coronal index for cycles 21 and 22.

5. Contribution of Heliospheric Parameters

Taking into consideration all the above and knowing that this solar cycle exhibited extra violent activity during and after the maximum of the cycle, we studied the contribution of each one of the these parameters (*e.g.*, the number of coronal mass ejections and the heliospheric current sheet tilt) on the cosmic-ray modulation during the three phases of the solar cycle and the possible improvement of this proposed empirical model based on new available data provided during the last cycle. The role of IMF in relation to these parameters is also discussed.

In our effort to improve the existing empirical model, we tried numerous successive approximations with a variety of different combinations of all considered parameters, keeping in mind the importance of both solar and heliospheric indices, and interchanging only indices of similar physical importance. Initially taking into account the effect of CMEs on the CR modulation, we replaced the index N_{f} with the total number of CMEs, adopting the following relation:

$$I = C - 10^{-3}(\alpha_1 A_{\mathrm{p}} + \alpha_2 R_{\mathrm{z}} + \alpha_3 N_{\mathrm{c}} + \alpha_4 \mathrm{IMF}\ [\mathrm{nT}]), \tag{5}$$

where the constant C depends linearly on the cutoff rigidity of each station, A_{p}, R_{z}, N_{c}, and IMF are the solar – terrestrial parameters incorporating the time lag, and α_i with $i = 1$ to 4 are factors calculated by the RMS-minimization method, which were found equal to 1.16, 3.99, 1.06, and 0.32, respectively. The standard deviation for this model was found to equal about 11.01% instead of 11.01% that was in the previous model. This result shows the contribution of the CMEs except that of the IMF on the long-term CR modulation. Later on, the effect of the HCS tilt on the CR modulation was checked, replacing the parameter of the IMF with this and adopting the following expression:

$$I = C - 10^{-3}(\alpha_1 A_{\mathrm{p}} + \alpha_2 R_{\mathrm{z}} + \alpha_3 N_{\mathrm{f}} + \alpha_4 \mathrm{HCS}), \tag{6}$$

where the constant C depends linearly on the cutoff rigidity of each station, A_{p}, R_{z}, N_{f}, and HCS (where represents the HCS tilt angle in degrees) are the solar – terrestrial parameters incorporating the time lag, and α_i ($i = 1$ to 4) are factors calculated by the RMS-minimization method (1.19, 4.09, -0.23, and 3.29, respectively). The standard deviation for this modulation is a little better than the previous one (10.97%) and suggests a good approximation, indicating the significance also of the HCS tilt on the CR modulation, in comparison with the IMF (Table 3). The time lag in each case is taken according to the values in parentheses in the last column of Table 1, which correspond to the maximum correlation coefficient.

Furthermore, based on these results of the contribution of the CMEs and HCS tilt on the long-term cosmic-ray modeling, we obtained the following empirical expression:

$$I = C - 10^{-3}(\alpha_1 A_{\mathrm{p}} + \alpha_2 R_{\mathrm{z}} + \alpha_3 N_{\mathrm{c}} + \alpha_4 \mathrm{HCS}), \tag{7}$$

where the parameters α_i ($i = 1$ to 4) were found to be equal to 1.19, 3.13, 1.19, 0.80, and 2.88, respectively. Indeed this model gave the best simulation of the observed CR intensity with a standard deviation of about 10.76% during the whole solar cycle, showing that the most appropriate heliospheric parameters that affect the CR modulation are the number of CMEs and the HCS tilt. The observed and calculated values from the best improved empirical modulation for Oulu and Moscow neutron monitor stations are presented in Figures 6a and 6b. A comparison of Figure 6a to Figure 4b for the Oulu neutron monitor data shows the improvement of our modeling owing to the CMEs and HCS tilt contribution, especially in the maximum phase of the cycle.

