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STRUCTURE OF IRREGULAR GALACTIC MAGNETIC FIELDS DETERMINED ON THE BASIS OF COSMIC RAY MEASUREMENTS

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ABSTRACT

Based on galactic cosmic ray anisotropy measurements and theoretical results concerning the relation of particle diffusion to the structure of the irregular magnetic field the power spectrum of the galactic magnetic field irregularities is estimated. Assuming the confining volume to be independent of particle energy the spectral index of magnetic irregularities is found to be between -0.5 and -1.5. Results obtained are in agreement with recent theoretical results concerning particle diffusion in the galaxy which support the 'macro' anisotropy model.

АННОТАЦИЯ

Опираясь на измерения анизотропии галактического космического излучения и на результаты теории, связывающей диффузию частиц со структурой нерегулярного магнитного поля, мы даем оценку спектра нерегулярностей галактического магнитного поля. Предполагая объем захвата, независимый от энергии частиц, спектральный показатель магнитных нерегулярностей дается между значениями -0.5 и -1.5. Полученные результаты находятся в согласии с новейшими, касающимися внутри галактической диффузии заряженных частиц, теоретическими результатами, которые опираются на модель "макро-анизотропии".

KIVONAT

Galaktikus kozmikus sugárzási anizotrópia-mérésekre és a részecske-diffuziót az irreguláris mágneses tér szerkezetével összekapcsoló elméleti eredményekre támaszkodva becslést adunk a galaktikus mágneses tér irregularitásainak spektrumára. Részecskeenergiától független befogó tartományt feltételezve a mágneses irregularitás spektrál kitevője -0.5 és -1.5 közötti értéknek adódik. A kapott eredmények összhangban vannak a töltött részecskék galaxisbeli diffuziójára vonatkozó ujabb elméleti eredményekkel, amelyek a "makro-anizotrópia" modellt támasztják alá.

1/ There are various methods to investigate integral properties of galactic magnetic fields experimentally /see e.g. the paper of Verschuur [1] for a comprehensive review/. Little or nothing is, however, known experimentally on the nature of the random component of these fields, at least as far as structures with characteristic lengths of the order of less than $\sim$ 1 pc are considered. In this paper a method will be described to determine the structural composition of random galactic fields on the basis of cosmic ray measurements, down to structures with characteristic lengths of the order of 0.001 to 1 pc.

Magnetic fields, the direction and magnitude of which vary randomly in space, can be characterized by their power spectra, i.e. by the function

$$M(k) = \int_{-\infty}^{+\infty} C(r)\exp(-i2\pi rk)dr \ .$$

with C(r) being the coherence function of the random field. It will be shown, in what follows, that the form of the function M(k) can be determined on the functions a(E), i.e. the anisotropy of galactic cosmic rays as a function of energy and L(E), the total path length of galactic cosmic rays as a function of energy. An attempt will be made to apply the procedure on the basis of our present knowledge of the function a(E) and L(E).

The energy range of the cosmic ray particles in question will approximately be 10^{12} eV $\lesssim E \lesssim 10^{15}$ eV. The lower limit ensures that the energy density of the particle radiation will be low enough to leave unaffected the traversed magnetic field on one hand, and excludes the possibility of the observed cosmic ray anisotropy being produced by interplanetary magnetic fields, on the other. The upper energy limit ensures that the concept of diffusion may be applied to describe the propagation of the particles considered.

2/ Let us proceed with deriving the energy dependence of λ_p, the diffusion mean free path of cosmic ray particles in the galaxy. For sake of simplicity we assume that the galactic cosmic radiation consists exclusively of protons. There is no principal difficulty in repeating the considerations to be outlined below for the actual chemical composition of the galactic radiation except that our knowledge of the chemical composition is very poor in the energy interval 10^{12} eV $\lesssim E \lesssim 10^{15}$ eV.

In a preceding paper [2] which will be referred to as Paper I in what follows arguments have been brought forward in favour of the "compound diffusion" [3] of cosmic ray propagation in the galaxy. According to this model we have got two relations between a, the anisotropy, D, the linear size of the volume to which cosmic ray particles are confined, L, the total path length of cosmic ray particles within this volume, λ_p, the diffusion mean free path of the particles, and λ_m, the characteristic length /mean free path/ of the "random walk" of magnetic field lines. The relations are the following:

$$D = a\,L \qquad \text{and} \qquad \lambda_m^2\,\lambda_p = a^4\,L^3, \qquad /1,\ a - b/$$

where constant factors of the order of unity were neglected.

The functions $a(E)$ and $L(E)$ can, on principle, be determined experimentally. $a(E)$ can be measured directly /compare Paper I/ and $L(E)$ can be evaluated on the basis of measurements concerning chemical composition of galactic cosmic rays [4,5,6]. According to Eq(1a), the product of $a(E)$ and $L(E)$ immediately gives the energy dependence of D, i.e. the linear dimension of the confinement region.

So as to deduce $\lambda_p(E)$, an assumption has to be made as to the form of $\lambda_m(E)$. We shall suppose that λ_m is independent of E. This seems to be reasonable on the basis of the assumptions made in the compound diffusion model, in particular that particles are spiralling along field lines whilst these latter are carrying out random motion in space.

