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Hysteresis Phenomenon: the Dimension of Modulation Region in Dependence of Cosmic Ray Energy

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Abstract

We continue our investigation of the CR-SA hysteresis phenomenon. On the basis of cosmic ray (CR) neutron monitor and muon detector data, as well as solar activity (SA) data for 4 solar cycles, the CR-SA hysteresis phenomenon is analyzed. In this paper we extended the period of the analyzed neutron monitor and muon telescope data. The obtained results show that by high rigidity CR particles it can be determined the effective dimension of modulation region in the Heliosphere (in dependence of particle rigidity), but not the distance of terminal shock wave from the Sun. High rigidity CR particles are not influenced out of modulation region till the terminal shock wave, but their global time variations contain important information on the CR diffusion coefficient distribution in the inner Heliosphere and on the connection with SA. The effective dimension of modulation region tend to decrease with increasing the CR rigidity.

1 Description of the Model:

In Dorman et al. (1999a) it was given a short historical introduction on investigations of CR-SA hysteresis phenomenon and it was described the model, with related references. Here we will use the same model of CR-SA hysteresis phenomenon described in detail in Dorman et al. (1999a). According to this model the expected value of the natural logarithm of CR intensity global modulation will be:

$$\ln\left(n\left(R,r_E,t\right)\right)_{\exp} = A - B\times\int_{X_E}^{X_o}\left(W\left(t-X\right)/W_{\max}\right)^{\frac{1}{3}+\frac{2}{3}\left(1-W\left(t-X\right)/W_{\max}\right)} X^{-\beta}dX\ , \quad (1)$$

where $X = r/u$, $X_E = 1AU/u$, $X_o = r_o/u$, $n\left(R,r_E,t\right)$ is the galactic CR density at the Earth's orbit, and A and B are constant values which can be determined by the comparison between $\ln\left(n\left(R,r_E,t\right)\right)_{\mathrm{obs}}$ and values of the integral in (1). r is the distance from the Sun, r_o the radius of modulation region, R the effective rigidity of detected CR particles, W the monthly sunspot number (or some other parameter of SA), and $W_{\max}$ the sunspot number in the maximum of SA. In (1), β is a parameter characterizing the dependence of CR diffusion coefficient on the distance from the Sun, as $D\left(R,r,t\right)\propto r^{\beta}$. In Dorman et al. (1997a, b) three variants of $\beta = 0;\ 0.5;\ 1$ have been considered; it was shown that the case $\beta = 1$ contradicts CR and SA observation data and that the case $\beta = 0$ is the most reliable. Therefore, we will consider here only the case $\beta = 0$. In Dorman et al. (1997a, b) we used monthly neutron monitor data. These data contain short-time variations (as Forbush-decreases and other events) caused by interplanetary shock waves and magnetic clouds from coronal ejection with very small CR-SA time-lag (few days); this is especially important for periods of high solar activity. Differently from Dorman et al. (1997a, b) we will use here also smoothed neutron monitor data obtained by 5-month moving averages (in this case the contribution of CR short-time variations with very small time-lag will be sufficiently reduced).

2 Results for Total Period of Observations by Climax and Huancayo/Haleakala Neutron Monitors and Huancayo Ionization Chamber:

By the correlation between the logarithm of observation data $\ln(n(R, r_E, t))_{\text{obs}}$ in the time interval $t_1 \le t \le t_2$ and the integral in (1)

$$F\left(t, \beta, X_o, W(t-X)\Big|_{X_E}^{X_o}\right) = \int_{X_E}^{X_o} (W(t-X)/W_{\max})^{\frac{1}{3}+\frac{2}{3}(1-W(t-X)/W_{\max})} X^{-\beta} dX \quad (2)$$

(which depends on t, on parameters β and $X_o = r_o/u$, and on the time distribution of SA in the interval from $t - X_o$ to $t - X_E$) it is possible to determine the correlation coefficient $\rho(X_o, \beta, t_1, t_2)$ as a function of X_o. In Figure 1 we show the dependencies of $\rho(X_o, \beta, t_1, t_2)$ on $X_o = r_o/u$ (in the interval $1 \le X_o \le 36$, where X_o is in units of the average month (365.25/12) days=2.628×10^6 s for $\beta = 0$ obtained for observations by Climax (USA, Colorado, N39, W106, H=3400 m, $R_c = 2.99\,GV$) neutron monitor for the period January 1953-February 1998 (monthly data and 5-month moving averages, Huancayo (Peru, S12,