Examining the entire current solar cycle, we can conclude that all the selected heliospheric parameters (IMF, N_{c}, and HCS) can give a very good approximation to the modulated cosmic-ray intensity, when including, at each time, only two of them in the model. The addition of all parameters together gives unsatisfactory results, as is expected from the integral equation (2), 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}, CME, and HCS, are global indices, whereas others, such as IMF, V_{p}, and A_{p}, are limited to the ecliptic plane. According to Usoskin *et al.* (1998) the cosmic-ray modulation is defined mainly by the

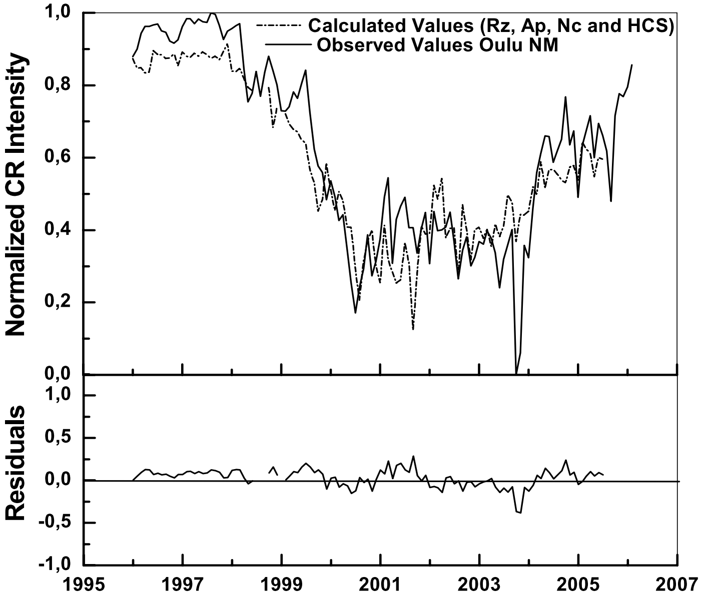

Figure 6a The observed values and those calculated from Equation (7) of the cosmic-ray intensity for Oulu station. The residuals are indicated in the lower panel. This modulation has a standard deviation of about 10.76%.

global indices because of their complicated transport in the heliosphere, consistent with our results in this work.

Another important piece of evidence for this proposed model is obtained from the hysteresis curves illustrated in Figure 3. These curves for the current solar cycle present in general a broad loop, as expected since it is an odd cycle (Nagashima and Morishita, 1980a). The same features are followed by all indices connected with the solar activity (left panels of Figure 3a). Furthermore, a similar behavior also appears in the model-fitted loops (right panels of Figure 3a), which verifies the reliability of this empirical model.

Additionally, to study the contribution of these parameters to the different phases of the solar cycle, we separated it into three parts, the ascending (starting in 1996 and ending in 1999), the maximum (from 2000 and ending in 2003), and the descending part of the solar cycle (starting in 2004). Applying our models to each solar cycle phase separately, we obtained interesting results. The standard deviations for the models and for the three phases of the cycle are presented in Table 3. In general most of our models present a rather large deviation from the observed values during the maximum and the descending phase, whereas during the ascending part of the cycle the deviation is fairly low, then practically doubles during the maximum, and starts declining slowly afterward in the descending part of the cycle. An exception seems to exist in the descending phase of the cycle as a result of the distribution functions of IMF and N_c and the standard deviation presents a smaller value of 8.22%. This is related to the high correlation values between the parameters considered here and the cosmic-ray intensity during the ascending part of the cycle (including the period with $qA > 0$ polarity of the magnetic field), which drops to lower levels in the maximum (close to and including the polar magnetic field reversals) and descending parts included in the $qA <$

