# Long-term Cosmic-ray Modulation during Solar Cycle 23rd

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**Abstract.** The long-term modulation of the current solar cycle 23 is of great interest, as this cycle is characterized by many peculiarities with double peaks. Many quiet periods (Gnevyshev gaps [1]) are interrupted by extreme solar activity, as for example in April 2001, October-November 2003 and January 2005. Previous works proposed an empirical model to describe the long-term cosmic-ray intensity modulation during solar cycles 20, 21 and 22. In this work an attempt to apply this model to the solar cycle 23 is made analyzing monthly cosmic ray data from the Neutron Monitor Stations of Oulu (cut-off rigidity 0.81 GV) and Moscow (cut-off rigidity 2.42 GV). An empirical relation obtained from the linear combination of the sunspot number $R_z$, the solar flares $N_f$ and the geomagnetic index $A_p$, is outlined incorporating the time-lag of these parameters against cosmic ray intensity. An extended study of the hysteresis phenomenon of cosmic ray intensity against different solar, interplanetary and terrestrial parameters during the time period 1996-2005 is also presented. This effect was found to have a high value, in average about 14 months, related to the size of the heliosphere and characterizing an odd solar cycle. Analytical modeling and numerical simulations are qualitatively consistent with experimental data. In our days a satisfied long-term cosmic ray model would be very useful for Space Weather studies given the possibility for cosmic-ray intensity prediction, especially now where these and satellite data are provided in real time to the Internet. A first evidence for the important role of coronal mass ejections to the long-term cosmic ray modulation is also discussed.

**Keywords:** Cosmic rays, hysteresis effect, long-term modulation, solar cycle, coronal mass ejections
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## INTRODUCTION

The cosmic-ray (CR) intensity as is well known exhibits an approximate 11-year variation anticorrelated with solar activity with perhaps some time lag [2], [3], [4]. A great effort is carried out in order to express this long-term variation of galactic cosmic-ray intensity by appropriate solar indices. Some of these indices has been used in previous works, such as the sunspot number by Nagashima and Morishita [5], solar flares by Hatton [6] and geomagnetic index by Chirkov and Kuzmin [7]. Other authors like Xanthakis, Mavromichalaki and Petropoulos [8] and Nagashima and Morishita [9] have taken into account the contribution of more than one solar and/or geophysical parameters to the modulation process. A relation between the modulated cosmic-ray intensity during the 20th solar cycle, and a combination of the relative sunspot number, the number of proton events and the geomagnetic index $A_p$ has been found by [10]. In a later work [11], this empirical relation was improved by including the number of corotating solar wind streams. On the other hand, a close relationship between the magnitude and frequency of Forbush decreases and the 11-year cosmic-ray variation was found by [12]; they concluded that the effect of Forbush and other transient decreases is a dominant factor in the long-term intensity modulation. Particular consideration of the cosmic ray modulation is given to the correlation of long-term cosmic ray variations with different solar-heliospheric parameters and to empirical models of cosmic ray intensity, as it is described in the review paper [13]. Recently, Lantos [14] proposed a method to predict cosmic ray intensity and solar modulation parameters. This method gives satisfactory results applied to prediction of the dose received on-board commercial aeroplane flights. He notes that prediction of the galactic cosmic ray intensity observed at a given station is preferable than prediction of the different potentials like as the modulation potential in terms of sunspot numbers [15]. 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 that is not the case for the data obtained from space observations.

It is known that there are differences in solar activity from cycle to cycle. There are series of cycles with very high activity level (odd cycles) as well as series of cycles with quite low activity (even cycles). Solar cycle 23rd is a cycle with a lot of extra violent phenomena even we are not in the maximum of solar activity. Some of those periods are April 2001, October-November 2003, January 2005, July 2005, August-September 2005 when the neutron monitors detected some of the strongest Forbush Decreases. Many quiet periods are interrupted by extreme bursts of solar activity, as in March 2001 and October 2003 [1],[16]. A result of this activity is the observation of aurora in Athens (Latitude: 37º 58' N) in November 20, 2003[17].

