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A model of galactic magnetic fields inferred from cosmic ray propagation

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Abstract. A model of galactic magnetic fields is proposed. The cosmic rays are scattered by the region with random isotropic magnetic fields, which looks like Brown motion in the galaxy. Comparing with the escape length observed by HEAO-3 and others, the average characteristics of galactic magnetic fields like the average distance and size of the scattering regions are derived.

1 Introduction

The cosmic rays are propagating in the Galaxy being scattered by the magnetic fields. But the phenomenological model of the propagation, the leaky box model cannot be related to the galactic magnetic fields (GMF), though it is most commonly used. The alternative model is based on the diffusion equation. In this case, the diffusion constant express the average behavior of GMF, but it does not explain any realistic structures of GMF. Here we present a model, which contains the average structure of GMF inferred from the cosmic ray propagation.

2 A Model of the Galactic Magnetic Field

We assume that cosmic ray particles are scattered at the regions placed at the three dimensional lattice points. In this region, there exist random magnetic fields, which cause the scattering of cosmic ray particles. The cosmic ray particles moves like Brownian motion particles in the galaxy. The spacing and size of the scattering regions and fields in this region are adjusted to the observation.

2.1 Two-Dimensional Model

To understand the essential feature of this model, the two-dimensional galaxy of the square with the side of 20 kpc long is considered first. [Hachisuka, K. (1998)]

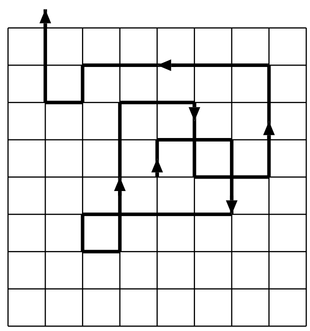

Fig. 1. Two-Dimensional Model

Cosmic ray particles are moving along the lattice. At each lattice point, the cosmic ray particle is scattered. The scattering is assumed to be not isotropic to introduce the fact that the higher momentum particle persists to go straight. This situation is introduced by the parameter as follows:

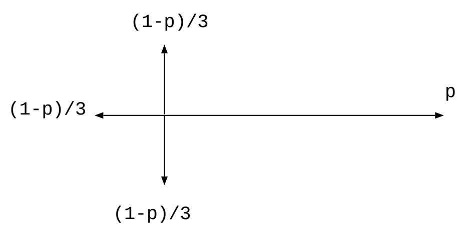

Fig. 2. Scattering in Two-Dimensional Model

$$p = \frac{1}{1 + \frac{3}{q}} \tag{1}$$

q is the momentum-like parameter and p is the probability going in the same direction on the lattice, the probability to change the direction is $(1-p)/3$ for all other 3 directions.

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This simple model can reproduce the rigidity dependence of the observed escape length, which indicates that the confinement of the cosmic rays in the galaxy shall be explained by the scattering by the magnetic fields.

2.2 Three-Dimensional Model — primitive

The lattice is three-dimensional and Brownian motions along the lattice points are examined.[Miura, Y. (1999)]

In the case of isotropic scattering at the lattice point, we can obtain the analytical results to compare with the Monte Carlo simulation. When cosmic ray particle has the tendency to keep the moving direction, the rigidity dependence of the observed escape length is again reproduced.

2.3 Three-Dimensional Model with scattering regions

So far the scattering takes place only at the lattice points, which is far from realistic though it is useful to understand the features of the model. Therefore we introduce the scattering region of the finite size.[Takahashi, K. (2000)]

The shape and parameters of the galaxy used here is summarized in the Table 1 and Figure 3.

