A Simulation of High Energy Cosmic Ray Propagation II

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Abstract

The cosmic ray propagation in the Galactic arm is simulated. The Galactic magnetic fields are known to go along with so called Galactic arms as a main structure with turbulences of the scale about 30pc. We study the distribution of cosmic ray in Galactic arm and discuss the escape time and the possible anisotropies caused by the arm structure.

1 Introduction

In the previous paper(1), we have reported a method to simulate the propagation of the cosmic ray in the turbulent magnetic fields. (We refer that paper as I here after). In this paper, we make a little extension of the work in I. The magnetic field in Galaxy is now considered to be alined along the Galactic arm. We simulate the propagation of the cosmic ray in the Galactic arm. It is expected that the cosmic ray is trapped in magnetic field of arm just like in TOKAMAK. We are interested in the distributions of cosmic rays in the Galactic arm by following reasons. As the origin of anisotropy of the arrival direction of cosmic ray, one may consider two reasons; the source distribution and the propagation in the Galaxy (including the leakage from it). If the distribution of the cosmic ray is not uniform, we can expect the anisotropy from the latter reason. As many authors suggested, the main reason of the acceleration of cosmic ray is by the shock waves from the supernova(2), the both reasons for anisotropy can be considered as the same thing. The study of the distribution of cosmic ray becomes important. We will study the possible anisotropy caused by the arm structure (or by the distribution of cosmic ray in the arm) and the escape of cosmic ray from the Galactic arm.

2 Magnetic field in Galactic Arm and Model

The method of Rotation Measure as well as others(3-4) gave us the informations of the Galactic magnetic fields. It can be summarized as follows; the main structure of magnetic fields is aline along the Galactic arms and its average strength is 3.0 micro gauss. About the turbulence of magnetic fields, the strength is about 1.5 micro gauss and the scale of the turbulences is 10-30pc in average.

As a model of the Galactic arm, we consider a right cylinder with the radius of 300pc, which is comparable to the thickness of Galactic disc determined by the rotation measure. We identify the axis of the cylinder with the z-axis. The 'average' magnetic field is assumed to be alined along the cylinder axis. The magnetic field is assumed as the sum of 'average' one and the turbulent ones. The 'average' magnetic fields varies with radius by

$$H(r)= H_0 x \exp(-r^2/r_0^2) \quad , \qquad (1)$$

where r_0 is taken to be the radius of galactic arm; 300pc. H_0 is determined so that the average of the magnetic field inside the arm is 3 micro gauss. (The average of turbulent magnetic fields is 0.) The generation of turbulent magnetic fields is essentially same with I. However, the strength of the turbulent magnetic fields with same r is generated proportional to 'average' magnetic field in average. The scale of magnetic fields' turbulence are taken 30pc.

3 Simulation

The simulation is executed almost same way with I. However, in this case the initial distribution of cosmic ray is taken as the uniform distribution in the Galactic arm. The directions of velocity are assume uniform. When a cosmic ray goes beyond r_1 from the arm axis, it is considered to escape from the arm. In this simulation r_1 is taken 600pc, with which distance, the gyro radius in the magnetic field given by (1) is comparable to or larger than r_1 for protons with energy greater than $10^{16.5}$ eV. (In this paper, we assume implicitly that the cosmic rays are protons.) We observe the distribution of cosmic rays and calculate the escape probability of cosmic ray from the arm. To save the cpu time, we made a trick that the escaped particles are resumed into the arm with the position determined by the probability proportional to the distribution of other cosmic rays. This resumption is executed for the every time step corresponding to 250 years. With this trick the number of cosmic rays in simulation is kept constant. The escape probability is calculated from the resumed particle number after the distribution of cosmic ray is considered stational for a few 10^4 years. The step time for the calculation of cosmic ray particle motion is taken 1 year for 10^{16} eV and $10^{16.5}$ eV and 10 years for greater energy than 10^{17} eV. The step time is same or smaller than that of I.

