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Electron Heat Transport in a Self-Similar Structure of Magnetic Islands

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A formula for the electron thermal conductivity in a self-similar structure of magnetic islands, e.g. in the edge region of a stellarator equilibrium, has been derived for the collisionless limit. It is described by using the non-Gaussian process with fractal nature. We have shown that the electron thermal conductivity in the edge region is reduced, if magnetic islands are large enough.

Keywords: anomalous conduction, confinement, non-Gaussian process, fractal nature, path integral method

1. Introduction

The subject in this article is to consider the electron heat transport in a self-similar structure of magnetic islands for the collisionless limit. In general, when an equilibrium magnetic field has a symmetry, the equations for a magnetic field line can be written as Hamilton's equations with an integrable Hamiltonian. [1] If the magnetic field is perturbed by a three-dimensional fluctuating magnetic field, then magnetic islands appear in the equilibrium. And in the statistical meaning, the structure with islands has a self-similarity, which is a generic feature in the structure described by a Hamiltonian with relatively large perturbation [2]. For example, the island structure can be found in the edge region of a stellarator equilibrium. While, recently the high temperature divertor plasma operation is considered to improve the energy confinement of helical devices. [3] In the operation, the edge temperature is kept high by the pumping in the divertor chamber. The divertor temperature is estimated by a power balance in the divertor channel, and is expected to become as high as several keV. [3] In the edge region of a helical system, the collisionless-plasma can be realized by this operation. Therefore, the heat transport in a self-similar structure of islands for the collisionless limit will be the realistic issue.

The electron heat transport in the only stochastic magnetic field has been studied by Rechester and Rosenbluth [4]. In the study of Ref.4, the random motion of electrons is described as the Brownian process and the diffusion coefficient is given by the quasilinear formula [5, 6]. While, the random motion in the structure of islands and stochastic sea with fractal nature cannot be described by using the usual Brownian process. The behavior of this motion belongs to the non-Gaussian process, which is represented by

the mean square displacement;

$$\mathsf{MSD} = \left\langle (\Delta x)^2 \right\rangle = \text{const. } t^{\mu}, \qquad (1)$$

and the non-Gaussian parameter;

$$\mathsf{NGP} = \frac{\left\langle (\Delta x)^4 \right\rangle}{3\left\langle (\Delta x)^2 \right\rangle^2} - 1 \neq 0, \qquad (2)$$

where $\langle \cdots \rangle$ means the statistical average and μ is a real-number. Here, if the random motion is the Brownian, then $\mu = 1$ in MSD and NGP $= 0$. Behaviors of Eqs.(1) and (2) were seen numerically in the field-line transport for the case of stochastic static magnetic fields with islands [7]. The motion in a fractal structure seems to be very anomalous, but we can analytically understand these properties by using the representation of random walk in fractal space-time [8]. This analytical method is based on the idea that from the particle's viewpoint, space-time seems to have non-integral dimensions, because the random particles are restricted to move on only fractal medium except for islands.

2. Derivation of the electron thermal conductivity

In this article, according to Ref.8, the electron heat transport theory of Rechester and Rosenbluth [4] is developed to the situation with a self-similar structure of islands for the collisionless limit. We use as an example, which is same as one in Ref.4, a magnetic configuration in cylindrical geometry;

$$\mathbf{B} = \mathbf{B}_z + \mathbf{B}_\theta(r) + \delta\mathbf{B}(r, \theta, z). \quad (3)$$

Note that most concepts in this model can be easily generalized to toroidal configurations. We assume that the system is periodic in the z direction with period $2\pi R$ in order to model toroidal periodicity and both of the rotational transform $\iota(r)/2\pi$ and the shear $\mathrm{d}(\iota/2\pi)/\mathrm{d}r$ are small. Then the fluctuating magnetic field $\delta\mathbf{B}$ can be written as

$$\delta\mathbf{B} = \sum_{m,n} \delta\mathbf{B}_{m,n}(r) \exp[\, \mathrm{i}(m\theta - n\zeta)\,] + \text{c.c.}, \quad (4)$$

where $\zeta = z/R$. Here, ζ means 'time', because of $\mathbf{B}_z \neq 0$ and $|\mathbf{B}_z| > |\delta\mathbf{B}_z|$ in this model. According to Ref.8, the random motion in a fractal structure except for islands can be understood as the Brownian motion in fractal space-time $(\tilde{r}, \tilde{\zeta})$, where $(\tilde{r}, \tilde{\zeta})$ are defined by the Hausdorff length;

$$\tilde{r} = \lim_{\rho \to 0} H_\rho^\alpha(\text{fractal-space}), \quad (5)$$

$$\tilde{\zeta} = \lim_{\rho \to 0} H_\rho^\beta(\text{fractal-time}). \quad (6)$$

Here, α and β are the fractal dimensions of space and time, respectively, which are defined later.