Table 1. parameters of the galaxy

the shape	cube
the edge length of the cube	$2L = 20$ kpc
thickness of the disk	$2D = 500$ pc
spacing of the scattering regions	$l = 20$ pc

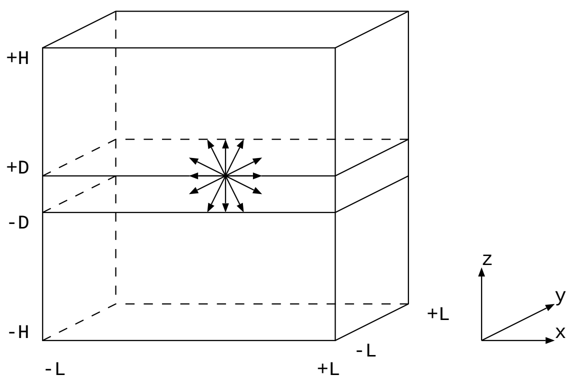

Fig. 3. Galaxy used in our simulation

In this galaxy, there are scttering regions located at the lattice point with the spacing of l. This scattering region, which is also cube with the edge length of a, is divided into smaller cubes (the magnetic cube) with the u long edge. This structure of our galaxy is shown in Fig. 4.

In the magnetic cube, each component of the magnetic fields is followed by Gaussian distribution with the analogy of the isotropic uniform turbulence.

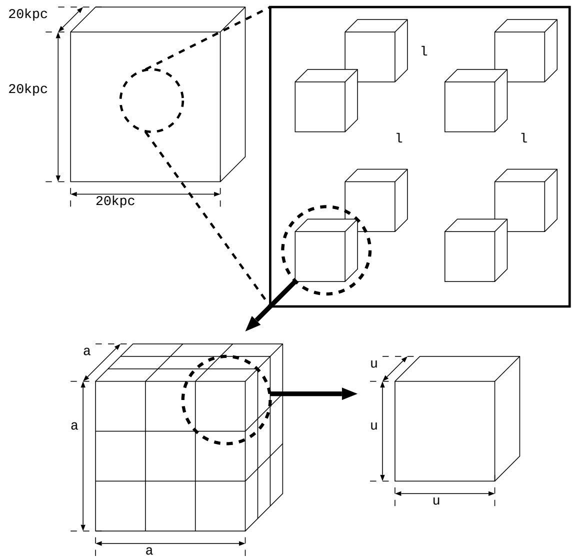

Fig. 4. Structures of the Galaxy

$$f(B_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{B_i}{2\sigma^2}} \quad (i = x, y, z) \tag{2}$$

$$\langle |\boldsymbol{B}| \rangle = 3\mu \text{ Gauss to fix } \sigma \tag{3}$$

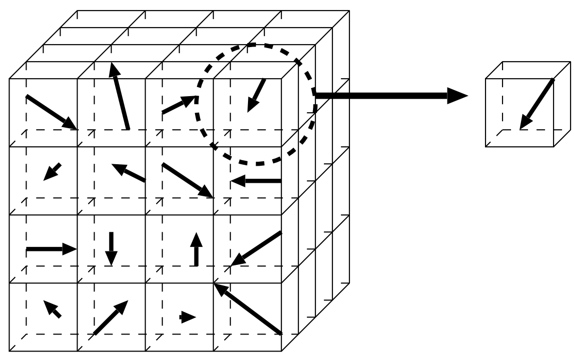

Fig. 5. Magnetic fields in the magnetic cube

3 Simulation Procedure

The simulation procedure [Ishikawa, T. (2001)] is as follows for the proton with a certain value of the momentum.

1. start from the center of the galaxy with isotropic distribution

   We use protons as the cosmic ray particles.

2. scattered in the magnetic cube where particles are deflected by the Lorentz force of the magnetic field

3. follow until the cosmic ray particle escapes from the galaxy and calculate the total track length

Repeating the procedure above 1000 times for each parameter set, the mean escape length is calculated.

4 Results

The simulation results are compared with the escape length depending on rigidities by HEAO-3-C2 [Garcia-Munoz, M., et.al. (1977)], which is parameterized as follows:

$$\lambda_{esc} = \begin{cases} 34.1\beta R^{-0.6} & \text{g/cm}^2 \quad (R > 4.4GV) \\ 14.0\beta & \text{g/cm}^2 \quad (R < 4.4GV) \end{cases} \tag{4}$$

Material densities in the galaxy we employed are shown in Table 2.

