DENSITY VARIANCE EFFECTS IN TURBULENT MAGNETIC RECONNECTION

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Abstract Density variance effects in the turbulent magnetic reconnection are investigated in the framework of the magnetohydrodynamics (MHD). In the presence of the density variance, which is expected to be large in the vicinity of shock where a large density gradient is located, several turbulent correlations arising from the density fluctuations affect the mean field evolutions. A contribution to the turbulent electromotive force (EMF) arises from the obliqueness of the mean magnetic field and the density gradient. In the slow mode MHD shock configuration, this effect is expected to enhance the turbulence level in the vicinity of shock front.

INTRODUCTION

Magnetic reconnections are ubiquitous phenomena which transfer the magnetic energy to the kinetic one in astrophysical, space physics, and laboratory plasmas. Several mechanisms for the fast reconnection have been proposed, including the shock waves [1], two-fluid effects (Hall MHD and electron pressure tensor), kinetic effects, etc. Turbulence is one of such candidates [2]. In the fully developed turbulence approach, stochastic motions of the magnetic fields play an essential role in enhancing the magnetic reconnection. Despite the fact that turbulence in magnetic reconnections is self-generated from definitely inhomogeneous field configurations, in most previous studies of fully-developed turbulent reconnection, homogeneous turbulence is externally injected by forcing. Very recently a self-consistent turbulence model for reconnection has been proposed [3, 4], where the transport equations of the turbulent energy and cross helicity (velocity–magnetic-field correlation in turbulence) are considered as well as the counterparts of the mean mass, momentum, and energy. This model (inhomogeneous turbulence model) was validated by a numerical simulation of explosive reconnection [5]. One possible direction to the further improvement of the model may lie in the treatment of a strong compressibility. As is well-known, associated with shocks, which is ubiquitous in fast reconnections, a very high density variance $\langle \rho'^2 \rangle$ region is present. The implementation of the density variance effect in the MHD turbulence model for the magnetic reconnection is of significant importance for further exploration of the fast magnetic reconnection.

PROPOSED CONTRIBUTION

In the strong compressibility case, several turbulent correlations related to the density fluctuation appear in the mean field equations. In the present work, the expressions for these turbulent correlations are derived with the aid of a closure theory of inhomogeneous MHD turbulence. which include the turbulent mass and energy fluxes, Reynolds and turbulent Maxwell stresses, and turbulent electromotive force (EMF). In addition to the expressions in the solenoidal or weak compressibility case, we have some contributions intrinsic to the strong compressibility, related to the density variance. For instance, the turbulent EMF is expressed as

$$\langle \mathbf{u}' \times \mathbf{b}' \rangle / \mu_0 = \alpha \mathbf{B} - \beta \mathbf{J} + \gamma \mathbf{\Omega} + \mathbf{B} \times \left(\chi_\rho \nabla \overline{\rho} + \chi_Q \nabla Q + \chi_D \frac{D\mathbf{U}}{Dt} \right) \tag{1}$$

($\mathbf{u}'$: velocity fluctuation, $\mathbf{b}'$: magnetic fluctuation, $\mathbf{B}$: mean magnetic field, $\mathbf{J}$: mean electric-current density, $\mathbf{\Omega}$: mean vorticity, $\overline{\rho}$: mean density, Q: mean internal energy, $\mathbf{U}$: mean velocity, μ_0: magnetic permeability). Here, the first three terms are similar to the expressions in the solenoidal case with the transport coefficients α, β, and γ being related to the turbulent residual helicity $\langle -\mathbf{u}' \cdot \boldsymbol{\omega}' + \mathbf{b}' \cdot \mathbf{j}' / \mu_0 \overline{\rho} \rangle$, MHD energy $\langle \mathbf{u}'^2 + \mathbf{b}'^2 / \mu_0 \overline{\rho} \rangle / 2$, and cross helicity $\langle \mathbf{u}' \cdot \mathbf{b}' \rangle$, respectively. On the other hand, the rest terms are intrinsic to the compressibility. All the transport coefficients χ_ρ, χ_Q, and χ_D are proportional to the density variance $\langle \rho'^2 \rangle$. We focus on the first one related to the obliqueness between the mean magnetic field and the mean density gradient, $\chi_\rho \mathbf{B} \times \nabla \overline{\rho}$. Physical origin of this effect can be understood by considering the equations of fluctuations:

