DEPENDENCE OF THE CHEMICAL COMPOSITION OF COSMIC RAYS ON THE NATURE OF THEIR MOTION IN THE GALAXY

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The diffusion and regular models of the motion of cosmic rays in the Galaxy are discussed. A method is indicated which can be employed for choosing between the models on the basis of the experimental values of the ratios $He^3/(He^3 + He^4)$ or D/He^4. Thus, even with the experimental accuracy attainable at present, a value $He^3/(He^3 + He^4) > 0.15$ ($D/He^4 > 0.1$) would suffice to indicate that the diffusion model is valid, whereas a value $He^3/(He^3 + He^4) < 0.15$ ($D/He^4 < 0.09$) would favor the regular model of motion of cosmic rays in the galaxy.

STUDY of the chemical and isotopic composition of the primary cosmic rays provides the possibility of obtaining a large amount of important information on the sources, acceleration mechanism, and nature of the propagation of cosmic rays in the galaxy. This information includes: the composition of the cosmic rays at their sources and the effective thickness of matter traversed before their incidence on the earth (see Refs. 1 and 2), the age of the cosmic rays and the average concentration of interstellar gas in the region occupied by them,[3] the energy dependence of the amount of interstellar gas traversed and the nature of the acceleration mechanism,[4] the duration of the acceleration process,[5,6] and the influence of ionization loss in the interstellar gas on the spectrum and composition of cosmic rays in the low-energy region.[7] In the present paper we will discuss the possibility of selecting a model of the propagation of cosmic rays in the galaxy, on the basis of data on their chemical and isotopic composition.

It is well known that in the analysis of the propagation of cosmic rays in the galaxy one of two models is usually used: the diffusion model or the regular model. The first of these (the diffusion model) corresponds to the random wandering of the cosmic rays in an irregular galactic magnetic field, this motion being described as isotropic diffusion with some effective diffusion coefficient D. The value of the diffusion coefficient is chosen on the basis of existing data on the chemical composition and isotropy of cosmic rays, as well as data on the characteristic size of the inhomogeneities (clouds) in interstellar gas.

The second model (the regular model) assumes that all particles pass through the same thickness of matter before incidence on the earth. The regular model is applicable, on the one hand, to the case where all particles move from the source to the earth along the same path, for example along the lines of force of a regular magnetic field. On the other hand, the regular model also describes the propagation of cosmic rays generated in infrequent and powerful explosions (the nonstationary model). In fact, if an overwhelming fraction of cosmic rays were formed at the same instant in the past (at the moment of the explosion), then at the time of observation all particles with a given velocity (or which is the same thing, with a given energy per nucleon) have traversed the same path in interstellar gas, i.e., for a uniform density, the same thickness of matter.

Ginzburg and Syrovat-skiĭ have presented in their monograph[1] a series of arguments in favor of the diffusion model and against the regular model, including the nonstationary model. They also suggest certain means of experimental choice between these two models, in particular by study of the chemical composition of the cosmic rays.

With respect to chemical composition, the difference between the diffusion model and the regular model lies essentially in the fact that in the former the cosmic-ray nuclei arrive at the point of observation by different paths, traversing different thicknesses of interstellar gas. Therefore the chemical composition at the point of observation is obtained by averaging over the thicknesses of matter traversed. The result of this averaging of the composition is not equivalent to use simply of an average thickness of matter for all arriving particles.

These differences in the propagation models must be taken into account in all calculations relating to the chemical composition. In addition, in view of the relative mathematical simplicity, very often only the regular model is discussed in the literature, even though its use is less justified. In this connection we must emphasize the fact[1,2] that the very data on chemical composition of cosmic rays permit, at least in principle, establishment of which of these two models is closer to reality. For this purpose it is sufficient to consider that according to astrophysical predictions not only L-nuclei (Li, Be, B) but also isotopes such as[1] He^3 and D must be practically absent in the sources of cosmic rays (in comparison, for example, with nuclei of group M).

It is well known that for a given propagation model the absence in the source of any of the elements (or isotopes) observed on earth permits a unique determination of the effective thickness of matter traversed and the composition of the cosmic rays at the source. Therefore in determination of the effective thickness on the basis of certain elements of low abundance, the model must be chosen so as to lead to noncontradictory results.

At the present time, the nuclei having small natural abundance and observed in cosmic rays include, in addition to the L-nuclei, the isotopes He^3 and D.[4,9,10] However, practically all of these observations refer to the nonrelativistic energy region, in which analysis of the composition is greatly complicated by the necessity of taking into account ionization losses and the shape of the energy spectrum,[7] and also by the effect of modulation in interplanetary space.[2] Furthermore, for this energy region we still do not have accurate measurements of such basic quantities as the relative number of nuclei of groups $H_1(Z \geq 20)$, $H_2(16 \leq Z \leq 19)$, $H_3(10 \leq Z \leq 15)$, $M(6 \leq Z \leq 9)$, and $\alpha(Z = 2)$.