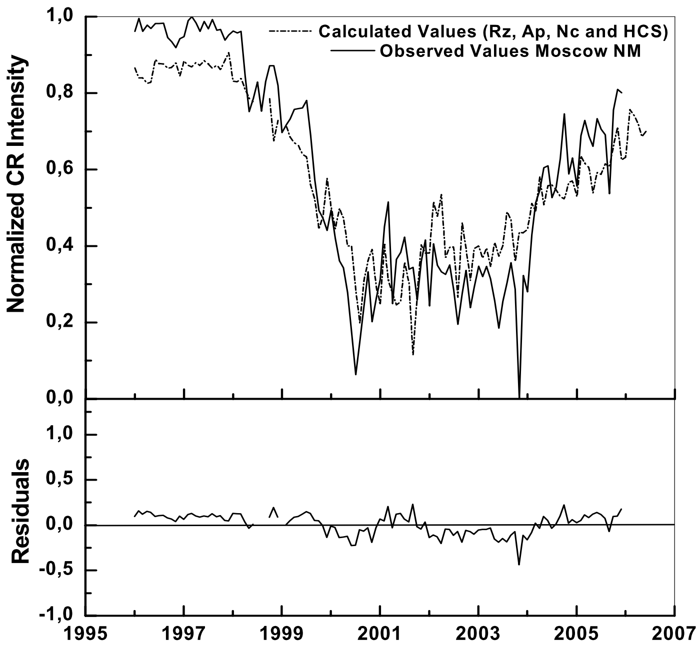

Figure 6b The observed values and those calculated from Equation (7) of the cosmic-ray intensity for Moscow station. The residuals are indicated in the lower panel. This modulation has a standard deviation of about 10.76%.

0 polarity. For comparison we can state that in the same time interval the standard deviation for the previous existing model without the contribution of the heliospheric variables was found to be $\sigma \approx 18\%$ (Mavromichalaki, Paouris, and Karalidi, 2006).

6. Discussion

In a review paper Belov (2000) noted that our current knowledge of cosmic-ray modulation depends on observations of the cosmic-ray modulation at the Earth and main characteristics of the accumulated experimental data, manifestations of the solar magnetic cycle in cosmic rays, the effect of hysteresis and its relation to the size of the heliosphere, the rigidity spectrum of long-term cosmic-ray variations, the influence of the sporadic effects on long-term modulation, long-term variations of cosmic-ray anisotropy and gradients, and the location of ground-level observations in current studies of cosmic-ray modulation.

In this work the modulation of cosmic-ray intensity is modeled on a monthly basis empirically by the source functions of Equation (2), which can be expressed by an arbitrary linear combination of various solar and heliospheric indices. In a previous work applying this relation using the sunspot number, the number of solar flares, and the geomagnetic index to the solar cycles 20, 21, and 22 it was shown that it is possible to model the cosmic-ray intensity variations with a good approximation. The characteristic function $f(r)$ of all these indices has a constant value during this solar cycle calculated by the RMS-minimization method. By this way the modulated cosmic-ray intensity is equal to galactic cosmic-ray intensity (unmodulated) at a finite distance, corrected by a few appropriate solar, interplanetary, and terrestrial activity indices, which cause the disturbances in interplanetary space and thus modulate the CR intensity.

Using these source functions on the current solar cycle 23 it was noted that it was simulated well in the ascending and descending phases, but it was not so good in the maximum phase. Numerous extreme events occurred during this cycle even at the end of this cycle, such as the recent events of December 2006.

On our effort to improve this empirical model, we studied the contribution of different heliospheric variables such as the interplanetary magnetic field, coronal mass ejections, and the heliospheric current sheet on the long-term CR modulation to obtain a better approximation. We thus confirm the important role that the IMF and the HCS tilt play in the long-term CR modulation, as was suggested by previous researchers (Wibberenz and Cane, 2000; Jokipii and Thomas, 1981). Additionally, we noticed that the replacement of the term that refers to the effect that the solar flares have on the CR modulation by the term that refers to the CMEs results in an even better approximation with a standard deviation of only about 11%, confirming the idea proposed by authors such as Newirk, Hundhausen, and Pizzo (1981) and Cliver and Ling (2001) that the CMEs play an important role in the long-term CR modulation.