In this contribution a simulation of the long-term cosmic-ray modulation for the 23rd solar cycle being very close to its end, has been attempted taking into account the influence of the sunspot number, the solar flares (≥ 1 B) and the geomagnetic index $A_p$. The monthly cosmic-ray intensity using the above mentioned parameters has been reproduced taking into account the effect of time-lag of them against the cosmic ray intensity. A study of the hysteresis effect of some other solar and heliospheric parameters confirm once again the different characteristics of even and odd solar cycles presenting a high value of the time lag during the odd cycles [18]. As it is easy to understand, the study of a solar cycle is difficult, so the study of a solar cycle with much more violent activity than others make the whole study far more difficult. If the empirical modulation could give us a good value of standard deviation between the observed and calculated from the model values, it would be a very trustful result and this study would be used in the future in order to study the solar cycles which are follow.

## DATA COLLECTION

In order to study the long-term modulation in cycle 23, monthly values of cosmic-ray intensity data 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. The pressure-corrected data for each station were normalized with the intensity taken equal to 1.00 at Cosmic-rays intensity minimum (October 2003) and equal to 0.00 at maximum (August 2000). In this study we have used also monthly values of the following parameters: the sunspot number Rz, the number of solar flares with importance ≥ 1 B $N_f$ and the geomagnetic index $A_p$ taken from the National Geophysical Data Center: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA. Moreover, monthly values of the interplanetary magnetic field IMF from Ulysses mission http://helio.esa.int/ulysses/archive/ and flare index FI from: http://www.koeri.boun.edu.tr/astronomy/findex.html are also obtained. Data for coronal mass ejections CMEs are taken from SOHO/LASCO CME Catalog in website 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. In this point we must mentioned the fact that there are not data for CMEs for the months July, August and September of 1998 and January of 1999. It is interesting to note that a new index $P_i$ based on the number of CMEs per month (*Nc*) and the mean plasma velocity (*Vp*) of CMEs during the examined monthly period, is defined in this work according to the following relation

$$P_i = 0.65 \cdot Nc + 0.35 \cdot Vp \qquad (1)$$

The factors 0.65 and 0.35 have been calculated by the best correlation coefficient values in linear fit. This index can well explain the cosmic ray intensity fluctuations due to the solar activity, as the main cause of Forbush decreases of cosmic ray intensity at the Earth are the coronal mass ejections traveling in the interplanetary space [19].

Time profiles of all parameters used in this work, as a function of time from 1996 to 2005 ($23^{rd}$ solar cycle), are given in Fig. 1. It is of great interest that this cycle presents the main features of an old solar cycle, as there are described in previous works [20],[21]. It appears a 'saddle-like' shape and a 'mesa-type' maximum. The recovery phase is of long duration is about 6-8 years. As it is seen in this figure the solar parameters sunspot number, solar flares and flare index present one maximum in the year 2000 together with the first maximum of cosmic ray intensity. The interplanetary parameter IMF presents also one maximum shifted to the year 2001, as it was expected, whereas the geomagnetic index $A_p$, the cosmic ray intensity and the coronal mass ejections index present a 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 one was in April 2001 [16]. It is remarkable that the time behavior of the defined coronal mass ejections index follows the cosmic ray intensity indicating the close relationship of these two parameters. As coronal mass ejections are recorded at the Earth orbit, it means that it is a very important index to the cosmic ray modulation recorded at ground based neutron monitors.

