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On the Relative Role of Drift and Convection-Diffusion Effects in the Long-Term CR Variations on the Basis of NM and Satellite Data

LEV DORMAN[1, 2],
[1]*Israel Cosmic Ray and Space Weather Center, Tel Aviv University, Israel*
[2]*Cosmic Ray Department of IZMIRAN, Russian Academy of Science, Russia*
lid@physics.technion.ac.il

Abstract: In the first part of paper on the basis of NM data for about 4 solar cycles we investigate hysteresis effects, and separate convection-diffusion and drift modulations in the suggestion that for NM data primary CR energies the diffusion time lag may be neglected. Then we determine the relative role of drift and convection-diffusion effects in the long-term CR variations. In the second part we solve the same problem but for small energy galactic CR on the basis of satellite data; in this case we take into account also the diffusion time lag.

Introduction

The hysteresis phenomenon was investigated In [1-3] on the basis of neutron monitor (NM) data for about one solar cycle in the frame of convection-diffusion model of CR global modulation in the Heliosphere with taking into account time lag of processes in the interplanetary space relative to processes on the Sun. It was shown that the dimension of the modulation region should be about 100 AU (much bigger than supposed in those times in literature, 5–15 AU). Let us note that many authors worked on this problem, used sunspot numbers or other parameters of solar activity for investigations of CR long-term variations, but they did not take into account time lag of processes in the interplanetary space relative to processes on the Sun as integral action (see review in [4]). CR and SA data were considered again by this method for solar cycles 19-22 in [5], but with taking into account also drift effects according to [6]. It was shown that including in the consideration drift effects (as depending from the sign of solar polar magnetic field with amplitude depending on tilt angle between IMF neutral current sheet and equatorial plane) explains the big difference in time-lags between CR and SA in hysteresis phenomenon for even and odd solar cycles. The main aim of this paper is to determine the relative role of drift and convection-diffusion mechanisms in formation of long-term CR variations in dependence of effective cutoff rigidity on the basis of ground-based and satellite data.

Hysteresis phenomenon and the model of CR global modulation in the frame of convection-diffusion mechanism

The time of CR diffusion propagation through the Heliosphere of particles with rigidity about 10 GV (to which NM are sensitive) is not longer than one month [1]. This time is at least about one order smaller than the observed time-lag in the hysteresis phenomenon. It means that the hysteresis phenomenon on the basis of NM data can be considered as quasi-stationary problem:

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

where $n(R,r_{obs},t)$ is the differential rigidity CR density, $n_o(R)$ is the differential rigidity density spectrum in the local interstellar medium out of the Heliosphere, $a \approx 1.5$, $u(r,t)$ is the effective solar wind velocity, and $\kappa_r(R,r,t)$ is the radial diffusion coefficient. According to [2, 3] the connection between $\kappa_r(R,r,t)$ and solar activity can be described by the relation

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

where

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

and $W_{\max}$ is the sunspot number in the maximum of solar activity cycle. According to Eqs 1-3

$$\ln(n(R, r_{obs}, t)) = A(R, X_o) - B(R, X_o)F, \qquad (4)$$

where

$$F = \int_{X_{obs}}^{X_o} \left(\frac{W(t-X)}{W_{\max}} \right)^{\frac{1}{3}+\frac{2}{3}(1-W(t-X)/W_{\max})} dX, \qquad (5)$$

and $X = r/u$, $X_{obs} = r_{obs}/u$, $X_o = r_o/u$ (X_{obs} and X_o are in units of average month = (365.25/12) days = 2.628×10^6 sec). A regression coefficient $A(R, X_o)$ determines the CR intensity out of the Heliosphere at $r_{obs} = r_o$, i.e. $A(R, X_o) =$ $\ln(n(R, r_o)) = \ln(n_o(R))$; $B(R, X_o)$ characterizes the effective diffusion coefficient of CR in the interplanetary space, and $X_o = r_o/u$ characterizes the dimension of modulation region.

Even-odd cycle effect in CR and role of drifts for NM energies

For drift effects we use results of [6], and assume that the drift effect has negative sign at A > 0 and positive sign at A < 0, and in the period of reversal we suppose linear transition through 0 from one polarity cycle to other. To determine $X_{o\max}$, corresponding to the maximum value of the correlation coefficient for regression Eq. 4, we used 11 months moving averages of the Climax and Huancayo/Haleakala NM data from January 1953 to August 2000 [5]. In Fig. 1 the dependences of $X_{o\max}$ on A_{dr} are shown for Climax NM.