It is well known that galactic cosmic-rays detected by neutron monitors are affected by the large-scale IMF inhomogeneities originating at the Sun well before the disturbances reach the Earth's orbit (geoeffective event) and geomagnetic disturbances occur (Kudela *et al.*, 2000; Akasofu, 1981; Gonzalez *et al.*, 1994). In a more general view, the IMF configurations that can produce Forbush decreases (the most common type of short-term decreases of the cosmic-ray intensity and observed by ground-based cosmic-ray detectors) are small-scale fluctuations in the direction and/or magnitude of the IMF, extended structures of intense ordered magnetic fields, and blast or shock waves and tangential discontinuities (Kudela *et al.*, 2000). Consequently, we cannot ignore the importance of the IMF and its effect to the cosmic-ray intensity modulation on short- and long-term bases.

Moreover, the heliospheric current sheet results in a drift, mostly radially, but also latitudinally when the HCS is significantly inclined, which facilitates cosmic-ray access to the inner heliosphere (Belov, 2000). Many theoretical researches have tried to find the connection between the HCS tilt and the CR modulation (*e.g.*, Jokipii and Thomas, 1981), which seems to be clearer, from an observational point of view, particularly near the minimum phases of solar activity (Lockwood, Webber, and Hoeksema, 1988; Belov, Gushchina, and Yanke, 1997). In Table 1, we notice that the correlation coefficient of the HCS tilt to the CR is very high, about 79%, whereas in Figure 4b we see that the anticorrelation of the HCS tilt to the CR is extremely high with a correlation coefficient of over 96% for the $qA > 0$ part of the solar cycle, but it drops drastically to only 12% for the $qA < 0$ part of the solar cycle. This is to be expected, since a very large part of the studied time interval in the $qA < 0$ time interval coincides with the time of solar maximum.

However, data of coronal mass ejections from the SOHO mission since 1996 are available. The strong events of solar activity such as solar flares and CMEs can cause Forbush decreases and ground-level enhancements in cosmic-ray levels (Cane, 2000). The most important link between solar activity and large, nonrecurrent geomagnetic storms are coronal mass ejections (Gosling *et al.*, 1993). These are spectacular manifestations of solar activity in which a great amount of solar material is suddenly propelled outward into interplanetary space (Kahler, 1987; Gosling *et al.*, 1991). A vast bubble of magnetized plasma erupts from the solar corona and travels through interplanetary space at a speed often well above that of the ambient solar wind (Kudela *et al.*, 2000). The long-lasting southward IMF can be caused by compression of the upstream IMF by the CME or can be in the CME itself (Kudela *et al.*, 2000). Approximately half of all CMEs and half of all shocks encountered by Earth do not produce any substantial geomagnetic activity, as the initial speed of the CME relative to the ambient solar wind is probably the most important factor in determining whether an earthward-directed coronal mass ejection will be geomagnetically effective or not (Gosling *et al.*, 1991). The interplanetary counterparts of CMEs, such as ejected material and shocks, are typically accompanied by the observation of strong enhancements of cosmic-ray anisotropies (Lockwood, 1971). The relationship between CMEs and CR modulation is analyzed in several works (*e.g.*, Cane, Richardson, and von Rosenvinge, 1996; Cane, Richardson, and Wibberenz, 1994; Cane, 1998, 2000).

Moreover, the newly defined index P_i, which is a function of the number of CMEs and the plasma velocity, seems to have a very good correlation with the cosmic-ray intensity variations. Time profiles of these two time series presented in Figure 1b appear to show the same behavior. It is interesting that most of the fluctuations of the P_i can explain the fluctuations of cosmic-ray intensity. It is also very interesting that P_i has a very high correlation coefficient (about 0.82), while at the same time this value for sunspot number is 0.87 (Table 1).

