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Residual cosmic ray modulation in the periods of solar activity minima

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Abstract. The residual cosmic ray modulation caused by the subsonic solar wind behind a front of the standing shock-wave has been considered. Under the assumption that the wind is turbulent and the energy is uniformly distributed, we have estimated the residual modulation depth. In this case, the Bohm's value for a diffusion coefficient has been taken. It is believed that the residual modulation disappeared in the period of the Maunder minimum, and a value of the corresponding increase of radiocarbon and ^{10}Be is found. The comparison with observation data shows the satisfactory agreement.

1 Introduction

Cosmic rays are closely associated with solar activity changes which, in turn, control many processes in the outer shells of the Earth and, in particular, influence on climate changes. Because a knowledge of the behavior of climate at the long-term scale is of not only academic interest but it is also necessary to predict future global changes, now all these interrelated phenomena are intensively studied. The investigation of the cosmic ray variations in the past epochs is also important in astrophysics, as in this case a range of solar wind parameters characterizing cosmic ray modulation can be extended and one can obtain new information on the modulation mechanism itself.

The knowledge about cosmic rays in the past are obtained in the tracks of their action on the isotopic composition of several chemical elements (Kocharov, 1996). One of them is the radioactive carbon accumulated in the wood. The existence of wood rings allows to date selected samples well.

Here we attempt to relate information about cosmic rays in the past to the phenomena of residual modulation. There is reason to believe that in the periods of solar activity minima the cosmic ray modulation does not disappear entirely especially at low energies. Therefore the periods of depressed solar activity for any length of time are of interest. For this purpose the theoretical estimations for the velocity of radiocarbon formation in the case if there were no modulation.

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2 Modulated Spectrum and Radiocarbon

We believe that the velocity of radiocarbon formation is proportional to the energy contributed by cosmic rays to the Earth's atmosphere. Apparently, it would be necessary to take into account the spatial distribution of the released energy: in geographic latitude, in height above the ground surface. As the first approximation we shall simply sum all released energy.

From theoretical considerations it is known that a distribution function of cosmic rays in the Galaxy must be of the form:

$$f(p) = Ap^{-(\gamma+2)}, \tag{1}$$

where $2 < \gamma < 3$ is an index of cosmic ray spectrum. It corresponds to a density of particles

$$n(p) = 4\pi Ap^{-\gamma} \tag{2}$$

The flux density of particles falling on the unit of surface of any body equals $J_0(p) = n(p)v/4$. The velocity is

$$v = pc^2/\varepsilon = cp/\sqrt{p^2+1}, \tag{3}$$

where p is a dimensionless impulse in units of mc.

Thus, the flux density in the Galaxy is

$$J_0(p) = \pi A \frac{p^{-(\gamma-1)}}{\sqrt{p^2+1}}. \tag{4}$$

The constant A can be expressed through the energy density of cosmic rays in the Galaxy, w_0. As

$$w_0 = mc^2 \int_0^\infty (\sqrt{p^2+1} - 1)n(p)dp, \tag{5}$$

then for $\gamma = 2.5$ we obtain

$$A = \frac{w_0}{4\pi mc^2 K_0}, \tag{6}$$

where

$$K_0 = \int_0^\infty (\sqrt{p^2+1} - 1) \cdot p^{-2.5} dp = 2.4717. \tag{7}$$

On the Earth's orbit we observe the flux modulated by the solar wind which differ from the galactic flux by a modulating factor $exp(-p_0/p)$. Such a form testifies that the diffusion coefficient is proportional to p that is a close approximation. Besides, the presence of the geomagnetic field leads to the cutoff of low-energy part of the spectrum which depends on geomagnetic latitude λ. The cutoff threshold

$$p(\lambda) = p_1 \cos^4 \lambda, \;\; p_1 = 15\, GeV/c \; = 16 \tag{8}$$

Here p_1 is a dimensionless value. According to this formula, the Earth's atmosphere area by irradiation with particles of momentum p is a part of total area which equals

$$\sigma(p) = \begin{cases} 1 - \sqrt{1 - \sqrt{p/p_1}}\,, & p < p_1 \\ 1\,, & p > p_1 \end{cases} \tag{9}$$