4 Result

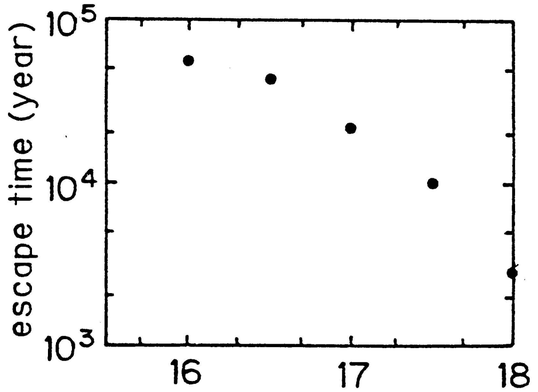

Fig. 1

In fig.1, we show the escape time calculated by the escape probability. It is interesting that the escape time for the cosmic ray with energy $10^{16-16.5}$ eV is consistent with the extrapolation of the life time of lower energy by $E^{-(0.3-0.4)}$. The slope of the escape time larger than $10^{17.5}$ becomes steeper, which can be considered as the reflection of the structure of the Galactic arm. We note the escape time of the energy 10^{16} eV may show a smaller value, because the r_1 used in this simulation is too small to consider that the cosmic ray at r_1 surely escape from the arm. They can be return into the arm with the gyro motion by the magnetic field. In the region $10^{16.5-17.5}$ eV, the escape time is proportional to $E^{-(0.5-0.6)}$.

In fig.2, we show the r-distributions of the cosmic ray for various energy after 10^5 years when the distribution of cosmic ray is considered already stational. The r-distribution of cosmic ray with the energy lower than $10^{17.5}$ eV show a similar feature. In this energy region the cosmic ray density decrease exponentially. We can consider that the cosmic rays are trapped in the Galactic arm. The r-distribution with the energy 10^{18} eV show a large difference from the lower one, which shows a slower decrease with r. This distribution suggests that the cosmic ray is not trapped in the arm so long time and easily escape from the arm. This is also shown in the escape time of this energy. It also noted that the distribution of cosmic ray with the energy 10^{16}eV is different from the $10^{16.5-17.5}$eV in the shape of the slope. This may indicate the distribution of cosmic ray with that energy is still in the course of the formation of stational form within the simulation corresponding to 10^5 years. After the formation of the stational form, the escape probability can be smaller.

In fig.3, we show the V_θ in average over all cosmic rays for various energies. V_θ is defined by;

$$V_\theta = \frac{X\cdot V_y - Y\cdot V_x}{\sqrt{X^2 + Y^2}} \qquad (2)$$

We can see the V_θ become considerably large for larger energy than $10^{16.5}$eV. It takes its maximum at $10^{17.5}$ and in the energy 10^{18}eV it becomes smaller value. This value have direct relation to the anisotropy of the arrival direction of cosmic rays. In the energy $10^{16.5}$eV, we can expect a few % of excess of the number of cosmic rays coming from the rotational direction around the arm axis and in the energy $10^{17.5}$eV a few 10%. In the energy of 10^{16}eV, this value also show a non-zero V_θ value. However, this value fluctuates with time and also varies with r. We are not sure the we can expect the anisotropy in this energy.