On the basis of Eq(1b) we have then

$$\lambda_p(E) \sim a^4(E)L^3(E) \qquad /2/$$

3/ Now, let us make resource to the formula of Jokipii [7] according to which for high energy protons, where particle rigidity and particle energy may be interchanged,

$$\lambda_p = \frac{E^2}{\pi M(k)} \qquad /3/$$

and $M(k)$, the amplitude of the power spectrum of magnetic irregularities, has to be taken at

$$k = 1/r_g(E)$$

where $r_g(E)$ stands for the gyroradius of the particle with energy E in the magnetic field in question. Since we are considering protons of energies between 10^{12} eV and 10^{15} eV, where particle rigidity and energy are interchangeable, Eq /3/ may be applied and, in addition to this, we may write

$$k = 1/r_g(E) = B/E, \qquad /4/$$

with B denoting the average strength of the magnetic field within the volume of confinement of the particles. On the basis of Eqs /2/, /3/, and /4/ we have

$$M\left(\frac{B}{E}\right) \sim \frac{E^2}{a^4(E)L^3(E)} . \qquad /5/$$

Eq /5/yields the form of M(k), the power spectrum of magnetic irregularities. If a(E) and L(E) are power functions of E, i.e.

$$a(E) \sim E^{\eta} \qquad \text{and } L(E) \sim E^{-\beta} \qquad /6\ a - b/$$

then M(k) too will be a power function, since according to Eqs /5/ and /6/

$$M(k) \sim k^{-(2+3\beta-4\eta)} \qquad /7/$$

Assuming the average field strength in the galaxy to be of the order of 10^{-6} Oe, protons of energies 10^{12} to 10^{15} eV will have gyroradii roughly 0.001 to 1 pc. Eqs. /5/ and /7/ may thus be applied in the region where

$$0.001 \text{ pc} < k^{-1} < 1 \text{ pc}.$$

It is usual to assume M(k) to be of the form of a power function:

$$M(k) \sim k^{-\alpha}$$

Eq /7/ gives the following expression for α in terms of η and β:

$$\alpha = 2 + 3\beta - 4\eta \qquad /8/$$

4/ Present experimental results do not allow to draw definite conclusions as to the values of η and β, i.e. the energy dependence of anisotropy and total path length of galactic cosmic rays, respectively. The following crude estimates can, however, be obtained:

On the basis of Fig. 1 of Paper I one may tentatively assume η values like

$$0.3 \lesssim \eta \lesssim 0.5 \qquad /9/$$

This estimation is supported mainly by the result of the measurement reported on in Paper I. Smaller values of η are improbable since otherwise the London measurement [8] carried out at rigidities around 10^{11} V would have given definite anisotropy instead of an upper limit only, and larger values of η are improbable by similar arguments concerning rigidities of $\sim 10^{15}$ V and various other measurements. /Compare Fig. 1 of Paper I./

On the basis of Fig. 3 of the paper of Ramaty and al. [6] one may tentatively assume

$$0.1 \lesssim \beta \lesssim 0.3 \qquad /10/$$

in the energy range $1 \lesssim E \lesssim 50$ GeV. Nothing is yet known as to the value of β in the energy range 10^{12} eV $\lesssim E \lesssim 10^{15}$ eV. Assuming, somewhat arbitrarily, that Eq. /10/ remains valid also in this energy range and putting

$$\eta = 0.4 \pm 0.1 \qquad \text{and} \qquad \beta = 0.2 \pm 0.1$$

one obtains on the basis of Eq. /8/

$$M(k) \sim k^{-(1.0\pm 0.5)}$$

Furthermore, on the basis of Eqs(1a) and /6a-b/, one has

$$D(E) \sim E^{0.2\pm 0.15}$$

i.e. D, the linear size of the confinement volume depends but weekly on E.

5/ One may, as an alternative to the procedure outlined in paragraph 2, assume that D, the linear size of the confinement volume, is independent of energy and disregard one of the functions a(E) and L(E).

Retaining a(E), we have, on the basis of Eqs. /1a-b/ and λ_m=const,

$$\lambda_p(E) \sim a(E)$$

and thus

$$M\left(\frac{B}{E}\right) \sim E^2/a(E);$$

or

$$\alpha = 2 - \eta.$$

This would result in $\alpha = 1.6 \pm 0.15$, a value which is near to that of α_k = = 5/3, the exponent of a Kolmogorov spectrum imposed by Skilling et al [9].

Retaining L(E) one has, again with Eqs. /1a-b/ and λ_m = const,

$$\lambda_p(E) \sim 1/L(E)$$

and thus

$$M\left(\frac{B}{E}\right) \sim E^2 L(E)$$

or

$$\alpha = 2 - \beta$$

which would yield $\alpha = 1.8 \pm 0.15$, again in reasonable agreement with $\alpha_k = 5/3$.

6/ In conclusion it may be stated that the form of the power spectrum of galactic magnetic irregularities may be determined on the basis of measurements concerning energy dependence of anisotropy and chemical composition of cosmic rays in the galaxy. The level of accuracy of these measurements is rather low at present, and thus the information obtained on the form of the galactic magnetic power spectrum is rather poor. Considerable efforts are, however, being made to increase the accuracy of the measurements in question and this will certainly result, in addition to many interesting direct results, also in improving our knowledge on the magnetic structure of the galaxy.

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