Long-term galactic cosmic ray variations and their forecasting for determining expected radiation dozes for spacecrafts and aircrafts

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Abstract: For long-line aircrafts at altitude about 10 km (pressure about 300 mb) and long-lived spacecrafts in the Earth’s magnetosphere and in interplanetary space the total radiation dozes are determined mostly by galactic CR. We introduce new nominations: integral multiplicity and coupling function for radiation dose inside aircraft or spacecraft caused by galactic CR. By the method of coupling functions, we estimate the connection between CR intensity long-term variation and radiation hazard for aircrafts in dependence of altitude, geomagnetic cutoff rigidity, and shielding inside aircraft or inside spacecrafts in dependence of their orbits near the Earth or in Heliosphere. We show that by this way we may made monitoring and prediction of expected radiation doze for any aircraft lines or spacecraft trajectories.

Keywords: Radiation dozes, Aircrafts and Spacecrafts, Galactic Cosmic Rays

I. THE METHOD

The method, described below, takes into account that CR intensity observed on the Earth at a time t is caused by solar processes started many months before t. In paper [2] it was considered this method of using CR and SA data for solar cycles 19-22, also taking into account drift effects according to [3]. It was shown that including drift effects (as well as also shock waves and high speed solar wind streams); and $D_s(R,t)$ 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 [8, 9] the connection between $D_s(R,t)$ and solar activity can be described by the relation

$$ D_s(R,t) = \alpha R^{\beta} \left( W(t-r/u) \right)^{-\alpha}, $$

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 [8, 9] that parameter $0 \leq \beta \leq 1$ and $\alpha = 1/3$ in the period of high solar activity ($W(t) = W_{\text{max}}$) and $\alpha = 1$ near solar minimum ($W(t) \ll W_{\text{max}}$). To combine these properties in one formula, we suppose, in accordance with [6], that

$$ d(t) = 1/3 + (2/3) [1 - W(t)/W_{\text{max}}], $$

where $W_{\text{max}}$ 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

$$ \ln \rho(R,X_o,\beta,r_E,t)_{\text{exp}} = A - B \times F(t,X_o,\beta,W(t-r/x)_x^{x_{E}}) $$

where
\[ F(t, X_0, \beta, W(t - X)^{\frac{1}{2X_0}}) = \int \left( \frac{1}{X_0} \right)^\frac{1}{3} \left( \frac{w(t - x)}{W_{\text{max}}} \right)^{\frac{1}{3}} X^{-\beta} dX, \]

\[ X = r/u , X_0 = 1AU/u , X_0 = r_0/u , \]

and \( n(R, X_0, \beta, t_1, t_2) \) is the expected galactic CR density at the Earth’s orbit in dependence of the values of parameters \( X_0 \) and \( \beta \). Regression coefficients \( A(R, X_0, \beta, t_1, t_2) \), \( B(R, X_0, \beta, t_1, t_2) \) can be determined by correlation between observed values \( \ln(n(R, r, t)) \) and the values of \( F(t, X_0, \beta, W(t - X)^{\frac{1}{2X_0}}) \), calculated according to Eq. (5) for different values of \( X_0 \) and \( \beta \) for the period of time between \( t_1 \) and \( t_2 \). In [5] three values of \( \beta = 0, 0.5, \) and \( 1 \) have been considered; it was shown that \( \beta = 1 \) contradicts CR and SA observation data, and that \( \beta = 0 \) is the most reliable value. Therefore, we will consider here only this value.

III. PROPERTIES OF THE MODULATION REGION NEAR SOLAR MINIMUM 1994-1996

We used monthly data of sunspot numbers and Climax NM data \((H = 3400 \text{ m}, R_c = 2.99 \text{ GV})\), as well as Huancayo \((H = 3400 \text{ m}, R_c = 12.92 \text{ GV})\) or Haleakala \((H = 3030 \text{ m}, R_c = 12.91 \text{ GV})\) NM data for the solar minima (January 1994 – January 1997, \(W \leq 40\)). We calculated correlation coefficients \( \rho(X_0) \) between the natural logarithm of observed and expected counting rate according to Eq. (5) in dependence of \( X_0 = r_0/u = 1, 2, 3, \ldots 60 \text{ av. months} \). \( X_0 \) is measured in units of av. month = 365.25/12 days, \( r_0 \) in AU, and \( u \) in AU/av. month). We estimate \( X_{\text{max}} \) at which correlation coefficients \( \rho(X_0) \) reaches the maximum value. To determine \( X_{\text{max}} \) more exactly, we approximated the dependence of \( \rho \) on \( X_0 \) in the vicinity of \( X_{\text{max}} \) by a parabolic function

\[ \rho(X_0) = aX_0^2 + bX_0 + c. \]