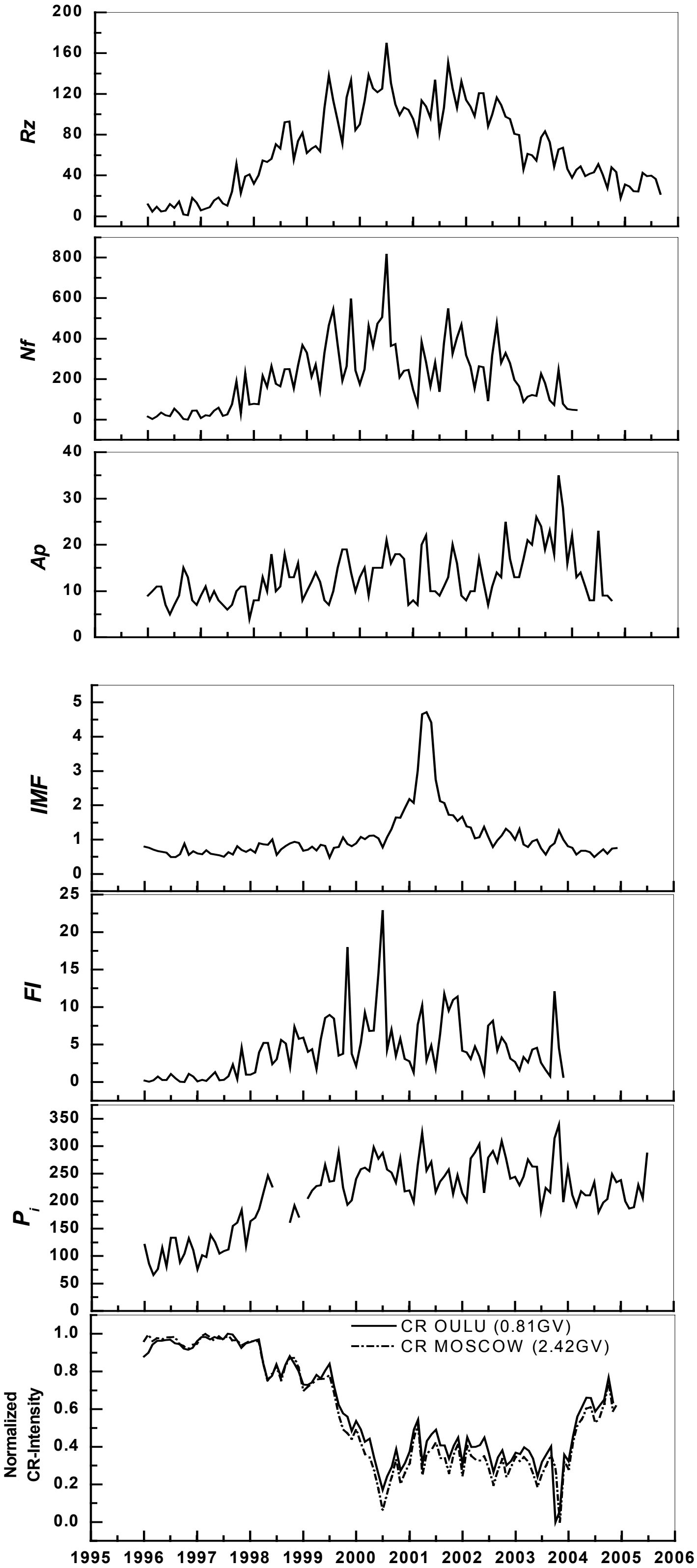


**FIGURE 1.** Time profiles of all parameters where used in this work for the 23rd solar cycle.

## HYSTERESIS EFFECT

The 11-year modulation of the cosmic ray intensity shows some time lag behind the solar activity, in other words some kind of hysteresis effect against the activity [22],[23]. A correlation analysis between the monthly values of the cosmic-ray intensity at Neutron Monitor Energies for the 23rd solar cycle and the solar activity indicated by the sunspot number Rz, the grouped solar flares Nf and the geomagnetic index Ap for the time period 1995-2005 as a function of the cosmic-ray intensity lag with respect to these parameters is performed [6], [11]. The same analysis has also been done for the interplanetary magnetic field IMF, the flare index FI and the