$H_\rho^\ell(X)$ is the length of the set X divided by N parts $\{X_i\}$ and is given by

$$H_\rho^\ell(X) = \inf\left\{ \sum_{i=1}^{N} {d_i}^\ell \,\middle|\, 0 < d_i \leq \rho, X \subseteq \bigcup_{i=1}^{N} X_i \right\}, \quad (7)$$

where ℓ is the Hausdorff dimension of X, and d_i is a diameter of the i-th part X_i and is measured in real space-time (r, ζ). The diffusion coefficient D_0 in fractal space-time is given as

$$D_0 = \frac{\left\langle (\delta\tilde{r})^2 \right\rangle}{2\delta\tilde{\zeta}} = \frac{(\delta r)^{2\alpha}}{2\,(\delta\zeta)^\beta} = \frac{(2\pi)^{2\alpha-\beta}}{2} \left\{ R^2 \sum_{m,n} \left| \frac{\delta B_{m,n}(r)}{B_z} \right|^2 \delta_{nq(r)-m} \right\}^\alpha, \quad (8)$$

where a step size δr can be described as

$$(\delta r)^2 \approx (2\pi)^2 R^2 \sum_{m,n} \left| \frac{\delta B_{m,n}(r)}{B_z} \right|^2 \delta_{nq(r)-m}, \quad (9)$$

time step $\delta\zeta$ is 2π, and $q(r) = 2\pi/\iota(r)$ is the safety factor, (see Ref.1). The distribution function in fractal space-time is given by using the path integral method; [8, 9, 10, 11]

$$f(\Delta\tilde{r}, \tilde{\zeta}) = \frac{1}{C_0} \exp\left\{ -\frac{(\Delta\tilde{r})^2}{4D_0\tilde{\zeta}} \right\} \cdot \underbrace{\prod_{n=0}^{\infty} \prod_{k=0}^{2^n-1} \int_{-\infty}^{+\infty} \mathrm{d}a_{n,k} \, \exp\left\{ -\pi\,(a_{n,k})^2 \right\}}_{\mathsf{A}}, \quad (10)$$

where $C_0 = \{4\pi D_0 \tilde{\zeta}\}^{1/2}$ is the normalizing factor: $\int_{-\infty}^{+\infty} \mathrm{d}(\Delta\tilde{r})\ f(\Delta\tilde{r}, \tilde{\zeta}) \equiv 1$, and $a_{n,k}$ is a coefficient of the Haar expansion [11, 12], (see Appendix A). Note that equation (10) is equivalent to Eq.(9) in Ref.8, [10] and the part A defined in Eq.(10) is not dependent on the coordinates in fractal nor real space-time. Under the expectation that important contributions to the integral of f will occur only for small Δr and ζ: $|\Delta\tilde{r}| = |\Delta r|^{\alpha}$ and $\tilde{\zeta} = \zeta^{\beta}$, we derive the distribution function in real space-time:

$$f(\Delta r, \zeta) = \frac{1}{C} \exp\left\{ -\frac{(\Delta r)^{2\alpha}}{4D_0\zeta^{\beta}} \right\}, \tag{11}$$

where $C = \{\Gamma(1/2\alpha)/\alpha\} \left(4D_0\zeta^{\beta}\right)^{1/2\alpha}$ is the normalizing factor; $\int_{-\infty}^{+\infty} \mathrm{d}(\Delta r)\ f(\Delta r, \zeta) \equiv 1$, and Γ is the gamma function. Thus, the mean square displacement MSD in real space-time is given by

$$\left\langle (\Delta r)^2 \right\rangle = \int_{-\infty}^{+\infty} \mathrm{d}(\Delta r)\ (\Delta r)^2 f\left(\Delta r, \zeta = \hat{\lambda}\right) = 2D\hat{\lambda}^{\beta/\alpha}, \tag{12}$$

where $\hat{\lambda} = \lambda/R$ and λ is the collisional mean free path in the z direction, and the diffusion coefficient in real space-time, D, is described as

$$D = \frac{(4D_0)^{1/\alpha}\Gamma(3/2\alpha)}{2\Gamma(1/2\alpha)} = \frac{2^{(1+\alpha^2-\beta)/\alpha}\pi^{2-\beta/\alpha}\Gamma(3/2\alpha)}{\Gamma(1/2\alpha)} R^2 \sum_{m,n} \left| \frac{\delta B_{m,n}(r)}{B_z} \right|^2 \delta_{nq(r)-m}. \tag{13}$$

