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1965

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Abstract

Full Text

PHYSICS

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DIFFUSION MECHANISM OF THE DIURNAL VARIATION OF COSMIC RAYS

(Presented by Academician M. A. Lavrent'ev, 2 VII 1964)

To explain the diurnal variation of cosmic rays, a number of mechanisms have been proposed, but each of the proposals encounters considerable difficulties of both an experimental and a theoretical nature. A review of these mechanisms is given in ⁽¹⁾.

At present the existence of a continuous flow of plasma from the Sun, or the so-called solar wind, may be regarded as established. With a nonuniform distribution of the sources of the wind, "jets," or tubes of matter, are formed. The magnetic fields carried in the tubes must be directed predominantly along their axes. If the kinetic energy of the gas is substantially greater than the energy of the magnetic field, then the motion of matter from the Sun will be radial. In this case the equation of an individual jet in polar coordinates is

$$\rho = \frac{vT}{2\pi} \varphi, \quad (1)$$

where ρ is the distance from the Sun; $T = 27^d$ is its period of rotation; φ is the heliolongitudinal angle, measured eastward from the source of the jet; v is the gas velocity. The angle θ between the axis of the tube in the Earth's orbit and the Earth-Sun line is determined from the relation

$$\text{ctg } \theta = \frac{1}{R_{\oplus}} \frac{d\rho}{d\varphi} = \frac{vT}{2\pi R_{\oplus}} \quad (R_{\oplus} = 1.5 \cdot 10^{13} \text{ cm}). \quad (2)$$

Thus, an interplanetary magnetic field is formed whose lines of force are oriented along Archimedean spirals ⁽¹⁾. The existence of such a field has been established from data on solar cosmic rays ⁽²⁻⁵⁾, and has also been considered theoretically ^(6,7). It is essential that, in a medium with such a magnetic field, the diffusion of cosmic rays will be anisotropic: the diffusion coefficient of cosmic rays along the axes of the jets, D_{\parallel} , will be greater than the transverse diffusion coefficient D_{\perp} .

Under these conditions the following diffusion mechanism of the diurnal variation must operate. The convection flux of cosmic rays from the Sun, associated

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

with the outward motion of the magnetic field, must be compensated by a diffusion flux toward the Sun. However, since diffusion proceeds predominantly along the axes of the jets, the compensating flux q will have a tangential component q_t . At the same time the convective flux of cosmic rays nv is radial. In the stationary case the convective flux and the radial component of the diffusion flux of cosmic rays q_r cancel each other, and the resulting flux proves to be directed perpendicular to the Earth—

—Sun from east to west (see Fig. 1, *a*). Such a flux should create an anisotropy of cosmic rays with a “positive source” located at an angle of 90° to the east of the Sun. This coincides with the direction of the anisotropy observed experimentally.

Let us now calculate the magnitude of the anisotropy due to this mechanism. In the first approximation we shall neglect the dependence on heliolatitude and consider a plane problem. The diffusive flux of cosmic rays is $\mathbf{q} = -D\vec{\nabla}n$ (n is the density of cosmic-ray particles). In this expression the diffusion coefficient D is a tensor. In a coordinate system

Fig. 1

Fig. 2. 1— $v = 600$ km/sec, 2—400, 3—300, 4—200, 5— $v = 100$ km/sec

whose x -axis is directed along the streams (see Fig. 1, *b*), its components are $D_{xx} = D_{\parallel}$; $D_{yy} = D_{\perp}$; $D_{xy} = D_{yx} = 0$.

When the coordinate axes are rotated $x \rightarrow r$; $y \rightarrow t$ through an angle θ , the components transform as:

$$\begin{aligned} D_{rr} &= D_{\parallel} \cos^2 \theta + D_{\perp} \sin^2 \theta, \\ D_{tt} &= D_{\parallel} \sin^2 \theta + D_{\perp} \cos^2 \theta, \\ D_{rt} &= D_{tr} = (D_{\parallel} - D_{\perp}) \sin \theta \cos \theta. \end{aligned} \quad (3)$$

Since the problem under consideration is symmetric with respect to the axis of rotation of the Sun, the vector $\vec{\nabla}n$ is directed along the radius: $\nabla n = \nabla_r n$. Then, taking (3) into account, we find

$$q_r = -D_{rr} \nabla_r n = -(D_{\parallel} \cos^2 \theta + D_{\perp} \sin^2 \theta) \nabla_r n,$$

$$q_t = -D_{tr} \nabla_r n = -(D_{\parallel} - D_{\perp}) \sin \theta \cos \theta \nabla_r n.$$

Hence, equating the radial component q_r to the convective flux nv and introducing the notation $F = D_{\parallel}/D_{\perp}$, we obtain:

$$q_t = \frac{q_t}{r_r} nv = \frac{(D_{\parallel} - D_{\perp}) \sin \theta \cos \theta \nabla_r n}{(D_{\parallel} \cos^2 \theta + D_{\perp} \sin^2 \theta) \nabla_r n} nv = \frac{(F - 1) \sin \theta \cos \theta}{F \cos^2 \theta + \sin^2 \theta} nv.$$

Taking into account the relation between θ and v according to formula (2), after simple transformations we have:

$$q_t = \frac{2\pi R_{\odot} v^2 T (F - 1)}{(2\pi R_{\odot})^2 + F v^2 T^2} n.$$

The flux q_t is related to the amplitude of the anisotropy of cosmic rays A by the expression $q_t = ncA/3$, where c is the speed of light.

Therefore

$$A = \frac{6\pi R_{\oplus} T v (F - 1)}{(2\pi R_{\oplus})^2 + F v^2 T^2} \frac{v}{c}. \quad (4)$$

From (4) it is evident that for $F \rightarrow 1$, i.e., $D_{\parallel} \rightarrow D_{\perp}$, this mechanism becomes ineffective. For $F \gg 1$ the anisotropy amplitude becomes independent of the wind velocity v and tends to the asymptotic limit: $A_{\max} = 6\pi R_{\oplus}/cT = 0.40\%$.

Figure 2 gives the dependence of the anisotropy amplitude on F and v , calculated from (4). As is seen from the figure, the diurnal variation at $D_{\parallel}/D_{\perp} \sim 10$ is equal to $\sim 0.3\%$, if the wind velocity is $v \sim 300 \div 600$ km/sec. Consequently, if the structure of the interplanetary magnetic field is such that $D_{\parallel}/D_{\perp} \sim 10$, the proposed mechanism can explain the existence of diurnal variations.

We note that exact compensation of the radial flux of cosmic rays is apparently achieved only on the average over a sufficiently long time interval. In individual intervals the phase of the diurnal variation must fluctuate about the mean value; in particular, diurnal variations with a maximum at night may appear.

In a detailed consideration of the model it will also be necessary to take into account the action of the electric field, which creates a component of the diurnal variation with a source from the Sun ^(8,9).

Comparison of detailed calculations with experiment may provide new information on the degree of regularity of the interplanetary magnetic field and on the properties of the "solar wind."

In conclusion, the author expresses his gratitude to A. I. Kuzmin, G. V. Skripin, and P. A. Krivoshapkin for discussing this work.

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Received
21 VI 1964

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Note: Figure translations are in progress. See original paper for figures.

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