In this case

\[ d\rho/dX_0 = 2aX_0 + b, \text{ and } X_{\text{max}} = -b/2a. \]

For Climax NM monthly data LN(CL1M) we obtain

\[ X_{\text{max}} = 20.6 \pm 1.2 \text{ av. months}, \rho_{\text{max}} = -0.939. \]  

(6)

For Huancayo/Haleakala NM monthly data LN(HU/HAL1M) we obtained

\[ X_{\text{max}} = 17.6 \pm 0.5 \text{ av. months}, \rho_{\text{max}} = -0.910. \]  

(7)

According to direct measurements on space probes the average solar wind speed for the period 1965-1990 near the Earth’s orbit at \( r = 1 \text{ AU} \) was \( u_1 = 4.41 \times 10^7 \text{ cm/s} = 7.73 \text{ AU/av. month} \). The function \( u(r) \) is determined by solar wind interactions with galactic CR and anomaly component of CR, with neutral atoms penetrating from interstellar space and others. According to calculations in [4] the change of solar wind velocity with the distance \( r \) from the Sun can be described approximately as

\[ u(r) = u_1 (1 - b(r/r_{\text{sw}})), \]

where \( r_{\text{sw}} \) is the distance to the terminal shock wave and parameter \( b = 0.13 \pm 0.45 \) in dependence of sub-shock compression ratio and from injection efficiency of pickup protons. On the basis of Eq. 8 we can determine radius of CR modulation region \( r_{\text{mod}} \) from equation:

\[ X_{\text{max}} = \frac{r_{\text{mod}}}{r_{\text{sw}}} \int_0^1 (u_1(1-b(r/r_{\text{sw}})))^{-1} dr \]

\[ = -r_{\text{sw}} \ln(-b + r_{\text{mod}}/r_{\text{sw}})/(bu_1) \]

from what follows

\[ r_{\text{mod}} = r_{\text{sw}} (b + \exp(-X_{\text{max}}bu_1/r_{\text{sw}})). \]  

(10)

In [8,9] about fifty years ago was estimated that \( r_{\text{sw}} = 100 \text{ AU} \), what was confirmed several years ago by direct measurements on spacecrafts. In this case for average \( b = 0.3 \) from Eq. 10 we obtain for Climax NM \( r_{\text{mod}} = 92.0 \pm 1.7 \) and for Huancayo/Haleakala NM \( r_{\text{mod}} = 96.5 \pm 0.8 \).

IV. PREDICTION OF COSMIC RAY VARIATIONS BY INTEGRAL F NEAR SA MINIMUM

As illustration, in Fig. 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(CL1M). In this case we did not take into account the drift effects because according to [3] 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(CL1M) 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/HAL1M) equal to 0.970 ± 0.007.
V. FORECASTING OF CR INTENSITY DURING THE PERIOD OF SA INCREASING

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 [3] 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 Eqs. 4 and 5 for convection-diffusion modulation and average value of $A_{dr}$ obtained for previous cycles 19-22 in [2]: $A_{dr} = 2\%$ 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 Fig. 2 for Climax NM. It can be seen again that near minimum (1996-1997) drift effects are negligible, but near maximum (1999) the taking into account drift effects is sufficient. Correlation coefficient between predicted and observed cosmic radiation is found 0.988. For Huancayo/Haleakala NM with $A_{dr} = 0.25\%$ at $W = 75$ the correlation coefficient is found 0.986.