When $\alpha = \beta = 1$, the diffusion coefficient D becomes one given by the quasilinear formula in Ref.4. Since the radial spreading of test electrons is the non-Gaussian process, the radial thermal conductivity for the collisionless limit will be given by

$$\chi_r = \frac{\left\langle (\Delta r)^2 \right\rangle}{2\tau} = \frac{D}{\tau}\hat{\lambda}^{\beta/\alpha}, \tag{14}$$

where $\tau = \lambda/v_t$ is the time interval and v_t is the electron thermal velocity.

Dimensions of fractal space-time, α and β, are defined from the self-similar structure of islands. We can consider that because of the self-similarity of islands, the cross section of the cylinder is a kind of the Sierpinski gasket (SG) or carpet (SC) [13]. Thus, dimensions of space and time are defined as

$$\alpha = \frac{\ln N}{\ln \delta}, \tag{15}$$

$$\beta = \frac{\alpha \ln(\delta^2 - 1)}{\ln \delta^2}, \tag{16}$$

where $N = N_0/\delta$; N_0 is the increase-rate of the number of areas except for islands, e.g. $N_0 = \delta^2 - 1$ for the SG/SC, and $\delta = d_0/d$. Here, d_0 and d are widths of the whole fractal structure and the largest island, respectively.

As shown in Eq.(14), we have the new formula for the electron thermal conductivity in a self-similar structure of islands for the collisionless limit. If the size of islands is small ($\delta \gg 1$), then $\alpha \sim 1$ and $\beta \sim 1$, i.e. the diffusion becomes the Brownian given in Ref.4. While, if the size is large enough ($+\infty \gg \delta > 1$), the thermal conductivity is reduced as compared with one in the only stochastic field, because $\chi_r \propto \hat{\lambda}^{\mu}$ and $\mu = \beta/\alpha = \ln(\delta^2 - 1) / \ln \delta^2 < 1$. We can interpret this result as follows. Since the random motion of electrons is suppressed by fractal islands and an electron has to take a detour around islands, the diffusion becomes slow effectively. While, if islands are not large and do not make the fractal structure, the effect of islands on the diffusion is negligible, because the dimension of the structure with islands projected onto the r or the θ axis is equal to unity, i.e. $\alpha = \beta = 1$.

3. Application to the realistic example

Using Eq.(14), we estimate the radial thermal conductivity of electrons, χ_r. Considering the thermal conductivity in the Large Helical Device (LHD) [14] with the major radius $R = 3.9$ m, and assuming that 1) the island structure in the edge region of LHD is represented by Sierpinski's model and 2) the edge temperature $T_e^{\rm edge} = 1$ keV and the edge density $n_e^{\rm edge} = 10^{18}$ or 10^{17} m^{-3} are realized by the high temperature divertor plasma operation, we obtain $\hat{\lambda}/2\pi = \lambda/2\pi R \approx 5 \times 10^2$ or 5×10^3, and the radial thermal conductivity χ_r shown in Fig.1. In Fig.1, the conductivity χ_r is normalized by the Rechester and Rosenbluth conductivity $\chi_r^{\rm st}$, which is defined as [4]

$$\chi_r^{\rm st} = \frac{\pi R^2 \hat{\lambda}}{\tau} \sum_{m,n} \left| \frac{\delta B_{m,n}(r)}{B_z} \right|^2 \delta_{nq(r)-m}. \tag{17}$$

Thus, we can see that χ_r is reduced for the case of $\delta < 10$. Note that in the Sierpinski model, δ is bounded larger than two. [13]

4. Conclusions and discussions

We have discussed the electron heat transport in a self-similar structure of magnetic islands and derived the formula for the thermal conductivity under the collisionless limit condition. Applying the formula to the realistic example (the edge region of LHD), we have shown that the electron thermal conductivity is reduced as compared with one of Rechester and Rosenbluth [4].

