29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

# Long-term cosmic ray intensity variation in near future and prediction of their contribution in expected global climate change

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On the basis of results obtained in our papers on hysteresis effects we determine the dimension of Heliosphere (modulation region), radial diffusion coefficient and other parameters of convection-diffusion and drift mechanisms of cosmic ray (CR) long term variation in dependence of particles energy, level of solar activity (SA) and direction of general solar magnetic field. By using these results and published regularly elsewhere predictions of expected SA variation in near future we may made prediction of expected in near future long-term CR intensity variation. From other hand, we use published in literature estimated properties of connection between CR intensity long-term variation and some part of global climate change, controlled by solar activity through CR. We show that by this way is possible to made prediction of expected in near future some part of global climate change, controlled by SA through CR.

## 1. Hysteresis phenomenon and model of CR convection-diffusion modulation

It was shown in [1] that the time of propagation through the Heliosphere of particles with rigidity > 10 GV (to whom NM are sensitive) is no longer than one month. This time is at least about one order of magnitude smaller than the observed time-lag in the hysteresis phenomenon. This means that the hysteresis phenomenon on the basis of NM data can be considered as a quasi-stationary problem with parameters of CR propagation changing in time. In this case [2]

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

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; $a \approx 1.5$; $u(r,t)$ is the effective solar wind velocity (taking into account also shock waves and high speed solar wind streams); and $D_r(R,r,t)$ is the effective radial diffusion coefficient in dependence of the distance *r* from the Sun of particles with rigidity *R* at the time *t*. According to [3, 4] the connection between $D_r(R,r,t)$ and SA can be described by the relation

$$D_r(R,r,t) \propto r^{\beta}\left(W(t-r/u)\right)^{-\alpha}, \qquad (2)$$

where $W(t-r/u)$ is the sunspot number in the time $t-r/u$. By the comparison with observation data it was determined in [3, 4] that parameter $0 \le \beta \le 1$ and $\alpha \approx 1/3$ in the period of high SA $(W(t) \approx W_{\max})$ and $\alpha \approx 1$ near solar minimum $(W(t) << W_{\max})$. Here we suppose, in accordance with [5], that

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

where $W_{\max}$ is the sunspot number in the maximum of solar activity cycle.

According to Eq. (1) the expected value of the natural logarithm of CR intensity global modulation at the Earth's orbit, taking into account Eq. (2) and Eq. (3), will be

$$\ln\left(n(R,X_o,\beta,r_E,t)_{\exp}\right) = A - B \times F\left(t, X_o, \beta, W(t-X)\Big|_{X_E}^{X_o}\right), \qquad (4)$$

where

$$F\left(t, X_o, \beta, W(t-X)\Big|_{X_E}^{X_o}\right) = \int_{X_E}^{X_o} \left(W(t-X)/W_{\max}\right)^{\frac{1}{3}+\frac{2}{3}\left(1-W(t-X)/W_{\max}\right)} X^{-\beta} dX \,, \quad (5)$$

$X = r/u$ , $X_E = 1AU/u$, $X_o = r_o/u$ , and $n(R, X_o, \beta, r_E, t)_{\exp}$ is the expected galactic CR density at the Earth's orbit in dependence of the values of parameters $X_o$ and β. Regression coefficients *A* and *B* can be determined by correlation between observed values $\ln(n(R, r_E, t))_{\text{obs}}$ and the values of *F*, calculated according to Eq. (5). In [6] three values of β = 0, 0.5, and 1 have been considered; it was shown that β = 1 strongly contradicts CR and SA observation data, and that β = 0 is the most reliable value. Therefore, we will consider here only this value.

## 2. Dimension of the modulation region near solar minimum 1994-1996

We used monthly data of sunspot numbers and Climax NM data (USA, Colorado, N39, W106, *H* = 3400 m, $R_c$ = 2.99 GV), as well as Huancayo (Peru, S12, W75, $R_c$ = 12.92 GV, *H* = 3400 m) or Haleakala (Hawaii, N20, W156, $R_c$ = 12.91 GV, H = 3030 m) NM data for the last solar minima (January 1994 – January 1997, W ≤ 40). We calculated correlation coefficients $\rho(X_o)$ between the natural logarithm of observed and expected counting rate according to Eq. (5) in dependence of $X_o = r_o/u$ = 1, 2, 3, … 60 av. months ( $X_o$ is measured in units of av. month = 365.25/12 days, $r_o$ in AU, and *u* in AU/av. month). For Climax NM monthly data LN(CL1M) we obtained $X_{o\max}$ = 20.6 ± 1.2 av. months, $\rho_{\max} = -0.939$. For Huancayo/Haleakala NM monthly data LN(HU/HAL1M) we obtained $X_{o\max}$ = 17.6 ± 0.5 av. months, $\rho_{\max} = -0.910$. The average solar wind speed for the period 1965-1990 near the Earth's orbit at *r* = 1 AU was $u_1 = 4.41 \times 10^7$ cm/s =7.73 AU/av. month. According to [7] the change of solar wind velocity with the distance *r* from the Sun can be described approximately as

