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# Hysteresis Phenomenon in Long-Term Cosmic Ray-Solar Activity Connection and Cosmic Ray Modulation in the Last 250 Years

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**Abstract**

In this paper we continue to investigate the hysteresis phenomenon in the connection between cosmic rays and solar activity. We use cosmic ray neutron monitor monthly data, as well as solar activity monthly data for the last 4 solar cycles (1953-1997). On the basis of low rigidity cosmic ray data we estimate the average (for these 4 solar cycles) dimension of the Heliosphere and cosmic ray propagation parameters. Then, by using the available solar activity data in the past (including the period of Maunder solar activity minimum), we obtain information on the time variations of solar wind properties and cosmic ray modulation for the last 250 years.

## 1 Introduction:

The investigation of the hysteresis phenomenon, caused by the large dimension of the modulation region, between long-term variation of cosmic ray (CR) intensity observed at the Earth and solar activity (SA) cycle, started about 40 years ago (Forbush, 1958; Neher, 1962; Neher & Anderson, 1962; Simpson, 1963). In Dorman & Dorman (1965, 1967a,b,c,d, 1968) the hysteresis phenomenon was analyzed on the basis of neutron monitor data for about one solar cycle in the frame of convection-diffusion model of CR global modulation in the Heliosphere; it was shown that the dimension of the Heliosphere cannot be smaller than 50 AU and greater than 200-300 AU. This result is in good agreement with modern information on the possible position of terminal shock wave bounding the Heliosphere. Investigations of comic ray/solar activity hysteresis phenomena continued in Dorman et al. (1997a,b,c,d) on the basis of data for about 4 solar cycles. In Dorman et al. (1997a,b,c,d) we used monthly neutron monitor data. These data contain a great number of short-time variations (as Forbush decreases and other events) caused by interplanetary shock waves and magnetic clouds from coronal ejection with very small time-lag (few days); this is especially important during periods of high solar activity.

Differently from Dorman et al. (1997a,b,c,d), we will use here smoothed neutron monitor data obtained by 5-month moving averages (in this case CR short-time variations with very small time-lag will be sufficiently reduced). In Dorman et al. (1997a,b) it was also shown that data of Huancayo neutron monitor (sensitive to primary CR with effective rigidity $\approx 46\,GV$) reflect the situation in the modulation region which is smaller than Heliosphere. Therefore, we will use here Climax neutron monitor data (sensitive to primary CR with effective rigidity $\approx 10\,GV$) which reflect the situation in about all Heliosphere. We will consider data for the total period 1953-1997 of CR intensity registration by neutron monitors. We use parameters of CR modulation, obtained by means of monthly data of sunspot numbers, to reconstruct the expected CR intensity after 1750. The obtained results can be useful in investigations on cosmogenic nuclides, as well as on CR solar cycle variations in the past.

## 2 On the Model of CR/SA Hysteresis Phenomenon:

It was shown in Dorman & Dorman (1965) that the time of propagation through the Heliosphere of particles with rigidity higher than 10 GeV (to which the neutron monitors are sensitive) is not more than one month. This time is about one order of magnitude smaller than the observed time lag in the hysteresis phenomenon. It means that the analysis of hysteresis phenomenon on the basis of neutron monitor data (and *a fortiori* of muon telescope data) could be done in the frame of quasi-stationary problem with parameters of CR propagation changing with time, insted of in the frame of non-stationary Fokker-Plank equation, but. In this case

$$n(R,r,t)/n_o(R) \approx \exp\left(-a\int_r^{r_o}\frac{u(r,t)dr}{D(R,r,t)}\right), \quad (1)$$

where $n(R,r,t)$ is the differential rigidity CR density, $n_o(R)$ is the differential rigidity density spectrum in the local interstellar medium out of the Heliosphere; parameter $a \approx 1.5$; $u(r,t)$ is the effective velocity of solar wind (by taking into account also shock waves and high speed solar wind streams) and $D(R,r,t)$ is the diffusion coefficient of particles with rigidity $R$ at the time $t$ in dependence of the distance $r$ from the Sun. According to Dorman (1975), the relation

