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ON THE ISOTROPY OF PRIMARY COSMIC RAYS

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Various mechanisms leading to the isotropy of primary cosmic rays are discussed on the basis of existing ideas concerning the interstellar magnetic field.

Relativistic cosmic-ray particles in the interstellar magnetic field $H \approx 10^{-5}$-10^{-6} Oe moves along the lines of force in helical trajectories, the gyroradius of particles with an energy $E \ll 10^{17}$ eV being very much less than the characteristic length of the nonuniformities of the magnetic field, $l_1 \approx 10^{20}$-$3 \cdot 10^{20}$ cm. As a result of this, the motion of most of the cosmic rays is almost entirely governed by the geometry of the force lines of the interstellar field. In the following, we will assume that the sources of primary cosmic rays are concentrated in the region of the galactic plane, while the orientation of the force lines of the interstellar field changes randomly in a quasi-uniform region with an average diameter l_1. Let us consider two cases of the time dependance of the magnetic field.

1. The magnetic field is quasi-static in character. Its geometry either does not change with time or, on account of the motion of the highly conducting interstellar gas, there are changes but the magnetic force tubes retain their individuality over a period of time comparable with the age of the Galaxy (there is no "crossing" of the force lines). The cosmic rays move along the field lines with a velocity $v \approx {}^1/_3 c$, gradually receding from the galactic plane, the motion being a kind of spatial diffusion with a mean free path l_1. Assuming that the Galaxy is without a boundary which reflects cosmic-ray particles or allowing for the natural decrease in the particle density as the result of nuclear interactions with the protons of the interstellar gas, we can expect that at a fixed point (in particular, in the vicinity of the solar system) the degree of anisotropy of the cosmic rays should be of the order of unity*. In this case, isotropy should only exist on the average in large regions of space containing a considerable number of magnetically nonuniform regions. It is clear that in the quasi-static case under consideration, isotropy of this kind has no direct bearing on the observed isotropy of cosmic rays at the earth ($\delta \leqslant 10^{-3}$ for particles with $E \approx 10^9$-10^{10} eV).

It seems to us that the isotropy of the primary cosmic rays observed on the earth can be explained if it is assumed that the motion of cosmic-ray particles along a given tube of magnetic force lines is not free, but is itself a one-dimensional diffusion with a mean free path l_2. In this case, the opposing streams of particles compensate each other to an increasing extent as l_2 decreases and with a suitable choice of l_2 the required degree of isotropy can be obtained. An elementary calculation which we do not present here for lack of space shows that $\delta \leqslant 10^{-3}$ is obtained when $l_2 \leqslant 3 \cdot 10^{21}$ cm. A "reflection" of cosmic-ray particles from individual sections of a given tube of magnetic force can arise from at least two causes. If the magnetic field strength H increases smoothly, such "reflections" can take place because of the conservation of the adiabatic invariant $\sin^2 \theta / H$, where θ is the angle between the velocity vector of the particle and the direction of the force lines of the magnetic field [1]. In the presence of macroscopic motions in the interstellar medium with velocities exceeding that of sound, the formation of hydromagnetic shock waves is also possible [2]. Since the discontinuous change of the magnetic field strength at a shock-wave front is apparently less than the gyroradius of a particle

* In the present discussion, the degree of isotropy δ will be taken to mean the relative difference between the cosmic-ray fluxes in two opposite directions parallel to to the magnetic field in the region under consideration. The estimate of δ given below is probabilistic in character. It is clear that with some particular and therefore highly improbable assumptions δ may be very much smaller than unity even in the model under consideration (for example, if the region in which δ is being determined lies at the "center of gravity" of the cosmic-ray sources or if the opposing streams of cosmic rays balance one another exactly because of a special choice of the source distribution along the given tube of force lines, etc.)

with $E \approx 10^9$ eV, the adiabatic invariant will not be conserved at the wave front. Then, with a probability close to $\frac{1}{2}$, the relativistic particle can either penetrate through the shock wave or be reflected from it (depending on the nature of the shock wave and on the direction of motion of the particle). Without stopping to consider the complex question of the number of hydromagnetic shock waves in the Galaxy, we note that if the average diameter of the clouds of interstellar gas is $l_1 \approx 10^{20} - 3 \cdot 10^{20}$ cm, the value $l_2 \lessapprox 3 \cdot 10^{21}$ cm found above is not unduly small and in any case it does not contradict available data.† We would like to emphasize once more that the estimates given above are also correct if the geometry of the magnetic field changes, provided that the motion of gas clouds does not influence its topology. Indeed, it is necessary to accept that the changes take place inasmuch as above we have discussed hydromagnetic discontinuities arising in the presence of macroscopic motions of the interstellar medium.