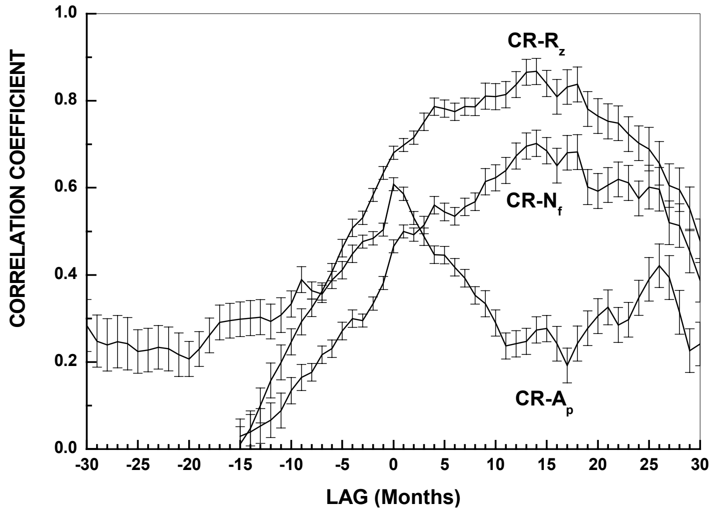


**FIGURE 2.** Correlation coefficients between monthly cosmic-ray intensity and sunspot number, grouped solar flares and Ap-index as functions of cosmic-ray intensity time-lag with respect to these indices for the 23rd solar cycle.

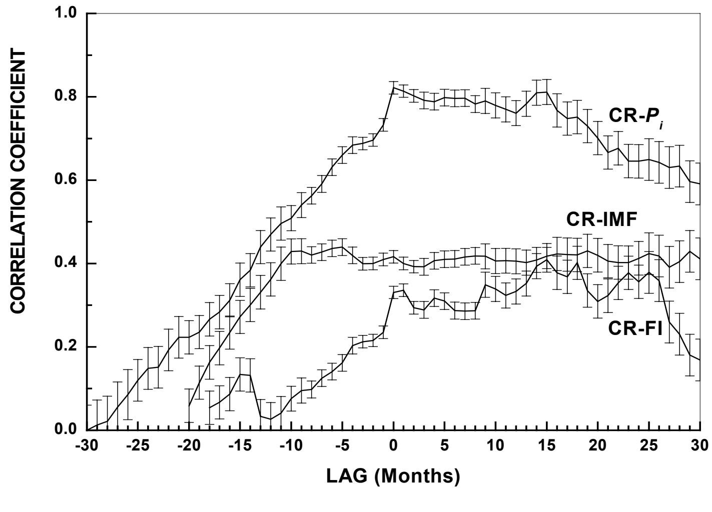


**FIGURE 3.** Correlation coefficients between monthly cosmic-ray intensity and the coronal mass ejections index (Pi), the interplanetary magnetic field (IMF) and the flare index (FI) for different cosmic ray time-lag with respect to these indices for the 23rd solar cycle.

TABLE I

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

| Indices | Correlation Coefficient (r) | Time-Lag (months) |
|---|---|---|
| Sunspot number: *Rz* | -0.87 ± 0.01 | 14 |
| Grouped Solar Flares: *Nf* | -0.70 ± 0.01 | 14 |
| Geomagnetic index: *Ap* | -0.61 ± 0.02 | 0 |
| Interplanetary magnetic field: *IMF* | -0.44 ± 0.02 | -5 |
| Flare index: *FI* | -0.41 ± 0.02 | 15 |
| Coronal mass ejections index: $P_i$ | -0.82 ± 0.01 | 0 |

coronal mass ejections index $P_i$. The correlation coefficients with their errors for different time lags calculating over the 23rd solar cycle are presented in Figs 2 and 3. The best correlation coefficients with their errors and the time lags of cosmic ray intensity corresponding to the cross-correlation coefficient of each parameter for the 23rd cycle are given in Table I. The high correlation values between cosmic rays and sunspot numbers ( r = 0.87) and coronal mass ejections index ( r = 0.82) as well, are indicated. The same value concerning the sunspot number was also calculated for the 21st cycle in a previous work [18]. This high correlation value of coronal mass ejections is given for first time, as the measurements of them have begun since 1996 covering only one solar cycle. An example of the correlation diagrams for the sunspot numbers and the Ap index is given in Fig. 4. The interrupted lines include points with confidence level 95%.