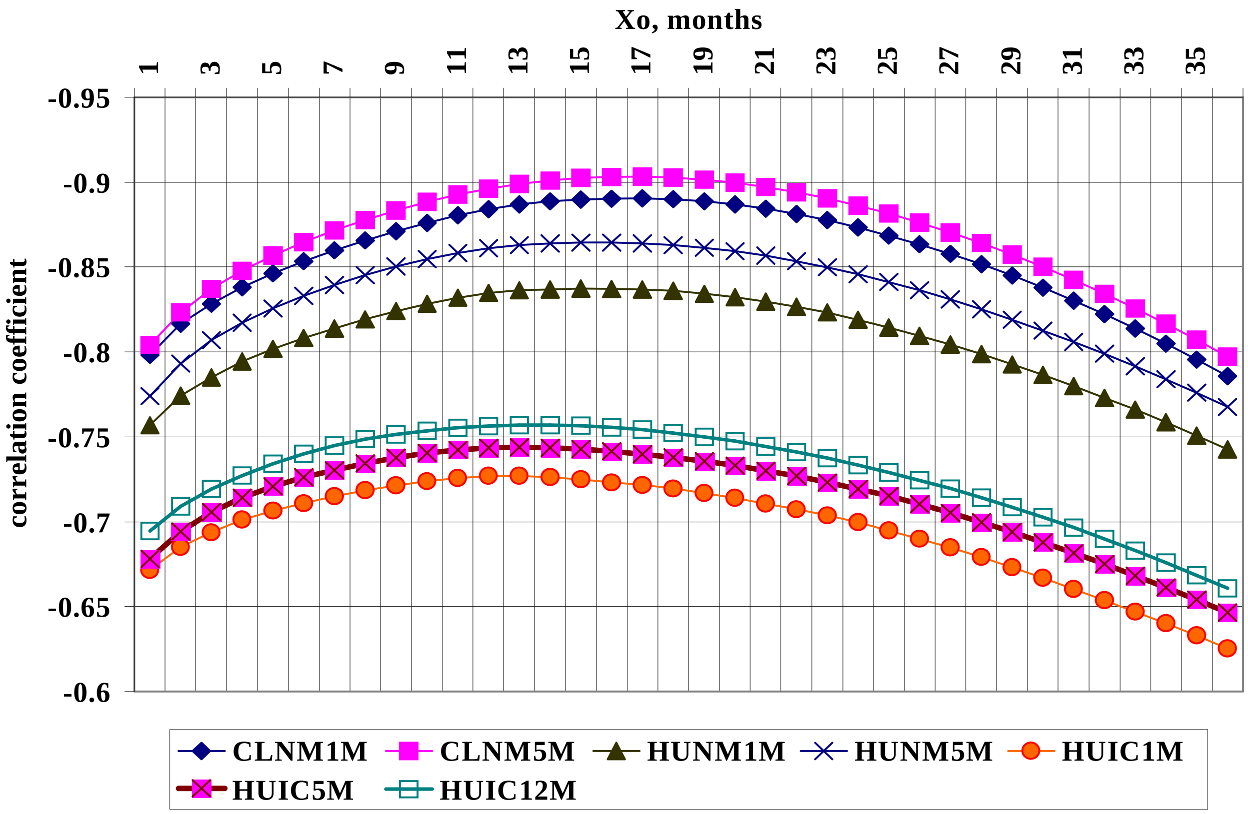

Figure 1: Dependencies of correlation coefficient $\rho(X_o, \beta, t_1, t_2)$ on $X_o = r_o/u$ for $\beta = 0$, obtained for observations by Climax neutron monitor for the period January 1953-February 1998, monthly data (curve CLNM1M) and 5-month moving averages (curve CLNM5M); Huancayo/Haleakala neutron monitor for the period January 1953-February 1999, monthly data (curve HUNM1M) and 5-month moving averages (curve HUNM5M); Huancayo ionization chamber for the period January 1953-July 1989, monthly data (curve HUIC1M) and 5-, 12-month moving averages (curves HUIC5M and HUIC12M).

W75, $R_c = 12.92\,GV$, $H = 3400m$)/Haleakala (Hawaii, N20, W156, $R_c = 12.91\,GV$, $H = 3030\,m$) neutron monitor for the period January 1953-February 1999 (monthly data and moving 5-month averages) and Huancayo ionization chamber for the period January 1953–July 1989 (monthly data and moving 5- and 12-month averages). From Figure 1 it can be seen that with increasing the effective primary particle rigidities (detected by Climax NM, Huancayo/Haleakala NM and Huancayo IC) the maximum of curves move to smaller X_o.