Furthermore, when creating the hysteresis loops for solar cycle 23, we noticed that they are broad for all the examined parameters with respect of the cosmic-ray intensity, verifying, even for such an "extreme" cycle, the characteristics of an odd cycle (Nagashima and Morishita, 1980a; Mavromichalaki, Belehaki, and Rafios, 1998). A similar feature also appears using the values calculated by our model of the cosmic-ray intensity, confirming once again the validity of this model. A different contribution of these parameters in the different phases of the solar cycle is noted. It is also characteristic that the reversal in the direction of the hysteresis curve coincides with the time interval in which the polar magnetic field reversal took place (Kane, 2006).

7. Conclusions

The long-term variations of galactic cosmic rays during the current solar cycle were compared with the behavior of various solar activity indices and heliospheric parameters. Emphasis was given to the interplanetary magnetic field, coronal mass ejections, and the tilt angle of the heliospheric current sheet as well as to a new heliospheric variable related to coronal mass ejections. We pointed out the different behavior of these heliospheric parameters compared with the solar ones for some interesting properties of the cosmic-ray intensity modulation. These are the hysteresis phenomenon and the correlation of these parameters with the cosmic-ray intensity in the three different phases of the solar cycle and according to the solar magnetic field polarity as well. Results from this analysis confirm different results among the three parts of the cycle, as well as the systematic differences determined from the even and odd solar cycles.

Anomalous phenomena in the solar modulation of cosmic rays in addition to the variation in time lag for the even and odd solar cycles have been reported. These phenomena are interpreted as the result of reversal of the polar magnetic field of the Sun (Kota and Jokipii, 1991). Such phenomena in the cosmic-ray intensity have also been observed after solar maximum as well as in the declining phases of earlier solar cycles (Nagashima and Morishita, 1980b). It has been suggested that the modulation of galactic cosmic rays should have a significant component controlled by the state of the interplanetary magnetic field as transported out from the Sun and hence there should be a solar cycle effect on the drift of the cosmic rays in the heliosphere. Different behavior between solar and heliospheric variables on the cosmic-ray modulation has been noticed according to these phenomena.

Moreover, the importance of these parameters in the cosmic-ray modulation, even for an active solar cycle, such as the 23rd, was proven via the proposed empirical models. Since this was the first solar cycle for which data concerning CMEs exist, a special interest was given to determining their importance in the cosmic-ray modulation, as coronal mass ejections are the direct outcome of the Sun's dynamic nature. An effort to see their effect on cosmic-ray modulation was made by using the mean plasma velocity of CMEs. In the future it will be necessary to continue with our effort to determine what effect additional CME parameters such as number, velocity, and magnetic field may have on the long-term modulation.

The proposed model is suitable to fit the actual cosmic-ray intensity variations measured by ground-based detectors, but constructing models based on parameters that cannot be obtained directly from observations is a complicated task, as noted recently by Alanko-Huotari *et al.* (2006). This model has so far been applied to four solar cycles (20, 21, 22, and 23) (Mavromichalaki, Belehaki, and Rafios, 1998) and can describe well the observed cosmic-ray variations and can be considered as a useful tool for understanding cosmic-ray modulation. The distinction between solar and heliospheric parameters concerning their modulated effects on cosmic ray intensity will be helpful to prediction studies.

In general the study of a solar cycle is difficult, so the study of this particularly violent solar cycle makes the whole study far more difficult. If the empirical modulation can give us a good standard deviation between the observed and calculated values, it would be a very satisfactory result and this study could be used in future studies of subsequent solar cycles. This will be helpful in studying space weather forecasting. The proposed model can be extended backward in time or used for predictions, if the corresponding heliospheric variables can be independently estimated. It is of theoretical interest to understand why some cycles are very active in the declining phase, and the high level of activity in the declining phase has practical implications for planning solar observations and forecasting space weather.

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