The hypothesis introduced above that the observed cosmic-ray isotropy is due to the diffusion of particles along the magnetic field lines means that the particle motion is in fact compounded from two diffusion processes (one-dimensional diffusion along the lines of force and three-dimensional diffusion on account of the randomly distributed breaks in the force lines). Such a diffusion model was used by the authors to derive an expression for the probability that a particle moves a certain distance from a given point in time _t_, as well as an expression for the mean-square displacement, $\tilde{R}^2 = \frac{(Dt)^{1/2} \cdot l_1}{\sqrt{\pi}}$, where $D = \frac{1}{2} \cdot v \cdot l_1$ is the diffusion coefficient, _v_ being the velocity of the cosmic-ray particles along the force lines of the interstellar field [3].‡ With $l_1 \approx 3 \cdot 10^{20}$ cm, $l_2 \approx 3 \cdot 10^{21}$ cm, and $t \approx 10^{17}$ sec; we have that $\sqrt{\tilde{R}^2} \approx 10^{22}$ cm, i.e., in a period of time comparable with the age of the Galaxy the particles move away from the galactic plane by an amount which is several times smaller than the radius of the halo. This fact, understandable on the basis of elementary considerations since one-dimensional diffusion leads to a marked decrease in the rate of diffusion transport of cosmic rays, in our opinion shows the exchange of cosmic rays between the flat subsystem and the halo cannot occur easily.

2. The topology of the magnetic field varies with time as the result of the "crossing" of force lines on the shock-wave fronts or in regions with other singularities of the magnetic field. If the velocity of the macroscopic motion of magnetized clouds of interstellar gas is $V \approx 10^6$ cm/sec, while their dimensions are of the order of $l_1 \approx 3 \cdot 10^{20}$ cm, then the topology of the magnetic field can change appreciably only over a period of time $t > l_1/V \approx 3 \cdot 10^{14}$ sec. During this time, a relativistic cosmic-ray particle moves along a force line of the magnetic field through a distance $L \approx vt > 3 \cdot 10^{24}$ cm ($v \approx \frac{1}{3} c \approx 10^{10}$ cm/sec). Since the distance L is probably considerably greater than the mean free path of the particle along the force line, estimates of the degree of anisotropy allowing for one-dimensional diffusion remain valid in the present case.

In the presence of the "crossing" of magnetic force lines, the degree of anisotropy must also decrease as a result of the "mixing" of cosmic rays with various directions of motion [4]. The efficiency of such a mechanism of lowering the degree of anisotropy depends primarily on the number of "crossings" of the force lines, as well as on the nature of the exchange of cosmic rays between individual clouds during the process of "crossing." For a given cloud, the maximum number of "crossings" N during the lifetime of the Galaxy ($T \approx 10^{17}$ sec) must be of the order of $N_{max} \approx TV/l_1 \approx 3 \cdot 10^2$. In the simplest case when the cloud contains N randomly orientated streams of particles of equal intensity, the degree of anisotropy is $\delta \approx 1/\sqrt{N}$. With $N \approx N_{max} = 3 \cdot 10^2$, we see that $\delta \approx 5 \cdot 10^{-2}$, i.e., still appreciably larger than the experimental value $\delta \lessapprox 10^{-3}$. With a suitable modification of the model of "crossing" and "mixing" it is possible to obtain smaller values of δ. In any case, it seems to us that in the absence of reliable data on the number of "crossings" and on the nature of the exchange of cosmic rays between individual clouds, it is not possible at the present time to obtain a reliable estimate of δ on the basis of the above "mixing" model. It is possible that the isotropy of cosmic rays in the Galaxy is governed both by the mechanism of "mixing" and the process of one-dimensional diffusion along the magnetic force lines which acts independently of the former. In this case, as we already mentioned above, the rate of diffusion transport of cosmic-ray particles decreases and the exchange of particles between the flat subsystem and the halo is made more difficult. To summarize, we see that the considerations concerning the explanation of the isotropy of the primary cosmic rays are also relevant to the question of their origins and impose a limit on the time during which the cosmic rays in the Galaxy

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†Note added in proof. It has been pointed out to us by S. B. Pikel'ner that the assumption of the presence of large numbers of hydromagnetic discontinuities in interstellar space encounters well-known difficulties of an energy character. To explain the observed isotropy of cosmic rays it is necessary to postulate that there is at least one discontinuity for every 10-30 interstellar gas clouds.

‡The above expression for $\tilde{R}^2$ can be obtained to within a factor of the order of unity from elementary considerations if in the formula for $\tilde{R}^2$ in the case of three-dimensional diffusion we substitute for the total path traversed by the particle in time _t_ the diffusion path length resulting from one-dimensional diffusion.