The flux averages over the total atmosphere surface is

$$\overline{J(p)} = J_0(p)\, e^{-p_0/p}\, \sigma(p). \tag{10}$$

This flux releases the energy which is expended in ionization of atoms, modification of isotopes and other manifestations. This energy per unit time (i.e. specific power) is

$$W = \pi A\, mc^2\, \sigma(p)\, p^{-(\gamma-1)}\, e^{-p_0/p}\, (1 - \frac{1}{\sqrt{p^2+1}}), \tag{11}$$

and the total power is found by integration over total range of changes of p. Integrating at $\gamma = 2.5$, we obtain total power N released by the particles in the Earth's atmosphere. In the absence of the modulation (at $p_0 = 0$) the power is

$$N = 0.0825\, (4\pi R_e^2)\, w_0 c. \tag{12}$$

Here $R_e = 6.37{\cdot}10^8$ cm is a radius of the Earth. It is customary to assume that $w_0 = 1\ \mathrm{eV/cm^3}$, from where it follows that cosmic rays in the Earth's atmosphere release about 2 GW.

The modulation decreases the released power. This decrease in per cent depending on the value of parameter p_0 is given in Table 1.

Table 1. δI at different values of the parameter p_0.

p_0, GeV/c	0.8	1.0	1.2	1.4	1.6	2.0	3.0
$-\delta I, \%$	10.1	11.8	13.5	15.0	16.4	19.0	24.2

3 Subsonic Solar Wind

In the period of solar activity minimum the supersonic solar wind, apparently, does not contain magnetic inhomogeneities and the cosmic ray modulation is produced by the electric field only. This is evident from the fact that at energies ~ 10 GeV, corresponding to the ground-based neutron monitors, the cosmic ray intensity obtained at solar activity minimum is 5% greater at the negative polarity of general magnetic field of the Sun than in the analogous periods at the positive polarity. Such as above difference is evident from the theory, if the scattering frequency of particles is much less than their gyrofrequency.

However, it is necessary to pay attention to the subsonic solar wind produced in passing through a front of standing shock wave. It would appear reasonable that in this wind the large-scale turbulence develop and conditions are ensured to arise equidistributions of energy between its different forms including the magnetic one. Under the assumption that the magnetic pressure is $1/3$ of total pressure in the subsonic wind we obtain

$$\frac{H^2}{8\pi} = \frac{1}{4}\rho u_0^2\,, \tag{13}$$

where u_0 is a supersonic solar wind speed, $\rho = \rho_0(R_0/R)^2$ is a solar wind density just ahead of a front of spherical shock wave of R radius, ρ is a wind density on the Earth's orbit, the radius of which is R_0. The shock wave is assumed to be strong and an index of gas adiabat to be $5/3$.

The field intensity according to the above assumptions is

$$H = u_0\, \frac{R_0}{R} \sqrt{2\pi\rho_0}. \tag{14}$$

Assuming in addition that the main turbulence scale is larger than the particle gyroradius and that its spectral index is close to 1, we consider the Bohm's approximation, i.e. the diffusion path length is equal to the gyroradius:

$$\lambda = \frac{pc}{eH}. \tag{15}$$

The diffusion coefficient, therefore, will be

$$\kappa = \frac{pc^2}{3eu_0\sqrt{2\pi\rho_0}} \frac{R}{R_0}. \tag{16}$$

4 Residual Modulation

Because the calculated diffusion coefficient does not depend on the presence magnetic inhomogeneities in the supersonic solar wind and its value is defined by the density and speed of wind then the cosmic ray modulation produced by the subsonic wind must also exist at solar activity minimum. Thus we are dealing with the residual modulation.

The solar wind speed outside of the shock wave is

$$u(r) = \frac{1}{4} u_0 (\frac{r}{R})^{-2}. \tag{17}$$

This is evident from the fact that the pressure and correspondingly density of wind do not almost depend on the radius r. The diffusion coefficient should not be also depended on r. As the wind divergence equals zero, then the transfer equation is of simple form:

$$\frac{\kappa}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial n}{\partial r}) - u\frac{\partial n}{\partial r} = 0. \quad (18)$$

The boundary condition at infinity is $n = n_0$ and a solution is

$$n = n_0\, exp(-\frac{u_0 R^2}{4\kappa r}). \quad (19)$$

As we are inside the shock wave, we are of interest the cosmic ray density at the shock front, at $r = R$. We see that the modulating factor is $exp(-u_0 R/4\kappa)$. When substituting κ, the exponent index does not depend on R and equals p_0/p, where

$$p_0 = \frac{3u_0^2}{4c^2}\, eR_0\sqrt{2\pi\rho_0}. \quad (20)$$

Substituting in (19) the typical values $u_0 = 4\cdot 10^{17}\mathrm{cm/s}$, $\rho_0 = 8\times 1.7\cdot 10^{-24}\mathrm{g/cm^2}$, we find $p_0 = 2.4\mathrm{GeV/c}$.