$$D(R,r,t) \propto (W(t-r/u))^{-\alpha}, \quad (2)$$

can describe the connection between $D(R,r,t)$ and $W(t-r/u)$, where $W(t-r/u)$ is the sunspot number at the time $t-r/u$. From comparison with observation data it was determined by Dorman & Dorman (1967a,b,c,d, 1968) the parameter $\alpha \approx 1/3$ in the period of high solar activity and $\alpha \approx 1$ near solar minimum. Here we suppose that

$$\alpha = 1/3 + (2/3)(1 - W/W_{max}), \quad (3)$$

where $W_{max}$ is the sunspot number in the maximum of solar activity cycle. We suppose also that

$$D(R,r,t) \propto r^{\beta}, \quad (4)$$

where $\beta$ is expected to range in the interval $0 \le \beta \le 1$.

According to (1) the expected value of the natural logarithm of CR intensity global modulation, by taking into account (2)-(4), will be

$$(\ln(n(R,r_E,t)))_{exp} = A - B\times\int_{X_E}^{X_o}(W(t-X)/W_{max})^{\frac{1}{3}+\frac{2}{3}(1-W(t-X)/W_{max})} X^{-\beta}dX, \quad (5)$$

where $X = r/u$, $X_E = 1AU/u$, $X_o = r_o/u$, and $A$ and $B$ are some constants that can be determined from comparison of $(\ln(n(R,r_E,t)))_{obs}$ with values of integral in (5). In Dorman et al. (1997a,b) three variants of $\beta = 0;\ 0.5;\ 1$ have been considered; it was shown that variant $\beta = 1$ contradicts CR and SA observation data and that the variant $\beta = 0$ is the most reliable. Therefore, we will consider here only the case $\beta = 0$.

## 3 Results for the Period 1953-1997:

To determine $X_o = r_o/u$ we compare the behavior of 5-month moving average data of Climax neutron monitor (USA, Colorado, N39, W106, *H*=3400 m, $R_c = 2.99\,GV$) from January 1953 to February 1998, with the expected one, according to (5). For each $X_o = r_o/u$ =1, 2, 3, ……50 months we analysed the correlation between observed and expected CR intensities. The dependence of correlation coefficient $\rho$ on $X_o = r_o/u$ is shown in Figure 1.

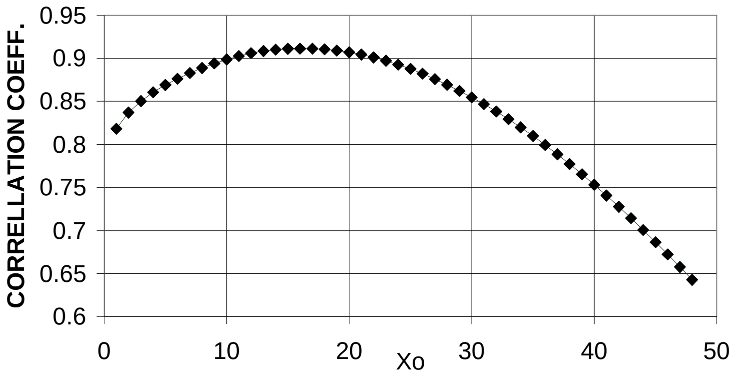


**Figure 1:** The dependence of $\rho$ on $X_o = r_o/u$ ($X_o$ is in units of the average month (365.25/12) days = $2.628\times10^6$ s).

From Figure 1 it can be seen that the maximum of $\rho$ is between $X_o = 10$ and $X_o = 24$. The dependence $\rho(X_o)$ in this interval can be approximated as

$$\rho(X_o) = -0.0003142 X_o^2 + 0.01022 X_o + 0.82834 \quad (6)$$

with correlation coefficient 0.99969. From (6) it follows

$$\rho_{\max} = 0.9114 \text{ at } X_{o\max} = 16.26. \quad (7)$$

Result (7) shows that, for the period 1953-1997 (about 4 solar cycles), the average radius of the Heliosphere is expected to be $r_o \approx 126 AU$ (according to direct measurements on space probes the average solar wind speed for the period 1965-1990 was $u = 4.41\times10^7\, cm/s$, so that one average month corresponds to 7.73 *AU*). For determining the expected CR intensity we will use the value of $X_o = 16$, nearest to $X_{o\max}$. In this case the obtained correlation coefficient $\rho$ and coefficients *A* and *B* in (5) for the period 1953-1997 are:

$$\rho = 0.911,\ A = 8.3744,\ B = 0.2126. \quad (8)$$

According to (5) and (8) the expected CR intensity out of the Heliosphere corresponds to

$$\left(\ln\left(n\left(R, r_E, t\right)\right)\right)_{\text{out}} = A = 8.3744, \quad (9)$$

which is a little bigger than the expected and observed ones in minimums of solar activity (residual modulation). We will use the obtained results for determining the expected CR intensity in the past.

