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Vortex electric field in interplanetary medium and the 11-year modulation of galactic cosmic ray anisotropy

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Abstract: Based on data of world network neutron monitors and muon telescopes at Yakutsk and Nagoya stations an anisotropy component of galactic cosmic rays directed across a mean field line (in the direction of 15 LT) has been revealed. This component undergoes the 11-year variation. Its value rises with increasing the interplanetary magnetic field intensity, solar activity level and neutral sheet deformation. Such a property of this component is explained by the action of the vortex electric field in the heliosphere. The 22-year variation of an anisotropy component directed along the magnetic field is of drift origin.

Introduction

In [1], [2] it was found that the cosmic ray anisotropy in the solar system arises due to their anisotropic diffusion in the spiral interplanetary magnetic field. This diffusion compensates a sweeping of cosmic rays by the solar wind and is directed inward the solar system. Such a simple picture was added with the presentations about the magnetic drift of particles [3], whereby the 22-year modulation of cosmic ray anisotropy is explained. Thus, mean characteristics of cosmic ray anisotropy are described by the convective-diffusion theory when the corresponding diffusion tensor is given [4]. At the positive polarity of general solar magnetic field (GSMF) the vector of cosmic ray anisotropy is shifted to the earlier time than the convective-diffusion mechanism gives. The reason is a drift mechanism which during the positive polarity epoch of GSMF provides the arrival of cosmic rays from the polar regions of the heliosphere towards the equatorial plane. In the present paper the long-term changes of electric and magnetic drift anisotropy of cosmic rays in a wide energy region ($10 - 200$ GeV) has been considered.

Data analysis

The monthly average values of the diurnal variation of neutron and muon cosmic ray components have been used as the initial data. The anisotropy parameters for the neutron component are determined using the global survey technique by neutron monitor (NM) data of world network stations for $1965 - 2000$, for the muon component - the data of continuous observations with vertical ground and underground telescopes at depths of 7, 20, 60 m w.e. (T0, T7, T20, T60) of the Yakutsk complex of muon detectors for $1972 - 2002$. Data of the telescope with a direction of 30° towards the North and South relative to the zenith at the Nagoya station (TN) for $1970 - 1974$ [5] have also been used. To obtain the primary anisotropy vector, the receiving vector method [6] is used. The primary anisotropy vectors are resolved into the drift components which are field aligned (magnetic) and perpendicular to the magnetic field (electric). In this case, it is assumed that the spiral angle of the interplanetary magnetic field is $45°$. The monthly average values of these anisotropy components are smoothed by the moving average by 13 points. The anisotropy values obtained by such a treatment are presented in Figs. 1a and 1b, respectively.

Temporal changes of the interplanetary magnetic field (IMF) intensity, numbers of sunspots (W), polarity of general solar magnetic field are also presented. The periods of change of GSMF are marked by hatching. The effective energies for each level of observations increase successively from the neutron monitor ($\sim$ 10 GeV) up to telescope T60 ($\sim$ 200 GeV).

The magnetic drift anisotropy $A_{m.dr}$ (Fig. 1a) depends on the magnetic field polarity. The 22-year variation is observed although together with it the changes of anisotropy close to 11 year are revealed. The maximum of $A_{m.dr}$ is at the negative polarity of GSMF and corresponds to the anisotropy along the IMF field line with the maximum at 21.00 LT. The certain peculiarity of anisotropy in the period of change of the sign from "plus" to "minus" and from "minus" to "plus" is observed. At the end of the change of sign from "minus" to "plus" $A_{m.dr}$ decreases sharply while at the end of the change of sign from "plus" to "minus" $A_{m.dr}$ increases with some delay.

The electric drift anisotropy $A_{el.dr}$ (Fig.1b) across a field line of IMF changes with a period of 11 years and doesn't depend on the polarity of general solar magnetic field. It immediately depends on the magnetic field intensity. Its value decreases near the solar activity minimum.

Discussion

The diffusion-drift picture of appearance of anisotropy remains true even when the frequency of accidental particle scattering becomes negligibly small and the particles will move in the regular electromagnetic field. Such a way for the description of phenomena allows to obtain the more visual clear notion. So let's take such a simplification and consider first the behaviour of cosmic rays in the potential electric field $E = -\frac{1}{c}[\vec{U}\vec{H}]$, and then take into account the effects caused by the vortex electric field. The simplest description is in the fact that the field is considered to be regular in the whole heliosphere and outside of it the field is supposed to be disappearing small.

The electric field in the heliosphere will be potential if the interplanetary magnetic field is axial symmetric and the neutral sheet is at a fixed heliolatitude, i.e. it represents a surface of circular cone. In particular, the sheet can be in the plane of helioequator. In this case, $\partial\vec{H}/\partial t = 0$ and the electric field is described by the potential $U(\psi)$, where ψ is the heliolatitude. This potential reaches its maximum on the neutral sheet. The cosmic ray modulation in this case is described by the formula $f(\varepsilon,\psi) = f_0(\varepsilon + eU(\psi))$, where f is a distribution function depending on the particle energy $\varepsilon(\varepsilon \gg mc^2)$ and f_0 is a distribution function beyond the borders of the heliosphere.