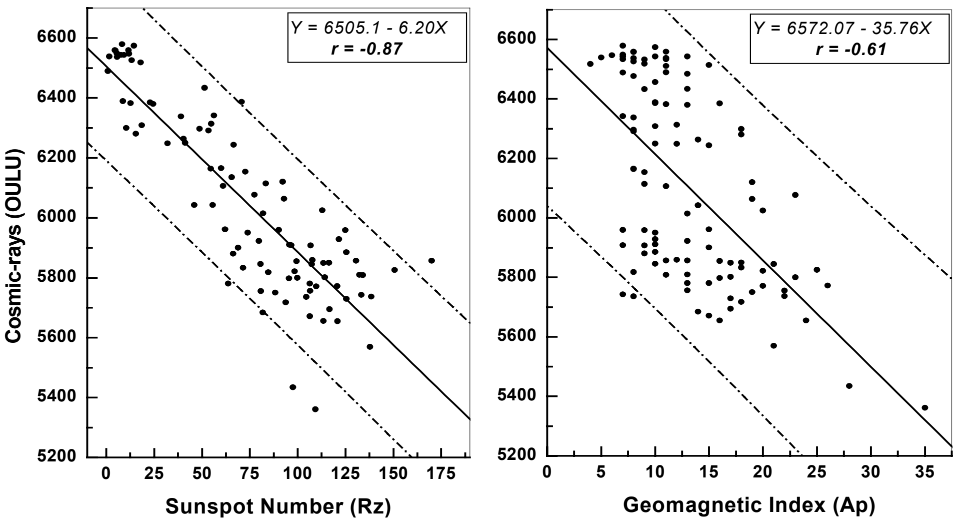


**FIGURE 4.** Cross-correlation coefficients between monthly cosmic-ray intensity and sunspot number Rz (left panel) and geomagnetic index Ap (right panel)

On the other hand, it is noteworthy that the sunspot number phase lag for the 23rd solar cycle is remarkably large (13.5 ± 0.6 months), whereas it was small in previous 20th and 22nd cycles (2 months and 4 months respectively) which are even cycles. This gives us more evidence that there is a distinction between even and odd solar cycles concerning the hysteresis phenomenon. To clarify this distinction, we present the time-lag of sunspot numbers with respect to cosmic-ray intensity for the last seven solar cycles in Table II.

TABLE II
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 (in months) | 9 | 1 | 10-11 | 2 | 16 | 4 | *14* |

This result for the first three solar cycles has been adapted from Nagashima and Morishita [9], while the hysteresis for the last three cycles has been computed for the purposes of a previous work [18]. Inspecting the whole set of results, we can clearly distinguish between even and odd solar cycles as far as the sunspot number time-lag in concerned. This is due to the 22-year variation in the time-lag already found [9],[24],[18]. Indeed particles reach the Earth more easily when their access route is by the heliospheric polar regions than when they gain access along the recurrent sheet. In this case, as the route of access becomes longer due to the waviness of the neutral sheet [25], the time lag is also longer as one would expect from theoretical considerations. This model can't explain, however, the double-maximum structure of the even cycles.

## EMPIRICAL MODULATION

An empirical model to describe the long-term cosmic-ray modulation during solar cycles 20, 21 and 22 was presented in previous works [8],[23],[25]. In the work [18], a generalized model applied over the three solar cycles mentioned before was proposed, as data are not available for earlier cycles. This model is derived by a generalization of Simpson's solar wind model using the diffusion-convection-drift model [5]. In this work we attempt to produce the monthly cosmic-ray intensity values as a function of solar and interplanetary indices for 23$^{rd}$ solar cycle. According to this, the modulated cosmic-ray intensity expressed by a constant *C* and the sum of some source functions appropriately selected from the solar and interplanetary indices that affect the cosmic-ray modulation. The empirical relation, used in the previous work, is given by the following expression:

$$I = C - 10^3 \times (a_1\, Rz + a_2\, Nf - a_3\, Ap) \qquad (2)$$

Where the constant *C* depends linearly on the cut-off rigidity of each station, Rz, Nf and Ap are the solar-terrestrial parameters incorporating the time-lag and i (i=1 to 3) are factors calculated by the RMS-minimization (5.1, 0.5 and 0.1 respectively).
In a previous work [23] found that the constant *C* is linearly correlated to the cut-off rigidity of each station, as:

$$C = 0.95 + 0.005 \cdot P \qquad (3)$$

where *P* is the cut-off rigidity for each station.