Table 2. material density in the galaxy

disk	1 hydrogen atom /cm^2
halo	0.28 hydrogen atom /cm^2

But to find general behaviors of cosmic ray protons in our galaxy, we simulate in the homogeneous galaxy without the halo. In this case we used the weighted average of the matter density, 0.3 hydrogen atoms / cm^2. Changing the parameters of a (the edge length of the scattering cube) as shown in Table 3 and u (the edge length of the magnetic cube), we carried out the simulations as follows:

Checking the results of simulations above, the parameters to reproduce the experimental results of the equations 4 are:

$$a = 4 \times 10^{-1} \text{ pc}$$
$$u = 1 \times 10^{-3} \text{ pc}$$

and the comparison is shown in Fig. 6.

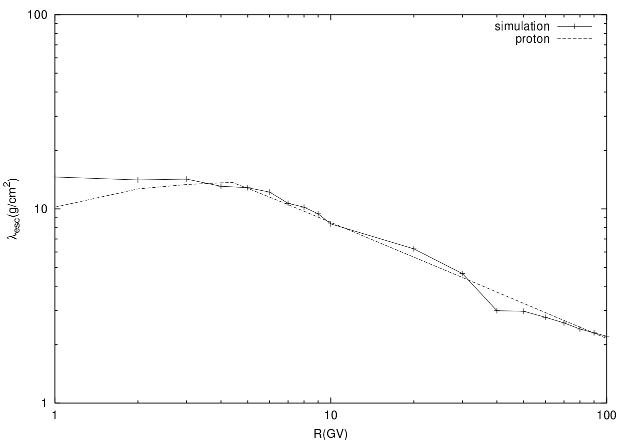

Fig. 6. Comparison of simulation results with the experimental result

Up to now, the source point of the cosmic rays is located at the center of the galaxy. The source is thought to be uniformly distributed in the disk of the galaxy. So we checked the effect of the source point location. The source point is located in the disk plane but off by 5 kpc in x and y directions.(Figure 7)

Table 3. parameters of the simulations

the edge length [pc]	
scattering cube	magnetic cube
1	10^{-1}
1	10^{-2}
1	10^{-3}
10^{-1}	10^{-2}
10^{-1}	10^{-3}
10^{-1}	10^{-4}
10^{-2}	10^{-3}
10^{-2}	10^{-4}
10^{-2}	10^{-5}

Thus the location of the source does not change the general tendency strongly. We will use the central source point only.

When we take into consideration the disk-halo structure of the galaxy, the parameters we choose are as shown in Table 4.

Table 4. parameters for disk-halo model

parameter	disk	halo
spacing of the scattering region	10 pc	100 pc
edge length of scattering cube	10^{-1} pc	4×10^{-4} pc
edge length of magnetic cube	10^{-4} pc	10^{-4} pc

We can see the satisfactory agreement of the simulation result with the experimental data in Figure 8.

5 Conclusion

Assuming the magnetic fields in the galaxy to be Gaussian type, we can find the size and spacing of the scattering regions and the size of magnetic cube (the random scale of