On the other hand, for the relativistic energy region (total energy $E \geq 2.5$ BeV/nucleon) the fluxes of the main groups of nuclei are known rather well, and the effect of ionization losses at these energies is already unimportant. In regard to the study of the isotopic composition (in particular, the measurement of the fraction of He^3 and D) at relativistic energies, it is faced with definite experimental difficulties but is possible in principle (see for example Refs. 9, 11, and 12). Therefore there is a basis to hope that just the relativistic energy region will turn out to be most suitable for the experimental solution of the problem of the applicability of the various models of cosmic-ray propagation in the galaxy.

We list below the results of calculations of the effective thickness of matter traversed for the relativistic energy region ($E \geq 2.5$ BeV/nucleon), for the diffusion model and for the regular model. The calculations are made on the assumption that the sources contain neither group-L nuclei nor the isotopes He^3 and D.

The data existing at the present time on the intensity of cosmic rays at the earth[1,3,13] in the energy region $E \geq 2.5$ BeV/nucleon are listed in Table I. Data on the intensity of deuterium in the relativistic region are very scanty; there is only an indication that at energies $E > 8$ BeV/nucleon it does not exceed 5 particles/m²-sec-sr.[9] For He^3 there are at the present time only preliminary results,[12] according to which the ratio $H^3/(He^3 + He^4) = 0.6 \pm 0.4$ for $E \geq 10$ BeV/nucleon.

The calculation of the thickness of matter traversed was made on the basis of the following equations:[1,2]

$$q_i = \sum_{k=1}^{i} \frac{1}{F_k} \sum_{l=1}^{l=k} a_{ikl} N_l, \qquad (1)$$

where q_i is the flux (or concentration) of nuclei of group i in the source of cosmic rays, N_l is the flux of nuclei of group l at the earth, and F_k is the propagation function of cosmic rays in the galaxy. For the two models of motion being considered,

Table I. Intensity of nuclei of different groups with $E \geq 2.5$ BeV/nucleon

Group of nuclei	Intensity, particles/m²-sec-sr
$H_1 \equiv VH$ $(Z \geqslant 20)$	0.54 ± 0.22
H_2 $(Z = 16 - 19)$	0.10 ± 0.10
H_3 $(Z = 10 - 15)$	1.30 ± 0.40
M $(Z = 6 - 9)$	5.70 ± 0.28
L $(Z = 3 - 5)$	1.60 ± 0.40
α $(Z = 2)$	88 ± 2
p $(Z = 1)$	1300 ± 50

1) There are data (see for example Ref. 8) on the presence, in the atmospheres of certain stars, of an anomalously large quantity of He^3. Therefore the conclusion that there is no He^3 in the sources of cosmic rays cannot yet be considered proved, although it is extremely likely for such most probable sources as supernova outbursts and explosions in the region of the galactic core.

2) In this connection we cannot regard the value $x = 2–16$ g/cm² obtained by Hasegawa et al.[10] for the thickness traversed by nonrelativistic nuclei as real. This value was computed on the assumption that all of the observed D nuclei are the result of fragmentation on the path from the source. However, this calculation did not take into account ionization losses, which are extremely important for the energy region being discussed.

the functions F_k will have the form: a) for the regular model,

$$F_k = \exp\{-x / \lambda_k\}, \quad (2)$$

b) for the diffusion model,

$$F_k = (4\pi Dr)^{-1} \exp\{-(2x / \lambda_k)^{1/2}\}. \quad (3)$$

Here λ_k is the absorption length in the interstellar medium of nuclei of the group k; D is the diffusion coefficient of cosmic rays in the galaxy; r is the distance from the earth to the cosmic-ray source; and x is the quantity of matter traversed by the cosmic rays in the galaxy before their incidence on the earth. Values of the interaction lengths Λ_k of nuclei are listed in Table II; these values are taken from Durgaprasad.[3] The quantities λ_k and Λ_k are related by the expression

$$\lambda_k = \Lambda_k / (1 - P_{kk}). \quad (4)$$

The coefficients a_{ikl} were obtained in explicit form by Davis,[14] but these expressions are unsuitable for direct calculation and we therefore used the recurrence relations[1]

$$a_{iii} = 1, \quad a_{iil} = -\sum_{k=l}^{i-1} a_{ikl}, \quad a_{ikl} = \frac{1}{p_i - p_k} \sum_{j=k}^{i-1} p_i^j a_{jkl}, \quad (5)$$

where

$$p_i = \rho c / \lambda_i, \quad p_i^j = p_i P_{ji} / (1 - P_{jj}).$$

For computation of the coefficients a_{ikl}, as we can see from formula (5), we must give the fragmentation parameters P_{ji}, which are also used in expression (4).