The observed and the calculated by the equation (2) values of the cosmic-ray intensity for Oulu Neutron Monitor station for 23rd solar cycle are presented in the upper panel of Fig. 5. The residuals are also indicated in the lower panel of the same figure. The standard deviation of this empirical modulation for the ascending and descending part of the cycle is about 12% that suggest a good approximation. It is noteworthy that this formula simulates fairly well the cosmic-ray intensity observed at the Earth during the onset and the declining phase of the solar cycles, whereas results are not satisfactory during the maximum phase of solar activity that is extreme long in this cycle. This is expected, because during the maximum phase of the cycle the solar magnetic polarity usually changes configuration. It is known that this change takes place over a period of several months. In our case the period from 1999.84 to 2001.99 years are characterized by magnetic field reversals according to [14]. Indeed, during this time interval the differences between observed and calculated values of the cosmic ray intensity seem to be high. It is also remarkable the fact that this solar cycle gave a lot of extra violent activity after the maximum of the cycle, so the need for better understanding leads to further improvements of this simulation. In the future this factor will be used for the improved empirical modulation.

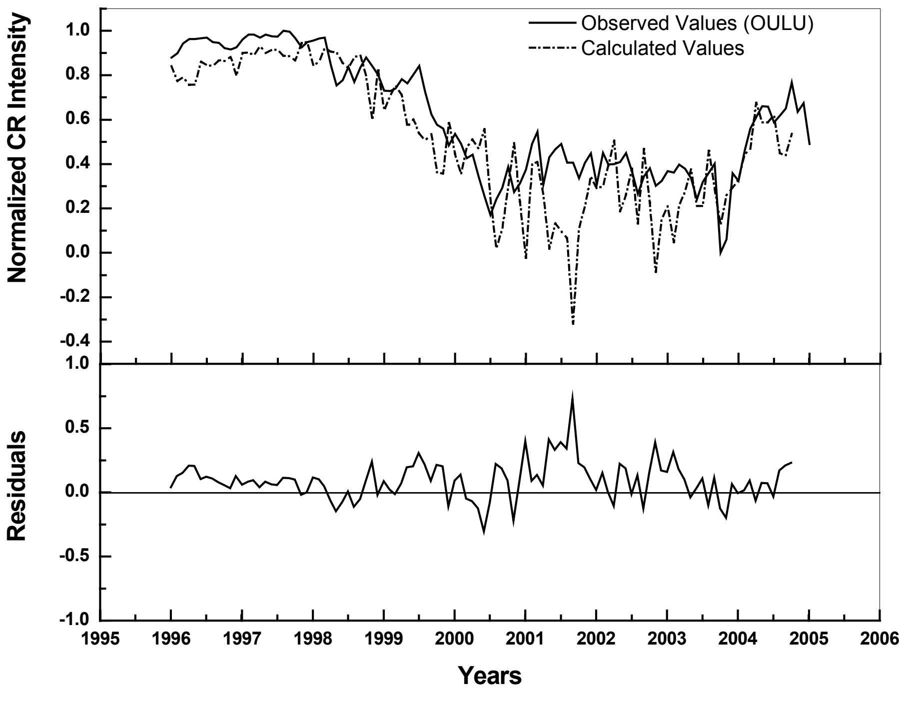


**FIGURE 5.** The observed and the calculated by the equation (2) values of the cosmic-ray intensity for Oulu Neutron Monitor station for 23rd solar cycle are presented (upper panel). The differences between these values are also depicted (lower panel)

## DISCUSSION

The cosmic-ray modulation depends upon various factors namely: the magnitude and direction of regular magnetic fields, the level of magnetic disturbances, the solar wind speed, the size and shape of the heliosphere. In a review paper [13], it was noted that the 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; the place of ground level observations in current studies of cosmic ray modulation and their future prospects.

In this work we have invoked the relation

$$I(t) = I - \int f(r)S(t-r)dr \quad (4)$$

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 index at a time *t-r* ($r \geq 0$) and *f(r)* is the characteristic function which expresses the time dependence of solar disturbances represented by *S(t-r)*.

The modulation of cosmic-ray intensity is described on a monthly basis empirically by the source function of Equation (4) which is an arbitrary linear combination of the three indices: the sunspot number *Rz*, the solar flares *Nf* and the geomagnetic index *Ap*. 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.