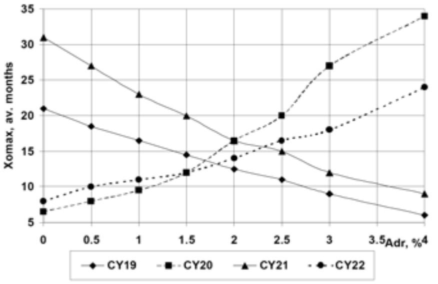

Figure 1: Dependences $X_{o\max}$ on A_{dr} (Climax)

From Fig. 1 can be seen that the region of crossings of $X_{o\max}(A_{dr})$ for odd and even cycles is: $13 \le X_{o\max} \le 16.5$, $1.7\% \le A_{dr} \le 2.3\%$. For Huancayo/Haleakala NM this region is: $13 \le X_{o\max} \le 18$, $0.23\% \le A_{dr} \le 0.43\%$. It means that for primary CR with rigidity 10-15 GV a relative contribution of drift effects is about 20-25%. For CR with rigidity 35-40 GV a relative role of drift effects is about 2-3 times smaller. For $X_{o\max}$ we obtained for both 10-15 and 35-40 GV about 15 av. months, what corresponds $r_o \approx 100$ AU (at solar wind speed 400 km/s).

Results for solar cycle 22 (NM data)

The dependencies of correlation coefficient (CC) from X_o and A_{dr} are shown in Fig. 2 for Climax NM.

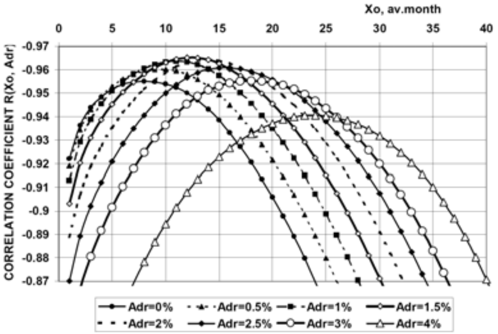

Figure 2: Results for SC 22 (Climax NM).

On the basis of these data we determine that the maximum correlation coefficient (about 0.965) is for $A_{dr\max} = 1.54 \pm 0.04\%$. By the same method for Kiel NM (sea level; $R_c = 2.32$ GV) we find $A_{dr\max} = 1.32 \pm 0.04\%$, for Tyan-Shan NM (altitude 3.34 km, $R_c = 6.72$ GV) $A_{dr\max} = 0.634 \pm 0.012\%$, for Huancayo NM (3.4 km, $R_c = 12.92$ GV)/Haleakala NM (3.03 km, $R_c = 12.91$ GV) $A_{dr\max} = 0.133 \pm 0.002\%$

Diffusion time lag

For small energy particles measured on satellites and balloons, it is necessary to take into account the additional time-lag $T_{dif}(R, r_{obs}, r, t)$ caused by the particle diffusion through the Heliosphere from r to r_{obs}. This diffusion time-lag can be approximately estimated as (on the basis of Eq. 1)

$$T_{dif} \approx \frac{(r-r_{obs})^2}{6\kappa_{r,ef}(t)} \approx \frac{C(R,t)(X-X_{obs})^2}{X_o - X_{obs}}, \quad (6)$$

where

$$C(R,t) = -\ln[n_{obs}(R,r_{obs},t)/n_o(R)]/6a. \quad (7)$$

On the basis of [6] we estimate $C(R,t)$ for small rigidities, observed on satellites. Results are shown in Table 1.

Table 1: Coefficient $C(R,t)$ for different rigidities, for periods of maximum and minimum SA

particle rigidity and kinetic energy	solar activity	
	MAX	MIN
3 GV (protons, 2.2 GeV)	0.107	0.067
1.0 GV (protons, 430 MeV)	0.30	0.20
0.3 GV (protons, 43 MeV)	0.55	0.41

The dependences of $C(R,T)$ from tilt angle T are shown in Fig. 3.

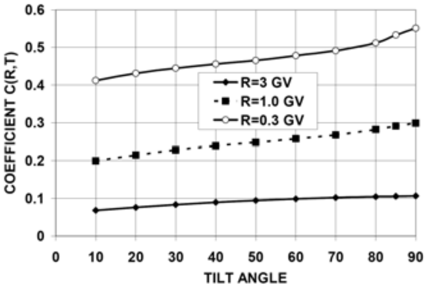

Figure 3: $C(R,T)$ as function of tilt angle T

Let us note that for NM (effective rigidity 10-15 GV) we obtain for solar maximum and minimum $C(R,t)\approx 0.028$ and 0.018, correspondingly; this means that for NM diffusion time lag is negligible in comparison with time of solar wind traveling to the boundary of modulation region X_o.

Convection-diffusion and drift modulations for small energy galactic CR

As a first approximation we based again on the quasi-stationary model of convection-diffusion modulation described by Eqs 1 – 5, only instead of X should be used

$$X^* = X + T_{dif}, \quad (8)$$

where T_{dif} is determined by Eq. 6. For the drift modulation we use results [6] for its dependence from tilt angle T for different R. The relative role of convection-diffusion and drift modulations we determine by comparison with satellite long-term variation data of protons and α-particles

The satellite proton data and their corrections on solar CR increases and jump in December 1995

We analyze the following data: IMP-8 monthly data of proton fluxes with kinetic energy $E_k \geq 106$ MeV ($R \geq 0.458$ GV) from October 1973 to December 1999 and GOES daily data of proton fluxes from January 1986 to December 1999 with kinetic energies $E_k \geq 100$, ≥ 60, ≥ 30, ≥10, ≥ 5 MeV, as well as fluxes in intervals 60-100, 30-60, 10-30, and 5-10 MeV.