3 Estimation of the Effective Dimension of Modulation Region:

From curves of Figure 1 it is possible to estimate the radius of modulation region $r_{\mathrm{mod}} = u \times X_o^{\max}$, where $X_o^{\max}$ is the position in which $\rho(X_o, \beta, t_1, t_2)$ reaches the maximum value. To determine $X_o^{\max}$ more exactly, we approximated the dependence of $\rho\left(X_o^{\max}, \beta, t_1, t_2\right)$ on X_o in the vicinity of $X_o^{\max}$ by a parabolic functions $\rho = aX_o^2 + bX_o + c$, so that $d\rho/dX_o = 2aX_o + b$, and $X_o^{\max} = -b/2a$. For example, for CLNM1M we approximated $\rho(X_o, \beta, t_1, t_2)$ by $\rho = 0.000307X_o^2 - 0.010163X_o - 0.806368$ with correlation coefficient 0.9986, so that $X_o^{\max} = 16.55 \pm 0.44$. For CLNM5M the obtained result is much more precise: the approximation was done with correlation coefficient 0.99993 and $X_o^{\max} = 16.64 \pm 0.09$. From the last result it follows that the radius of modulation region $r_{\mathrm{mod}} = u \times X_o^{\max} = 128.67 \pm 0.74\,AU$ (according to direct measurements on space probes the average solar wind speed for the period 1965-1990 was $u = 4.41 \times 10^7\ cm/s$, so that one average month corresponds to 7.73 *AU*). Results of determination of $X_o^{\max}$ and r_{mod} are summarized in Table 1.

Table1: Results of determination of $X_o^{\max}$ (in units of average month) and r_{mod} (in *AU*)

VALUES	CLNM1M	CLNM5M	HUNM1M	HUNM5M	HUIC1M	HUIC5M	HUIC12M
$X_o^{\max}$	16.5±0.4	16.65±0.09	15.40±0.98	15.55±0.46	12.8±1.2	13.3±0.7	13.6±0.1
r_{mod}	127.9±3.4	128.7±0.7	119.1±7.6	120.2±3.6	99.1±9.3	102.5±5.6	105.4±0.9

4 Cosmic Ray Intensity out of the Modulation Region and Effective Cosmic Ray Propagation Parameters:

The physical meaning of regression coefficients *A* and *B* in (1) is the following:

$$A = \ln(n_o(R)) \quad (3)$$

is the galactic CR density (or intensity) out of the modulation region, and

$$B = au^2/D_{\max}(R), \quad (4)$$

where constant $a \approx 1.5$, and $D_{\max}(R)$ is the effective diffusion coefficient for particles with rigidity *R* in the maximum of SA. Therefore, the determination of parameters *A* and *B* makes it possible to estimate the CR intensity out of the modulation region and the effective diffusion coefficient in dependence of effective particle rigidity *R*.. The use of monthly data allows us to determine regression coefficients *A* and *B* only for integer values of X_o. Therefore, for example, for CLNM1M we determine *A* and *B* for X_o=16 (*A*=8.370209, *B*=-0.01380) and for X_o=17 (*A*=8.370600, *B*=-0.012456), and then by interpolation for

X_o^{max} =16.5±0.4: A=8.370424±0.000172, B=-0.01304±0.00059. Results are shown in Table 2.

Table 2: Regression coefficients A (logarithm of intensity out of the modulation region) and B (proportional to solar wind speed to the square and inversely proportional to diffusion coefficient in the maximum of SA) in (1), corresponding to X_o^{max} and r_{mod} given in Table 1.

OBSERVATIONS	COEFFICIENT *A*	COEFFICIENT *B*
CLNM1M	8.370424±0.000172	-0.01304±0.00059
CLNM5M	8.369976±0.000036	-0.012654±0.000069
HUNM1M	7.467043±0.000080	-0.003617±0.000214
HUNM5M	7.466939±0.000039	-0.003528±0.000100
HUIC1M	7.474099±0.000098	-0.004160±0.000386
HUIC5M	7.474211±0.000036	-0.004010±0.000202
HUIC12M	7.474038±0.000006	0.003830±0.000030

5 Conclusions:

- Our findings given in Figure 1, Table 1 and Table 2 show that the use of 5-month moving averages for neutron monitor data do not change the main results, but do increase their precision; there is a tendency of slightly increasing X_o^{max} with increasing the period of averaging the data, particularly for ionization chambers;
- The data averaging procedure is particularly important for ionization chambers; especially when 12-month moving averages are used to eliminate seasonal variations caused by temperature effect;
- There is a clear tendency of decreasing the dimension of modulation region r_{mod} with increasing the CR effective rigidity: 128.7±0.7, 120.2±3.6, 102.5±5.6 for 5-month averages of Climax NM, Huancayo NM and Huancayo Ionization chamber respectively;
- There is clear indication of increasing the effective diffusion coefficient with increasing the CR effective rigidity (see coefficient *B* in Table 2 and (4));
- The considered model gives the possibility to estimate CR intensity out of the modulation region and the residual modulation in dependence of effective particle rigidity (see coefficient *A* in Table 2 and (3)).

References

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