## 4 Expected Cosmic Ray Intensity Global Modulation in 1750-1970 and Comparison with Observations in 1953-1970:

To determine the expected CR intensity global modulation in 1750-1970, we will use data of monthly sunspot numbers from WDC-A (starting from January 1749) and take into account the hysteresis phenomenon caused by time lag of processes in the Heliosphere, responsible for CR modulation, relative to the corresponding processes on the Sun. For calculating (5) we will use $X_o = 16$ and coefficients given in (8), which have been determined in Section 3 as average for about 4 solar cycles. Results are shown in Figure 2. From this Figure it can be seen that the expected ln(Climax NM intensity) and observed in 1953-1970 are in such good coincidence to make us confident that the expected ln(Climax NM intensity) according to the model (5) is well describing the real situation in the period 1750-1953. It can be seen that the depths of CR modulation in maximums of SA are very different. The maximums of CR intensity near SA minimums are not equal, the difference can reach few percents (the residual modulation changed from one minimum to another). The period of modulation is mostly 10-11 years, but during 1790-1830 it was remarkably increasing. Figure 2 gives information on the CR intensity long-term variations in the past (approximately for CR primary particles with rigidity $R \approx 10 \div 20\,GV$ ) and can be useful for investigations on CR solar cycle modulation in the past and for researches on cosmogenic nuclides.

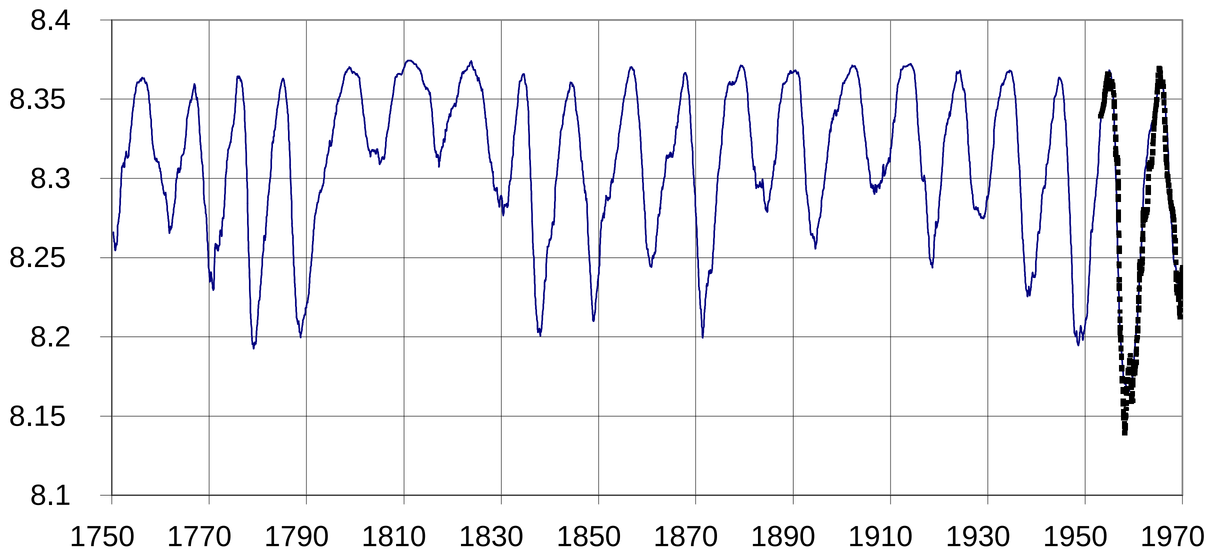


**Figure 2:** Expected ln(Climax NM intensity) in 1750-1970 (full line) and observed in 1953-1970 (dotted line). The distance between two horizontal lines corresponds to 5%.

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