Comparing this value with the Table, we see that the residual modulation in radiocarbon data must be approximately 20%. An accuracy of this value naturally depends on the validity of the above assumptions, which can be verified, if ρ_0 is determined in an independent way.

5 The Maunder Minimum

According to measurements of the radiocarbon content in the rings of trees and the isotope ^{10}Be in kernels of ice, the solar activity in he last 800 years was 4 times in the deep depression condition over several decades (Kocharov, 1996; Beer et.al., 1991; 1994), i.e. at minima of Wolf (1280-1350), Sperer (1420-1540), Maunder (1645-1715) and Dalton (1790-1830). The Maunder minimum is considered to be the deepest.

On the basis of the detailed analysis of historical data about the sunspot numbers for 1645-1715, Eddy (1976) drew the conclusion that the solar activity late in the 17^{th} - early in 18^{th} century was very low and the 11-year cycle was even absent. In the later half of the 17^{th} century aurorae were also observed sufficiently rarely.

Bonino (1996), by using radiocarbon and ^{10}Be measurements of high accuracy, established the existence of the galactic cosmic ray modulation oven in the absence of the sunspots. From the work (Kocharov, 1996) it follows that the magnetic dynamo solar mechanism did not stop its action at the Maunder minimum; and the disappearance of sunspots was caused by the superposition of minima of several long-term solar activity variations.

As established by Kocharov (1996), there is an in exceeding cosmic ray intensity observed in the period of that minimum relative to its maximum level during minima of the 19^{th} and 20^{th} cycles. The value of this ”excess”, apparently, is not more than 30%. On the assumption that the heliosphere at the Maunder minimum was transparent for galactic cosmic rays, Vasilyeva and Dergachev (1980) have estimated the velocity of radiocarbon production which is greater by $20-30\%$ than the average one. Such a value is apparently obtained from ^{10}Be measurements (Beer et.al., 1991).

6 Parameter of Residual Modulation

According to the Table, the 20% residual modulation in the present epoch corresponds to the parameter $p_0 \approx (2\div 3)\ GeV/c$. It is consistent with the value expected from the theory. Hence it follows that in the periods of solar activity minimum we must see a maximum at certain $p = p_*$ in the momentum spectrum of cosmic rays. It is not difficult determined: differentiating the spectrum $J(p)$ with respect to p and equating the derivative to zero, we obtain the equation (at $\gamma = 2.5$)

$$\frac{p_0}{p_*} = \frac{3}{2} + \frac{p_*^2}{p_*^2+1}. \quad (21)$$

The solution of this equation linearized near $p_0 = 2$ is

$$p_* = \frac{1}{5} + \frac{2}{5}p_0. \quad (22)$$

Therefore, we obtain $p_* = 1.0\div 1.4$ at $p_0 = (2\div 3)$. The location of maximum in the spectrum observed at minimum solar activity does not apparently contradict to this value.

7 Conclusion

Thus, the theoretical estimation of the residual modulation in the solar system has found the confirmation in cosmic ray data. It means that suppositions, on which this estimation is based (about the equidistribution of energy in the subsonic solar wind and about the Bome’s form of diffusion coefficient), are close to the reality.

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References

Kocharov, G.E., Paleoastrophysics and Cosmic Rays, Nuovo Cimento, 6, 883–892, 1996.

Beer, J., Baumgartner, S.T., Dittrich-Hannen, B., et.al., Solar Variability Traced by Cosmogenic Isotopes, The Sun as a Variable Star, IAU Col.143 proc., Cambridge University Press, 291–300, 1994.

Beer, J., Raisbeck, G.M. and Yuio, Time variation ^{10}Be and Solar Activity, The Sun in Time, University of Arisona Press, Tuscon, 343–359, 1991.

Eddy, J.A., The Maunder minimum, Science, 192, 1189–1201, 1976.

Bonino, G, Record of Gaactic Cosmic Ray Variations in Terrestrial Archives and Meteorites, Nuovo Cimento, 6, 865–882, 1996.

Vasilyeva, V.A., Dergachev, V.A., Solar Activity during the Maunder Minimum, Izv. AN SSSR, ser. fiz., 44, 12, 2510–2527, 1980 (in Russian).