DIMENSIONS OF THE SOLAR WIND CAVITY AND OF THE REGION OF INTERPLANETARY COSMIC RAY MODULATION

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Abstract. We discuss the problem of determining effective dimensions of the region of global galactic cosmic ray modulation from the data on II-year CR variations and the data on the parameters of the solar activity and the solar wind.

I. Effects limiting solar wind propagation. CR propagation is limited to the following effects: I) Pressure of interstellar medium (according to the estimates /I/ this gives $r_{sw} \sim$ IOOO A.U. for the boundary between helio-magnetosphere and solar wind); 2) Pressure of the galactic magnetic field $H_G \sim 3\ IO^{-6}$ G (this gives $r_{sw} \sim$ IOO A.U. in the direction perpendicular to the field /2/); 3) Deceleration both by CR and due to charge exchange of interstellar neutral hydrogen (according to nonlinear theory of modulation /3, 4, 5/ this gives $r_{sw} \sim$ 50-IOO A.U. depending on the CR energy density in interstellar space and on the interstellar hydrogen concentration in the vicinity of the Sun). We should emphasize here that we do not know the effects capable of limiting solar wind to $r_0 \sim$ IO-20 a.e. Meanwhile, investigating the correlation between CR intensity variations and solar activity variations, many researchers concluded earlier that the dimensions of the modulation region are extremely small ($r_M \approx$ IO-20 A.U. and even $r_M \approx$ 2-3 A.U.). Moreover, many papers have recently appeared which suggest, as before, that $r_M \approx$ IO-20 A.U. Let us try to explain the reason for such a difference and to understand whether the solar wind dimensions can generally coincide with the effective solar wind dimensions, i.e. $r_{sw} \approx r_M$.

2. Estimation of effective dimensions of the interplanetary CR modulation region and investigation of the structure of this region; time and energy hystereses. This estimate can be obtained from calculation of the delay of the observed galactic CR modulation with respect to the processes on the Sun (time hysteresis). Indeed, as shown in /2/, the hysteresis between the total number W of solar spots on the solar disk and the intensity variations of the CR neutron component (observed on the stations Ottawa - the geomagnetic cutoff rigidity R=I.2 GV, Chicago - I.8 GV, Climax - 3.2 GV, and Huankayo - I3.5 GV) is explained well by the convective diffusion model of global galactic CR modulation with an account of the delay $\Delta t \sim r/u$ (u is the mean velocity of the solar wind /2,6/) of the electromagnetic conditions in interplanetary space at a distance r from the Sun with respect to the corresponding processes on the Sun. From the comparison between calculations and observations it follows that I) For particles with a rigidity of several

GV the radius of the modulation region $r_M \sim 100$ A.U.; 2) the effective free path for scattering $\Lambda \backsim R$, where R is particle rigidity (in the region where R exceeds several GV), it decreases as $\Lambda \backsim W^{-1/3}$ with an increase of the solar activity; 3) For CR with high rigidities (tens of GV) r_M decreases approximately as $r_M \backsim R_{ef}^{-1}$, where R_{ef} is the effective rigidity of primaty CR registered by a given device; 4) At very small rigidities the delay in the recovery of CR intensity exceeds the theoretical value as the solar wind activity weakens. This indicates the presence, besides the convective-diffusion modulation region (with $r_M \sim 100$ A.U.), also of a "buffer" layer between solar wind and interstellar medium in which the wind velocity is close to zero but there exists an interplanetary magnetic field amplified due to a permanent pumping by the solar wind. In this layer there is no convective CR outflow, but the delay in the recovery of CR intensity inside the modulation region increases due to a comparatively slow diffusion of low-energy particles. The estimation of the thickness of this diffusion layer gives $L_D \sim 100$ A.U. (the influence of this layer on particles of high rigidities can be neglected due to relatively small magnetic fields there). It was shown in /6/ that in the buffer layer particles can be accelerated to comparatively small energies, which can explain the appearance of an anomalous CR component. Note that at small distances CR are scattered by magnetic inhomogeneities of solar wind, whereas at large distances the main role in CR scattering and their convective outflow must be played by large solar wind perturbations of the type of shock waves.

We believe that r_M is close to r_{sw} only for particles of rather small rigidities. At large r_M distant regions of heliosphere will not modulate particles with rigidities of tens of GV because the azimuthal component of the interplanetary magnetic field decreases with distance ($\backsim r^{-1}$); this fact leads to a decrease of R (corrolary 3).

Corrolaries 3 and 4 discussed above lead to the energy hysteresis which has been thoroughly investigated in recent years.

3. The shift of helio-latitude of active regions within a cycle of solar activity and the dimension of the modulation region. In many papers attempts have been made to explain time hystere is by the shift of the effective helio-latitude of solar activity from higher to lower values in the course of an II-year cycle (see, for example, /7-9/). In this case the hysteresis disappears in a first approximation, and so the authors have concluded that the modulation region is very small. In our opinion, such a conclusion is to a great extent groundless. A more accurate account of the helio-latitude shift by means of the HL-index /IO/ shows that hysteresis disappears only for an effective angular flux width $\theta \approx 5\text{-}10°$. But in this case there is a sharp contradiction between the observed /II/ and the calculated

annual variations. The results are in agreement only for $\theta \sim 30\text{-}50°$, but in this case the time hysteresis does not disappear and leads to the results discussed in 3.

4. Short-time variations of solar activity and the dimension of the effective modulation region. The study of the socalled "stepwise" variations in the solar activity and their manifestations in cosmic ray variations /I2/ has led to the conclusion that the corresponding delay in CR with respect to the processes on the Sun makes up I-2 months, which gives $r_M \sim$ 7-IO A.U. But as shown in /I3/, during short-time variations of solar activity only a small part of the modulation region nearest to the Sun takes part in the modulation, and the smaller the characteristic period of solar activity variations, the smaller part of the modulation region is involved in the formation of a corresponding CR variation.

5. Anisotropic diffusion model and the dimension of the modulation region. More accurate calculations of the CR intensity modulation in the framework of the anisotropic diffusion model with an account of polarity reversal of the total magnetic field of the Sun also give large dimensions of the modulation region ($r_M \sim$ 50-IOO A.U.) (see e.g. /I4/).

6. Measurements in space and the dimension of the modulation region. The recent measurements of long-term CR variations and their radial gradient (on a cosmic apparatus (CA) Pioneer IO and II, and on Voyager I and 2) give at least $r_M >$ 65 A.U. /I5/, and according to /I6/, /I7/, the calculations which made use of the same data and took into account the CA measurements near the Earch as well as the ground-based neutron monitor measurements (for elimination of CR time variations) give $r_M \sim$ IOO a.e.

Conclusions: I. Dimensions of the effective modulation region r_M for low-energy (less than several GeV) particles are close to the solar wind dimensions r_{sw}, where $r_M \sim r_{sw} \sim$ IOO a.e. 2. As the particle rigidity R increases, the value of r_M decreases, so that in this case r_M can be much smaller than r_{sw}. The value of r_M also decreases with a decrease of the characteristic period of CR variation (it reaches the maximum value only for long-term variations, such as II- and 22-year ones). 4. The region of effective modulation and solar wind is surrounded by a buffer layer which causes the delay in the recovery of CR intensity. 5. The energy hysteresis is caused by two factors: the dependence of r_M on R and the presence of a buffer layer (the time of diffusion through this layer essentially increases as the particle energy decreases).

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