VI. CONNECTION OF GALACTIC CR INTENSITY WITH RADIATION DOSES

Let us introduce some new definition: integral multiplicity $M_{rd}(R,S,h)$ for radiation dose from one primary CR particle with rigidity $R$ (in GV) inside the aircraft under shielding $S$ (in g/cm$^2$) at altitude determined by air pressure $h$ (also in g/cm$^2$). In this case the differential radiation dose per unit of time $I_{rd}(S,h,R_c,t)$ will be:

$$D_{rd}(S,h,R_c,t) = \int_{R_c}^{\infty} D(R,t)M_{rd}(R,S,h)dR,$$  \hspace{1cm} (11)

where $D(R,t)$ is the differential primary rigidity spectrum of CR. Let us suppose that $D_{rd}(S,h,R_c,t)$ are measured in a broad interval of cutoff rigidities, and $D(R,t)$ is also known. In this case, from Eq. 11 we obtain

$$\frac{\partial D_{rd}(S,h,R_c,t)}{\partial R_c} = -D(R_c,t)M_{rd}(R_c,S,h) \hspace{1cm} (12)$$

From Eq. 12 follows

$$M_{rd}(R,S,h) = \left( \frac{\partial D_{rd}(S,h,R_c,t)}{D(R_c,t)R_c} \right)_{R_c \rightarrow R} \hspace{1cm} (13)$$

The integral radiation dose $I_{rd}(S,h,R_c,t_1,t_2)$ during the flight from $t_1$ to $t_2$ will be determined by

$$I_{rd}(S,h,R_c,t_1,t_2) = \int_{t_1}^{t_2} D_{rd}(S,h(R_c(t)),R_c(t))dt \hspace{1cm} (14)$$

VII. VARIATIONS OF DIFFERENTIAL RADIATION DOSE WITH TIME

Let us consider the relative variations of the differential radiation dose:
\[ \frac{\delta D_{rd}(S,h,R_c,t)}{D_{rd}(S,h,R_c,t_0)} = \int_{R_c}^{\infty} \frac{\delta D(R,t)}{D(R,t_0)} W_{rd}(R_c,R,S,h) dR + \int_{R_c}^{\infty} \frac{\delta M_{rd}(R,S,h)}{M_{rd}(R,S,h)} W_{rd}(R,R_c,S,h) dR_c \]

where

\[ W_{rd}(R_c,R,S,h) = \frac{D(R,t_0)M_{rd}(R,S,h)}{D_{rd}(S,h,R_c,t_0)} \]

is the radiation dose coupling function for aircrafts, determined the connection between observed variation of the differential radiation dose inside the aircraft with variation of primary CR spectrum outside the Earth’s magnetosphere (the first member in the right part of Eq. 15), with changing of integral multiplicity (the second member in Eq. 15), and with changing of cutoff rigidity (the last member in the right part of Eq. 15).

VIII. COUPLING FUNCTIONS FOR RADIATION DOZE: ANALYTICAL PRESENTATION

In many papers it was shown (see review in Chapter 3 of [1]) that any coupling function (for neutron monitors, for muon telescopes, for aircraft CR measurements, for CR measurements on balloons and satellites) can be presented in analytical form through the polar normalized coupling functions by the so called in literature Dorman function (introduced in [7])

\[ W_{ord}(R) = a_{rd} k_{rd} R^\frac{1}{(2-k_{rd}+1)} \exp\left[-a_{rd} R^{k_{rd}}\right], \quad (17) \]

where parameters \( a_{rd} \) and \( k_{rd} \) depend from the air pressure \( h \) and the level of solar activity. The normalized coupling functions for point with cutoff rigidity \( R_c \), will be:

\[ W_{ord}(R_c,R,S,h) = a_{rd} k_{rd} R^{-\frac{1}{(2-k_{rd}+1)}} \exp\left[-a_{rd} R^{k_{rd}}\right], \]

if \( R \geq R_c \); and \( W_{ord}(R_c,R,S,h) = 0, \) if \( R < R_c \). \quad (18)

From Eq. 16 and Eq. 18 can be determined integral multiplicity \( M_{rd}(R,S,h) \) for radiation doze.

In Fig. 3 is shown the polar coupling function \( W_{ord}(R) \) according to Eq. 17 based on experimental data of Peter Beck, presented to the COST-724 Meeting in Vienna in April 2005 (for these data we obtained parameters \( a_{rd} = 5.025 \), \( k_{rd} = 0.875 \), correlation coefficient 0.96).

![Figure 3. Polar coupling function for differential radiation doze for aircraft at altitude about 10 km.](image)

IX. CONCLUSION

On the basis of results obtained in Sections I–V, can be made forecasting of expected galactic CR intensity variation, and then by formulas in Sections VI–VIII – forecasting of the expected radiation doze for any type of aircraft characterized by some effective shielding \( S \) and any flight trajectory characterized by parameters \( h(t) \) and cutoff rigidity \( R_c(t) \) as well as for spacecraft in the Earth’s magnetosphere or in the interplanetary space.

X. REFERENCES