$$u(r) \approx u_1\left(1 - b(r/r_{\text{tsw}})\right), \quad (6)$$

where $r_{\text{tsw}}$ is the distance to the terminal shock wave and parameter $b \approx 0.13 \div 0.45$ in dependence of sub-shock compression ratio and from injection efficiency of pickup protons. On the basis of Eq. (6) we can determine radius of CR modulation region $r_{\text{mod}}$ from equation:

$$X_{o\max} = \int_0^{r_{\text{mod}}} \left(u_1(1 - br/r_{\text{tsw}})\right)^{-1} dr = -r_{\text{tsw}} \ln\left(-b + r_{\text{mod}}/r_{\text{tsw}}\right)/(bu_1) \quad (7)$$

from what follows

$$r_{\text{mod}} = r_{\text{tsw}}\left(b + \exp\left(-X_{o\max} b u_1 / r_{\text{tsw}}\right)\right) . \quad (8)$$

Let us assume that the radius of modulation region $r_{\text{mod}}$ for Climax NM data (effective rigidity 10-15 GV) is about the same as radius of the Heliosphere $r_{\text{tsw}}$ . In this case at $r_{\text{mod}} = r_{\text{tsw}}$ and $b \approx 0.3$ we obtain

$$r_{\text{mod}} = -bu_1 X_{o\max}/\ln(1-b); \quad u_{\text{av}} = -u_1 b/\ln(1-b) = 0.84 u_1 \,, \quad (9)$$

what for Climax NM gives $r_{\text{mod}}$ = 134 ± 8 AU, and for Huancayo/Haleakala NM $r_{\text{mod}}$ = 114 ± 4 AU.

## 3. Estimation of correlation and regression coefficients

Determination of regression coefficients *A* and *B* in Eq. (4) makes it possible to determine the CR intensity outside of the modulation region, and the effective radial diffusion coefficient depending on the effective particle rigidity *R*. The use of monthly data allows the determination of regression coefficients *A* and *B* only for integer values of $X_o$. To increase the accuracy, we also use 11-month-moving averaged data. Therefore, for example, for LN(CL11M) we determined *A* and *B* for $X_o$ = 20 (*A* = 8.367430, *B* = 0.006678) and for $X_o$ = 21 (*A* = 8.367825, *B* = 0.006285), and then by interpolation for $X_{o\,\max}$ = 20.6. In the same way we determined *A* and *B* for LN(HU/HAL11M).

## 4. Cosmic ray intensity outside the Heliosphere

The regression coefficient *A* in Eq. (4) according to Eq. (1) is $A = \ln(n_o(R))$, i.e. this coefficient determines the galactic CR intensity outside of the modulation region. Many scientists assume that for minimum SA detected by NM CR reaches an intensity very near to the intensity outside the Heliosphere. Let us check this. The maxima of LN(CL11M) and LN(HU/HAL11M) were reached in June and July 1997 with values 8.360387 and 7.46112 (minimal residual modulations of 0.361 ± 0.004% and of 0.249 ± 0.008% for 10-15 and 30-40 GV particles). The obtained results show that even high energy CR particles (10-15 GV and 30-40 GV) inside the Heliosphere on the Earth's orbit never reach the intensity out of the Heliosphere (in the interstellar space) even near the minimum of SA.

## 5. Prediction of CR variations by integral *F* near SA minimum

As illustration, in Figure 1 are shown predicted by the integral *F* (calculated on the basis of monthly sunspot numbers *W* according to Eq. (5)) time variations and comparison with the observed natural logarithm of the month's average counting on Climax NM LN(CL1M) and for 11 months smoothed LN(CL11M). In this case we did not take into account the drift effects because according to [8] for high energy particles (for protons with energy much more than 1 GeV) near the SA minimum they are negligible in comparison with convection-diffusion modulation which does not depend from the sign of the solar general magnetic field. For Climax NM the correlation coefficient between predicted *F* and observed values of CR intensity LN(CL11M) was found equal to 0.993 ± 0.002. The same analysis for Huancayo/Haleakala NM gave correlation coefficient between predicted *F* and observed values of CR intensity LN(HU/HAL11M) equal to 0.970 ± 0.007.

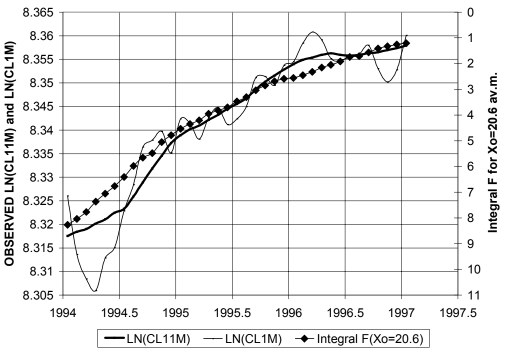


**Figure 1.** Comparison of integral ***F***, calculated according to Eq. (5), with observations by the Climax NM CR intensity: **LN(CL11M)**, and **LN(CL1M)**.