We should notice the following fact. Under the condition that the step size of random particles, δr, is constant as in Eq.(9), the random walk on a fractal medium is analytically solved (see Ref.8), and the distribution function (11) is derived. Therefore, the problem treated in this article is different from the problem of the Levy random walk discussed in Ref.15. The Levy random walk is discussed under the assumption that random particles have the set of the step size $\{\delta r\} = \{l_0, l_1, \ldots, l_n, \ldots \mid l_n = l_0 \lambda_l{}^n, \lambda_l \geq 1\}$, where λ_l is the scaling parameter for the length of flights. [15]

To check the validity of our analytic results in detail, we are planning to do a simulation of the heat transport in an equilibrium with magnetic islands, and make a comparison each other.

Appendix A. Derivation of the distribution function

We show here the derivation of the distribution function in fractal space-time, $f(\Delta\tilde{r}, \tilde{\zeta})$, using the Haar expansion. Considering the random motion in a fractal structure except for islands as the Brownian process in fractal space-time $(\tilde{r}, \tilde{\zeta})$, we can introduce the distribution function in fractal space-time by using the path integral method; [8, 9, 11]

$$f(\Delta\tilde{r}, \tilde{\zeta}) = \int \mathcal{D}\tilde{x}(\tilde{t}) \ \exp\left\{ -\frac{1}{4D_0} \int_0^{\tilde{\zeta}} {\rm d}\tilde{t} \ [\tilde{v}(\tilde{t})]^2 \right\}. \tag{A1}$$

By using the Haar expansion [11, 12], the velocity of a random particle in fractal space-time, $\tilde{v}(\tilde{t})$, can be defined as

$$\tilde{v}(\tilde{t}) = \frac{\Delta\tilde{r}}{\tilde{\zeta}} + \left\{ \frac{4\pi D_0}{\tilde{\zeta}} \right\}^{1/2} \sum_{n=0}^{\infty} \sum_{k=0}^{2^n-1} a_{n,k} \ \psi_{n,k}(\tau), \tag{A2}$$

where $\tau = \tilde{t}/\tilde{\zeta}$ is the normalized time; $\tau \in [0,1]$, $a_{n,k}$ is a coefficient, and $\psi_{n,k}(\tau)$ is the orthonormal function;

$$\psi_{n,k}(\tau) = 2^{n-n/2}\ Y_k(2^n\tau), \tag{A3}$$

$$Y_k(2^n\tau) = \begin{cases} +1 & \text{for } 2^n\tau \in (k, k+1/2) \\ -1 & \text{for } 2^n\tau \in (k+1/2, k+1) \\ 0 & \text{for the others.} \end{cases} \tag{A4}$$

Note that the orthonormal functions $\{\psi_{n,k}(\tau)\}$ satisfy the following two conditions;

$$\int_0^1 \mathrm{d}\tau\ \psi_{n,k}(\tau) = 0, \tag{A5}$$

$$\text{and} \quad \int_0^1 \mathrm{d}\tau\ \psi_{n,k}(\tau)\cdot\psi_{m,j}(\tau) = \begin{cases} 1 & \text{for } n = m \text{ and } k = j \\ 0 & \text{for the others.} \end{cases} \tag{A6}$$

Using Eqs. (A5) and (A6), we have

$$\exp\left\{-\frac{1}{4D_0}\int_0^{\tilde{\zeta}} \mathrm{d}\tilde{t}\ \left[\tilde{v}(\tilde{t})\right]^2\right\} = \exp\left\{-\frac{(\Delta\tilde{r})^2}{4D_0\tilde{\zeta}} - \pi\sum_{n=0}^{\infty}\sum_{k=0}^{2^n-1}(a_{n,k})^2\right\}. \tag{A7}$$

According to Davison's treatment [10], we derive the distribution function $f(\Delta\tilde{r},\tilde{\zeta})$ as shown in Eq.(10).

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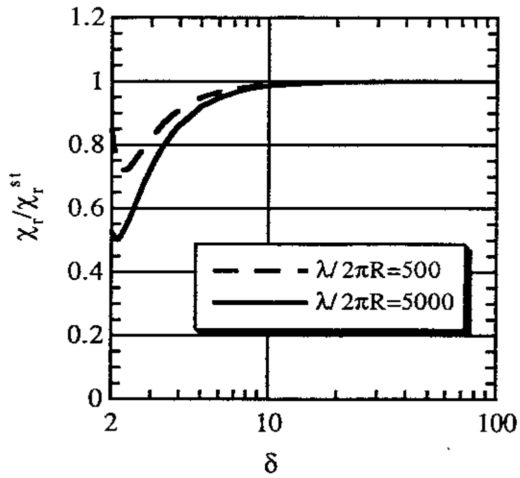
Figure caption

FIG.1. The radial thermal conductivity of electrons.



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