## CONCLUSIONS

From the above we can summarize the following:

It is noteworthy the fact that the $23^{rd}$ solar cycle, which is an odd cycle, has a remarkable large time lag as it was expected due to the magnetic cycle [18]. This cycle shows a time-lag phase of about 14 months for the solar and heliospheric parameters consistent with the characteristics of an odd cycle.

On the other hand, the empirical modulation showed that there are very good results for the ascending and descending part of the $23^{rd}$ cycle, but it is also obvious the need for further improvements for the period of the solar maximum. Studying better the connection between the solar activity, specially the violent activity of the sun and the cosmic-ray intensity, we expect that the use of the new index of coronal mass ejections will improve the attempted cosmic ray simulation throwing some more light to the unexplained yet mechanism of long term modulation[19],[27]. Theoretical and statistical analysis of this index and its key role to the cosmic-ray intensity modulation will be published elsewhere very soon. This is another characteristic of the fact of the violence of this solar cycle.

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## REFERENCES

1. Gnevyshev M.N., *Solar Phys.* **51**, 175 (1967)
2. Forbush, S.E., *J. Geophys. Res.* **63**, 651 (1958)
3. Pomerantz M. A. and Dugal S. R., Rev. Geophys. Space Phys. 12, 343 (1974)
4. Perko J. S. and Fisk L. A., J. Geophys. Res. 12, 343 (1983)
5. Nagashima K. and Morishita I., *Plan. Space Sci.* **28**, 117 (1980a)
6. Hatton G.J., *Solar Phys.* **66**, 159 (1980)
7. Chirkov N. P. and Kuzmin A.I , *Proc. 16th ICRC 4, 360* (1979)
8. Xanthakis J., Mavromichalaki H. and Petropoulos B., *Astrophys. Space Sci.* **74**, 303 (1981)
9. Nagashima K. and Morishita I., *Plan. Space Sci.* **28**, 177 (1980b)
10. Mavromichalaki H. and Petropoulos B., *Astrophys. Space Sci.,* **106**, 61 (1984)
11. Mavromichalaki H. and Petropoulos B., *Earth, Moon and Planets.* **37**, 79 (1987)
12. Lockwood J.A. and W.R. Webber, *J. Geophys. Res.* **83**, 17 (1984)
13. Belov A., *Space Science Reviews*, **93**, 79 (2000)
14. Lantos P., *Solar Physics*, **229**, 373 (2005)
15. Badhwar G. D. and O'Neil P. M., *Proc. 23rd ICRC* **3**, 535 (1993)
16. Eroshenko E., Belov A., Mavromichalaki H., Mariatos G., Oleneva V., Plainaki C., Yanke V., *Solar Physics*, **224**, 345 (2004)
17. Belov A., Baisultanova L., Eroshenko E., Mavromichalaki H., Yanke V, Pchelkin V, Plainaki C., Mariatos G., *J Geophys. Research-Space Physics* **110,** 9, A09S20, doi:10.1029/2005JA011067, 2005
18. Mavromichalaki H., Belehaki A. and Rafios X., *Astron. and Astrophys.* **330**, 764 (1998)
19. Cane H. V., *Space Science Reviews*, **93**, 55 (2000)
20. H. Mavromichalaki, E. Marmatsouri and A. Vassilaki, *Earth, Moon and Planets*, **42**, 233 (1988)
21. Mavromichalaki H., A. Belehaki, X. Rafios and I. Tsagouri, *Astrophysics and Space Science* **246**, 7 (1997)
22. Moraal H., *Space Sci. Rev.* **19**, 845 (1976)
23. Mavromichalaki H., Marmatsouri E. and Vassilaki A., *Solar Phys.* **125**, 409 (1990)
24. Otaola J., Perez-Enriquez R. and Valdes-Galicia J.F., *Proc. 19th ICRC (La Jolla)* 4**,** 93 (1985)
25. Kota J. and Jokipii J.R., *Geophys. Res. Let.* **8**, 1979 (1991)
26. Marmatsouri L., Vassilaki A. and Mavromichalaki H., *Adv. Space Res.* **16** (9), 245 (1995)
27. Mavromichalaki H., A. Papaioannou, A. Petrides, B. Assimakopoulos, C. Sarlanis and G. Souvatzoglou, *Modern Journal of Physics A*, **20**, 6714 (2005)