## 6. Forecasting of CR intensity during the period of SA increasing

In Section 5 we considered the forecasting of CR intensity near the minimum of SA when the drift effects are negligible. To demonstrate how can be taken into account the drift effects, let us consider, for example, the forecasting of CR intensity during the period of SA increasing in the onset of solar cycle during January 1996 – August 1999. In this case there are no information on the amplitude of drift modulation $A_{dr}$, which is suggested proportional to the theoretically expected according to [8] and normalized to sunspot number W = 75. If the cycle is only started, we did not know $A_{dr}$ for this cycle, but it is known type of cycle (odd or even) and we can use published predicted values of sunspot numbers for few years ahead. That let us use Eq. (4) and (5) for convection-diffusion modulation and average value of $A_{dr}$ obtained for previous cycles 19-22 in

[9]: $A_{dr} \approx 2\%$ and 0.25% at W = 75 for Climax NM (effective rigidity of primary particles 10-15 GV) and Huancayo/Haleakala NM (35-45 GV) accordingly. Predicted CR intensity variations (separately expected convection-diffusion modulation and expected convection-diffusion + drift modulations) and observed CR long-term variation during 1996 - 2000 are shown in Figure 2 for Climax NM. It can be seen that in this case the taking into account drift effects is sufficient. Correlation coefficient between predicted and observed CR intensity variations is found 0.988. For Huancayo/Haleakala NM with $A_{dr} \approx 0.25\%$ at W = 75 the correlation coefficient is found 0.986.

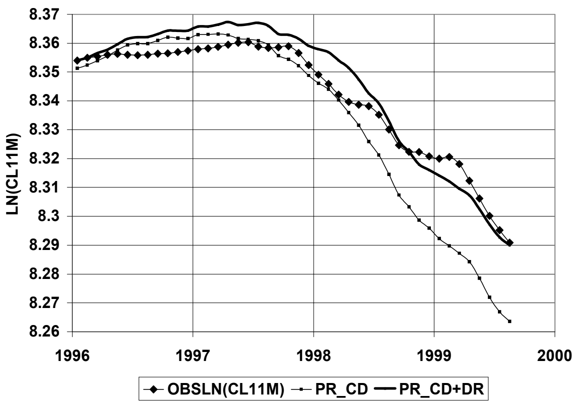


**Figure 2.** Comparison of predicted convection-diffusion modulation **PR_CD** and predicted with taking into account drift effects **PR_CD+DR** with observation **OBSLN(CL11M)** by Climax NM for period January 1996-August 1999.

## 7. On the connection of CR variation with changing of planetary cloud coverage

A very important results for understanding of the mechanism of the influence of SA on the Earth's climate has recently been obtained: it was found that the Earth's cloud coverage (observed by satellites) is strongly correlated with CR intensity [10-12]. It was found that the correlation of global cloud coverage with CR intensity is much better than with SA: about 20% of CR intensity decrease in Climax NM for solar cycle corresponds to about 4% decrease of global cloud covering, what give sufficient change in radiation balance influenced on climate change.

## 8. Discussion and conclusions

1. The developed model of CR-SA hysteresis effects which included convection-diffusion and drift modulations can predict the long-term variation of CR intensity on the basis of monthly SA data for about 3 years ahead near the minimum of SA 1994-1996 with correlation coefficients 0.993 and 0.970 for Climax NM (effective rigidity of primary particles 10-15 GV) and Huancayo/Haleakala NM (35-45 GV), respectively. The prediction made for the period 3.5 years ahead during SA increasing (January 1996 – August 1999), when the drift modulation is more important, gave correlation coefficients for Climax NM 0.988 and for Huancayo/Haleakala NM 0.986.

2. For the period of 3 years from 1994 to 1996 the CR intensity expected to be increase according to Figure 1 on about 4% (in good agreement with observations), so it is expected some small global climate cooling and small increasing of precipitation corresponded to increase of the global cloud covering on about 0.8%. For the period of 2 years from the middle of 1997 to the middle of 1999 the CR intensity expected to be decrease according to Figure 2 on about 7% (in good agreement with observations), so it is expected some small global climate warming corresponded to decrease of the global low cloud covering on about 1.4%. Of course, these small cooling or warming can be compensated with the processes of global warming caused by increasing of green gases or by some other phenomena, but in any case it is necessary to take into account all processes influenced on global climate change.

3. If sunspot numbers will be predicted by experts in solar physics for about one solar cycle ahead, the prediction of CR intensity and corresponding part of climate change caused by galactic CR intensity long-term variation can be made by the described method, for about 10−12 years ahead with high correlation coefficient between predicted and observed CR variations determined mostly by the accuracy of SA prediction.

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