Just in the epochs of positive polarity $U > 0$ there exists heliolatitudinal modulation leading to the cosmic ray minimum on the sheet and their gradient directed to the both sides from it. The anisotropy at which the excess of particles is to be at $\sim$ 03.00 LT (the anisotropy is directed perpendicularly to interplanetary magnetic field lines) corresponds to this gradient. Under the action of electric field the particles make a drift to which the anisotropy with the maximum at $\sim$ 15.00 LT corresponds. In sum these two effects are mutually compensated and the anisotropy is absent. We will have the analogous result in the epoch of negative polarity where the magnetic and electric fields and also the gradient have the reverse signs and the corresponding anisotropy conserves its value and direction. This result is quite natural because the particles, falling into the point of observation, propagate in the potential electric field and so they have the identical intensity independent on their trajectory of movement (and, correspondingly, on the direction).

If we now consider the deformed neutral sheet with a "goffer" then we will see that the picture of potential electric field conserves everywhere besides the neutral sheet itself, where $rot\vec{E} \neq 0$. The fast drift of particles along the sheet in the absence of the electric field in it equalizes the cosmic ray intensity within heliolatitudes to which the "goffer" reaches. As a result, in the epoch of positive polarity the anisotropy with the maximum at 15.00 LT should be observed. At the negative polarity the picture differs from the above in that the sweeping of cosmic ray particles due to the electric drift is not compensated by their arrival from high latitudes. Really, the magnetic drift is now directed to the both sides from the sheet. Therefore, the radial component of flow should be compensated by the arrival of particles towards the Sun along magnetic field lines. As a result, the anisotropy has its maximum at 18.00 LT.

Such a behaviour explains the 22-year modulation of the anisotropy. As to the 11-year modulation, it is explained by two reasons: the magnetic field intensity and by the range of heliolatitudinal deformations of the neutral sheet. Both the reasons define the limiting particle energy higher of which the anisotropy is not observed. During the solar activity maximum the action of both the reasons is enhanced and the energy spectrum of anisotropy extends to the higher energies. The faster change of anisotropy from "+" to "-" is connected with the fact that the drift from high latitudes begins to act just after the change of sign. In the case of the change of sign from "-" to "+" the anisotropy is established only once the change have been originated in the whole heliosphere.

Conclusions

The cosmic ray anisotropy is a sensitive instrument reflecting large-scale processes in the heliosphere. In particular, the potential electric field is accompanied by the disappearance of anisotropy. The energy spectrum of anisotropy allows to estimate the degree of deformation of the neutral sheet.

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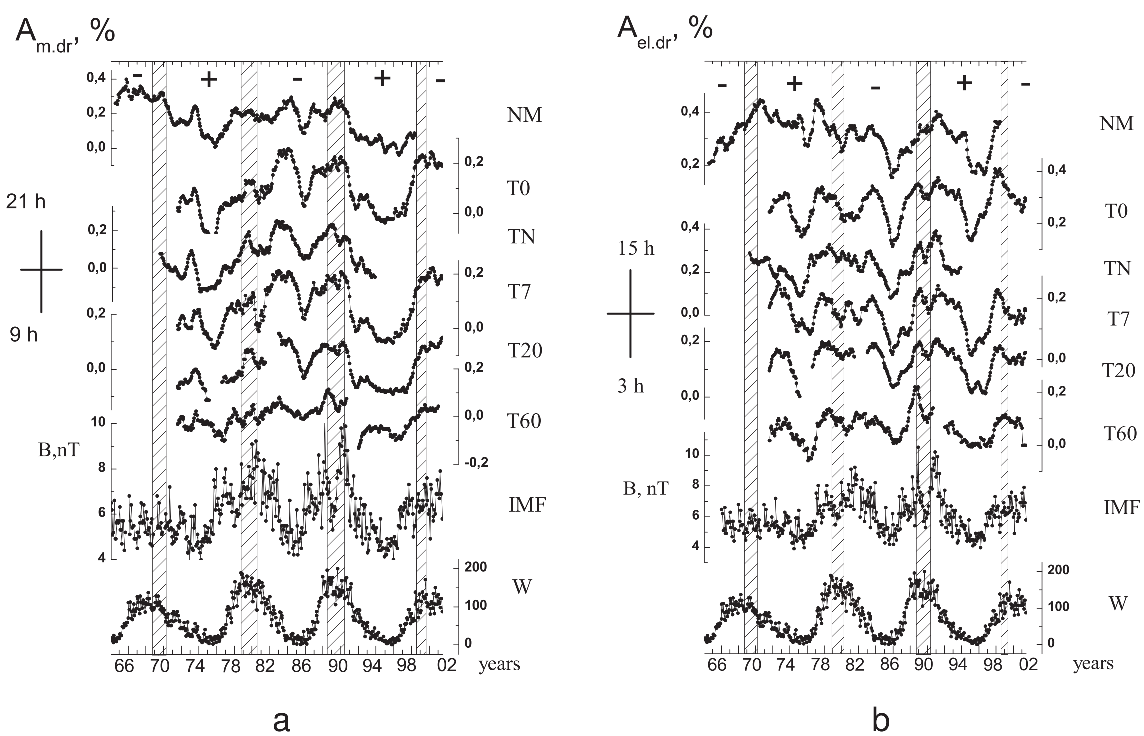

Figure 1: (a) Longitudinal (field-aligned) cosmic ray anisotropy. (b) Electric drift cosmic ray anisotropy