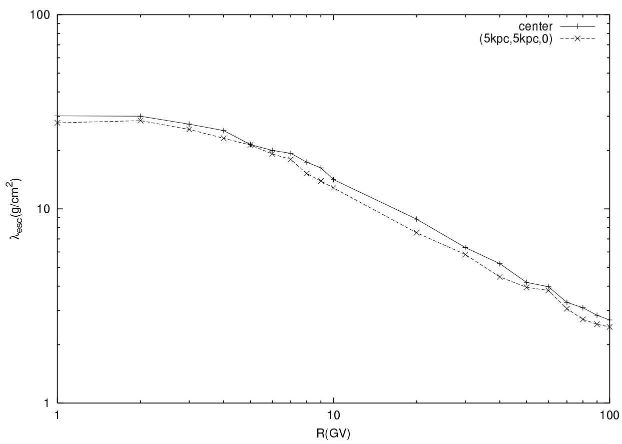

Fig. 7. Comparison of simulation results with the experimental result

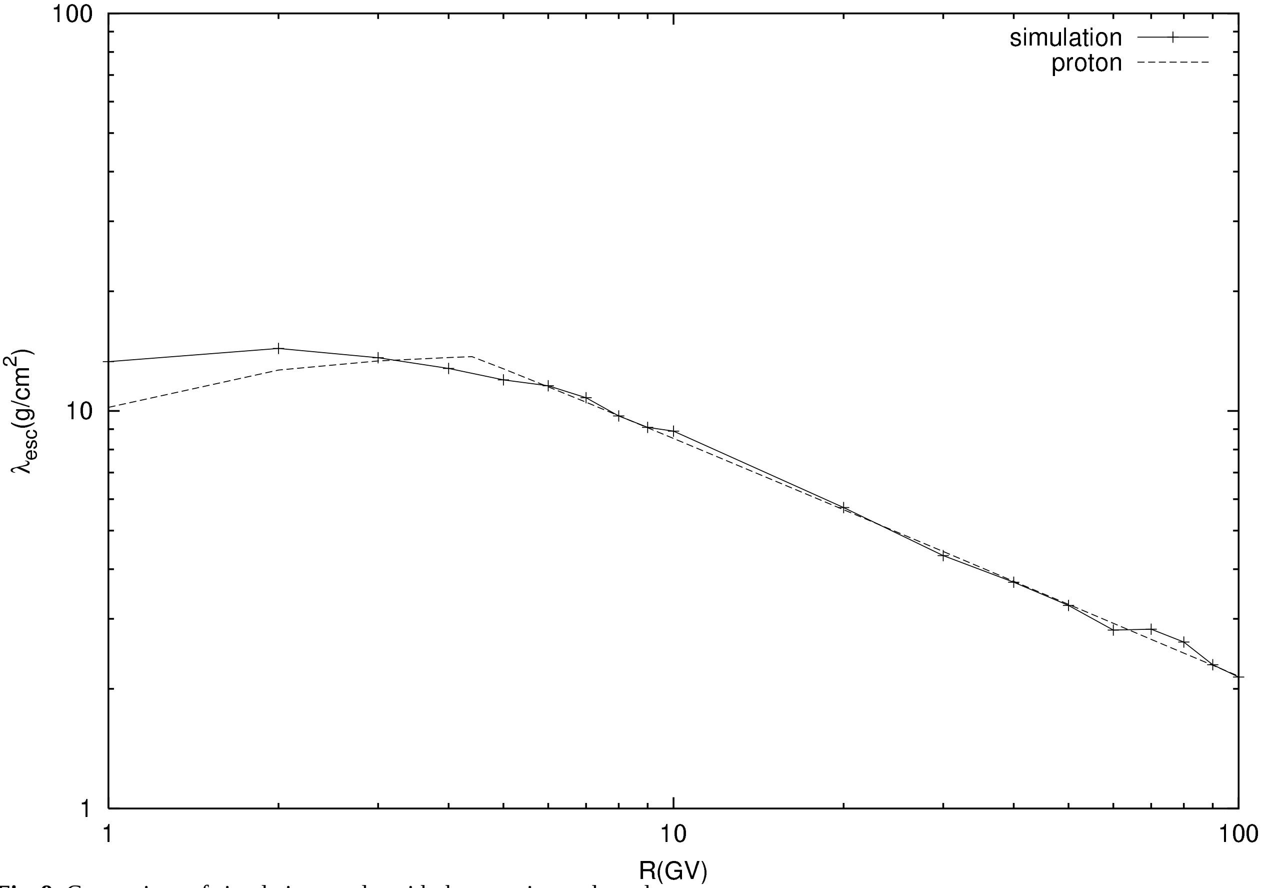

Fig. 8. Comparison of simulation results with the experimental result

the magnetic field) by the compariosn of the experimental results.

We would be able tp understand the structure of the galactic magnetic field in this direction.

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