Many theoretical and experimental studies have been devoted to the fragmentation parameters, and at the present time we can consider that these parameters are rather reliably determined in the relativistic energy region.[3,15-18] The parameters $P_{H_1\alpha}$, $P_{H_2\alpha}$, $P_{H_3\alpha}$, and the parameters for fragmentation into the nuclei He^3 and D are exceptions. For these nuclei, in view of the absence of data for relativistic energies, we took the fragmentation parameters obtained in Refs. 10 and 19 for non-relativistic energies (kinetic energy of the order of 200—300 MeV/nucleon). This fact introduces a definite error into the results; however, if we take into account that at energies above several hundred MeV the fragmentation parameters already depend only weakly on energy, we can hope that the error introduced does not exceed the inaccuracy in determination of the parameters themselves. In regard to the remaining parameters we note the following.

Since, as we will see later, the flux of group H_2 nuclei detected at the earth is compatible with the complete absence of these nuclei in the cosmic-ray sources, the effect of an uncertainty in the parameter $P_{H_2H_2}$ is negligibly small. In the present paper the fragmentation parameters $P_{H_2H_2}$ and $P_{H_3H_3}$ are assumed equal. The parameters P_{H_1L}, P_{H_2L}, P_{H_3L}, and P_{ML} require further refinement in the first place, since the thickness of matter traversed, which is determined from the L-nuclei, depends substantially on them. All of the fragmentation parameters used are collected in Table III.

Calculation by means of formula (1) of the amount of matter traversed by cosmic rays in the galaxy before incidence on the earth, on basis of nuclei of group L, gives for the regular model the value $x = 3.9 \pm 0.4$ g/cm^2, and for the diffusion model $x = 3 \pm 1$ g/cm^2.

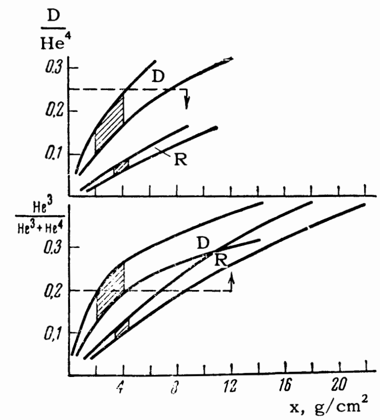
Since there are no reliable data at the present time on the flux of He^3 nuclei at the earth, we determined the relation between the thickness traversed, obtained by solution of Eq. (1) for He^3 nuclei, and the value of the ratio $He^3/(He^3 + He^4)$ for the two models. This relation is shown in the figure. The region R represents the values of amount of matter traversed, x, obtained for the regular model if the fluxes of nuclei of the different groups at the earth lie within the interval shown in Table I; the region D represents the values of x obtained for the diffusion model. The cross-

Table II. Interaction length in the interstellar medium

Group of nuclei	Λ, g/cm^2
$H_1 \equiv VH$	2,5
H_2	3,2
H_3	4,3
M	6,1
L	10
He^4	20
He^3	25
D	33

Table III. Fragmentation parameters in the interstellar medium

	$H_1 \equiv VH$	H_2	H_3	M	L	He^4	He^3	D
H_1	0,44	0,16	0,14	0,09	0,12	0,22	0,05	0,10
H_2		0,30	0,28	0,32	0,12	0,60	0,10	0,10
H_3			0,28	0,32	0,24	0,60	0,10	0,10
M				0,15	0,32	1,22	0,33	0,17
L					0,15	1,09	0,20	0,20
He^4						0,41	0,40	0,20
He^3							0,40	0,20
D								0,5



hatched "allowed" regions indicate the values of x which agree with the determinations for the L group. The total range of values of the ratio $He^3/(He^3 + He^4)$ which agrees with any model is 0.09—0.26.

We can see from the figure that the cross-hatched regions overlap for certain values of the ratio $He^3/(He^3 + He^4)$, namely in the region 0.12—0.14. It has already been pointed out that there is a definite inaccuracy in the fragmentation parameters. However, refinement of the parameters, while important in itself, will result primarily in a general shift of the whole picture and will have comparatively little effect on the relative locations of the "allowed" regions. Therefore in this case a more important role will be played by decreasing the errors in determination of the fluxes of the different nuclei at the earth (if, of course, the error in the fragmentation parameters is not so great as to change the whole picture substantially).