The first problem is that the original GOES data contain many increases caused by SEP events. To exclude these days we sorted daily data for each month and determined the averages from ten minimal daily values. Then, we determined 11-months moving averages. The second problem is that the original GOES data contain a jump in December 1995. To exclude this jump we compared GOES data for $E_k \geq 100$ MeV with IMP-8 monthly data for $E_k \geq 106$ MeV. As an example, in Fig. 4 the corrected data of IMP-8 data are shown.

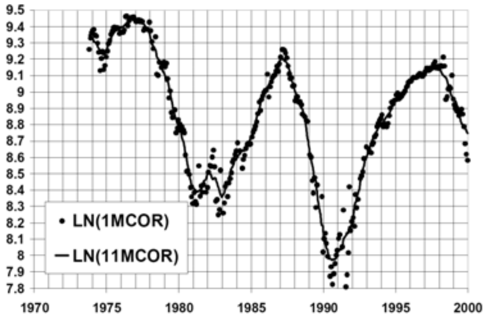

Figure 4: Natural logarithm of monthly and 11-month moving averages IMP-8 data of corrected proton intensities with energy $E_k \geq 106$ MeV.

CC in dependence of X_0 and A_{dr}

In Fig. 5 we show dependences of correlation coefficient (CC) between natural logarithm of 11-month moving averages IMP-8 data of proton intensities (see Fig. 4) corrected for drift effects with different amplitudes, with the value expected from convection-diffusion mechanism by taking into account the diffusion time-lag (Eq. 5 with X* according to Eq. 8).

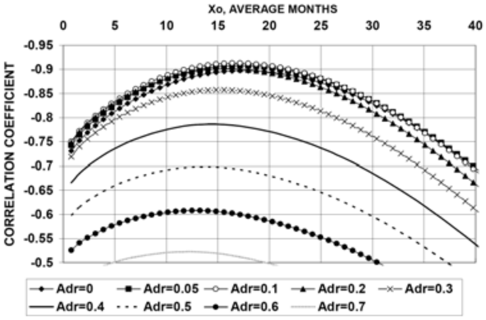

Figure 5: CC for 11-month moving averages of IMP-8 proton data from October 1973 to December 1999, corrected for drift modulation with different amplitudes A_{dr} from 0 to 0.7.

From Fig. 5 can be seen that CC reaches the greatest values for $A_{dr} \approx 0.1$ (i.e. 10%) with maximum value 0.913 at $X_{o\max} \approx 17$ av. months.

Results for satellite α-particle data

We used 5-minute GOES data of small energy α-particle fluxes from January 1986 to May 2000 in energy intervals 60-160, 160-260, and 330-500 MeV. Corrected variations of 330-500 Mev α-particle fluxes are shown in Fig. 6, and for CC –in Fig. 7.

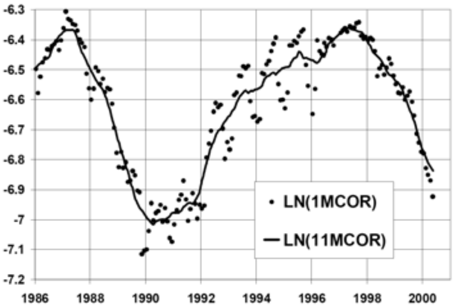

Figure 6: Natural logarithm of monthly LN(1MCOR) and 11-month moving averages LN(11MCOR) of corrected GOES data.

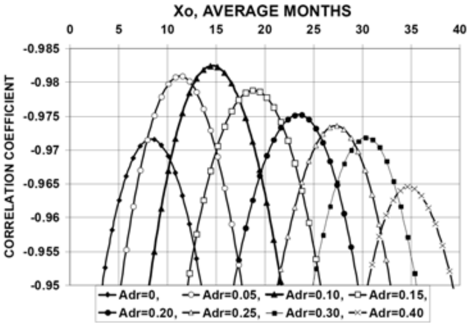

Figure 7: Results for CC for different A_{dr} in dependence of X_o for 330-500 MeV α-particle fluxes during January 1986 - May 2000 (on the basis of GOES data).

Conclusion

For 35-40 GV (equatorial NM) convection-diffusion mechanism gives about 90%, and drift mechanism about 10% in long-term CR variations. For 10-15 GV (middle latitude NM) we obtained 75 and 25%, and for 1-3 GV (satellite proton and α-particle data) – about 50 and 50%.

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