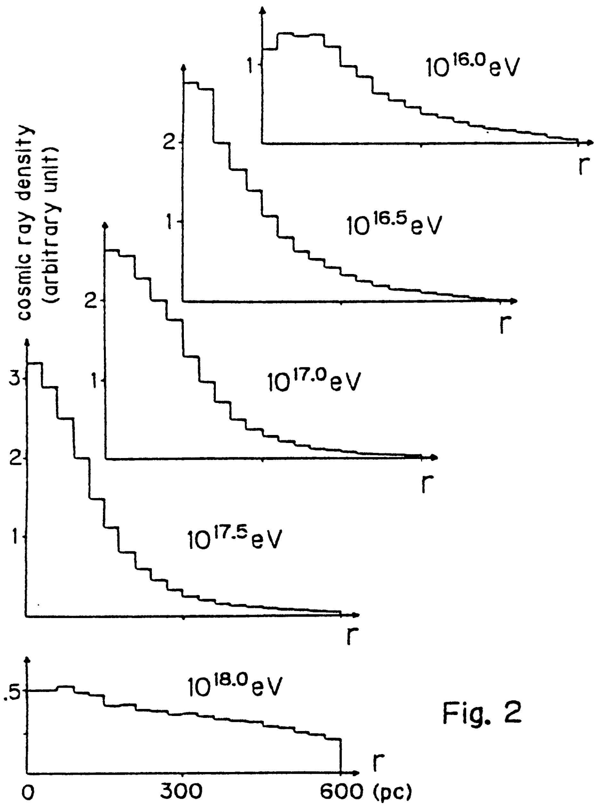

Fig. 2

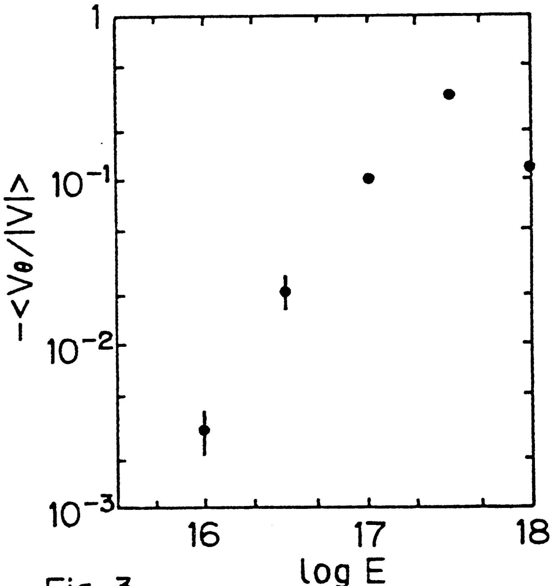

Fig. 3

In fig.4 we show the average of $|V_z/V|$ in various energies. If the direction of cosmic ray velocity is isotropic, this value is 0.5. In the energy 10^{18}eV, it shows a large deviation from 0.5 to a larger value: 0.6. The direction of velocity of cosmic rays, which stay in the arm for long time, are not uniform in this energy. In the lower energy, the value is very near to 0.5. In the context of anisotropy, $|V_z/V| > 0.5$ means there is an excess in the numbers of cosmic rays coming from the direction parallel to the arm axis. In this case the anisotropy is observed as the second harmonics.

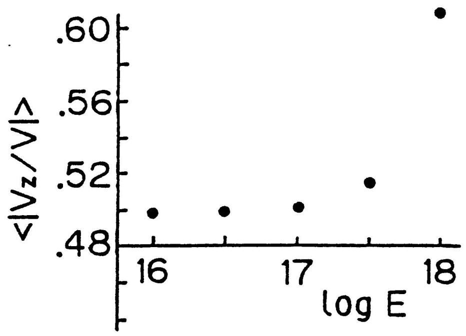

Fig. 4

5 Summary and Discussions

We have shown that the cosmic rays with the energy lower than 10^{18} eV are trapped in the Galactic arm. As the physical consequences, we can expect a few % (first harmonics) anisotropy of the arrival direction of cosmic rays in the energy region $10^{16.5-17.5}$ eV to the rotational direction around the arm axis. We note this is the direct consequence of the distribution of cosmic ray and the gyro-rotation of them in the magnetic field. In the energy 10^{18} eV, the cosmic ray become easy to escape from the Galactic arm. The cosmic ray, which stay long time in the arm have smaller pitch angles. Therefore we can expect the anisotropy of second harmonics to the direction of arm axis. (Of course, if there is typical source near to the Earth, the anisotropy in this energy region is affected by it.) For the lower energy than 10^{16} eV, the effect of arm structure in anisotropy of the arrival direction is uncertain. The anisotropy observed in this energy may be the reflection of the local structure of the Galactic magnetic field. It should be noted the magnitude of the anisotropy predicted here is consistent with the observations(5). However, the direction determined by the observation is different from our result. The observation of the anisotropy in the energy region above $10^{16.0}$ eV have some ambiguity yet caused by poor statistics. The more elaborate experiments are expected.

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