In the final analysis this will lead to a non-overlapping of the "allowed" regions, which will make it possible to solve the question of the applicability of the different theories of cosmic-ray motion in the galaxy. However, we can already state at this time that in the case when the value of $He^3/(He^3 + He^4)$ is greater than 0.15, this will be direct evidence that the real nature of cosmic-ray motion in the galaxy corresponds more to the diffusion model; on the other hand, a value of the ratio less than 0.15 would argue in favor of the regular model of the motion.[3)]

A similar calculation has been made for D nuclei. The same figure shows the connection between the region of values of thickness of matter traversed, for the regular model (region R) and the diffusion model (region D), and the ratio of the fluxes of D and He^4 at the earth. The cross-hatched regions, as in the case of He^3, give values of x which agree with the determinations based on the L group. The cross-hatched regions for D do not overlap for any value of the ratio D/He^4. However, it should be noted that in this case further refinement of the fragmentation parameters and fluxes is necessary.

The figure shows the upper limit of the ratio D/He^4 on the assumption that the flux of D amounts to 5 particles/m^2-sec-sr, a value obtained in the work of Ganguli et al.,[9] which was carried out near the equator (threshold energy 8.45 BeV/nucleon); here it is assumed that the D nuclei have the same energy spectrum as the He nuclei.

The flux of He nuclei is rather well known over a wide range of energies (see for example Ref. 21). In addition, we have marked in the figure the lower limit of the ratio $He^3/(He^3 + He^4)$ obtained by Balasubramanyan et al.[12] If we assume that the lower limit of this ratio corresponds to reality, we can conclude that the diffusion model of cosmic-ray motion in the galaxy is valid; this model, for this value of $He^3/(He^3 + He^4)$, gives the same thickness both for L nuclei and for He^3.

It is clear from the discussion above that measurement of the fluxes of He^3 and D nuclei in the relativistic region, together with improved measurements of the fluxes of the remaining nuclei and the fragmentation parameters, will permit us to choose quite reliably between the above two models. The preliminary data[12] already in existence, and also theoretical considerations,[1] favor the diffusion model. The final experimental solution of this problem presents considerable interest, especially in connection with the recently discussed nonstationary model of the origin of cosmic rays in the galaxy in explosions in the region of the galactic core.[22,23] As we have pointed out above, the regular model of cosmic-ray propagation in the galaxy corresponds to the nonstationary model with respect to chemical composition. Therefore the unsuitability of the regular model for explanation of the observed composition would be a serious argument also against the hypothesis of the nonstationary generation of the main part of the cosmic rays in the galaxy.

In conclusion we will dwell briefly on the composition of cosmic rays at the sources. Table IV

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3)According to the data for the nonrelativistic energy region,[4,7,20] the ratio $He^3/(He^3 + He^4)$ amounts to 0.20 ± 0.05. If this result also applies in the relativistic energy region, the regular model can be considered unsuitable for description of cosmic-ray propagation in the galaxy. We note that the preliminary data [12] for relativistic energies favor a comparatively large value of the ratio, $He^3/(He^3 + He^4) \geq 0.2$.

Table IV. Composition and sources of cosmic rays

	H_2/H_1	H_3/H_1	M/H_1	L/H_1	He^4/H_1
Diffusion model	0.09	2,3	8,8	0	86.4
Regular model	0.00	2.1	7.8	0	83.8
Abundance in the Universe	0.8–3.2	15–16	44–202	10^{-4}	4300–20800

lists the composition at the sources for the regular propagation model (x = 3.9 g/cm^2) and the diffusion propagation model (x = 3 g/cm^2). Both models indicate the practically complete absence of nuclei of group H_2 in the sources. Since the natural abundance of the chemical elements gives a ratio $H_2/H_1 \geq 1$ (see Table IV and Ref. 2), this result can be due either to a major difference of the abundance of the elements in the source from their natural abundance, or to a selective nature of the acceleration mechanism of heavy cosmic particles. In regard to the possibility of error in the value chosen for the parameter $P_{H_1H_2}$, this error can hardly be important since in the observed composition (see Table I) the nuclei of group H_2 are already considerably fewer than nuclei of group H_1. Refinement of the experimental data on the fluxes of nuclei of the groups H_1, H_2, and H_3 is especially important in this connection, since in the case of the preferential acceleration of heavy elements (see Ref. 1) we would expect a monotonic increase with Z of the excess of cosmic-ray nuclei in the source with respect to the natural abundance of these nuclei. As can be seen from Table IV, the diffusion model, within the accuracy of the existing data, is consistent with the behavior of the cosmic-ray composition at the source, while the regular model leads to a sharp dip in the region of group H_2 nuclei.

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