$$\frac{\partial \mathbf{u}'}{\partial t} = -(\gamma_{\mathrm{s}} - 1) \frac{q'}{\overline{\rho}} \nabla \overline{\rho} + \cdots = +(\gamma_{\mathrm{s}} - 1)^2 \tau_q \frac{Q}{\overline{\rho}} (\nabla \cdot \mathbf{u}') \nabla \overline{\rho} + \cdots , \tag{2}$$

$$\frac{\partial \mathbf{b}'}{\partial t} = -(\nabla \cdot \mathbf{u}') \mathbf{B} + \cdots \tag{3}$$

(γ_{s}: specific heats ratio, q': internal energy fluctuation, τ_q: internal energy timescale of turbulence). From Eqs. (2) and (3), the contribution to the turbulent EMF can be estimated as

$$\frac{\partial}{\partial t} \langle \mathbf{u}' \times \mathbf{b}' \rangle \simeq (\gamma_{\mathrm{s}} - 1) \tau_q \langle (\nabla \cdot \mathbf{u}')^2 \rangle \frac{Q}{\overline{\rho}} \mathbf{B} \times \nabla \overline{\rho} + \cdots = (\gamma_{\mathrm{s}} - 1) \frac{\tau_q}{\tau_\rho^2} \frac{\langle \rho'^2 \rangle}{\overline{\rho}^2} \frac{Q}{\overline{\rho}} \mathbf{B} \times \nabla \overline{\rho} + \cdots \tag{4}$$

(τ_ρ: density timescale of turbulence), which corresponds to the $\chi_\rho \mathbf{B} \times \nabla \overline{\rho}$ term in Eq. (1). Equations (2) and (3) suggest that the variations of velocity and magnetic fluctuations, $\delta \mathbf{u}'$ and $\delta \mathbf{b}'$, depend on the sign of local turbulent dilatation ($\nabla \cdot \mathbf{u}' > 0$ for expansion, $\nabla \cdot \mathbf{u}' < 0$ for contraction). However, we see from Eq. (4) that the resultant contributions to the EMF are always in the direction of $\mathbf{B} \times \nabla \overline{\rho}$ irrespective of the local expansion or contraction (Fig. 1).

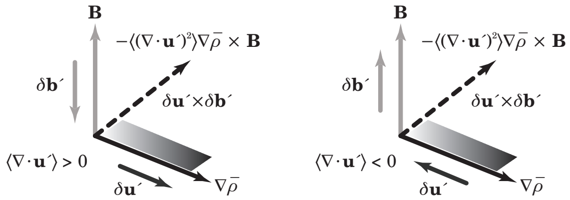

Figure 1. Turbulent electromotive force due to the obliqueness of the mean magnetic field and density gradient.

SAMPLE RESULTS

We consider the effect of the obliqueness between $\mathbf{B}$ and $\nabla \overline{\rho}$ in the context of the fast reconnection. The slow MHD shock is considered to be one of the candidate mechanisms for the fast magnetic reconnection. As usual, a very strong density gradient $\nabla \overline{\rho}$ will be associated with the shock front, which leads to a large density variance in the vicinity of the shock waves. In the shock for a slow mode waves, the configurations of the mean magnetic and velocity fields are schematically depicted as in Fig. 2. In the foreshock region, the $\mathbf{B} \times \nabla \overline{\rho}$ term always give a contribution to the electromotive force in the direction same as the original reconnection current $\mathbf{J}$. This means that in the region, the turbulent energy is generated by the production term $-\langle \mathbf{u}' \times \mathbf{b}' \rangle \cdot \mathbf{J}$, which enhances the level of turbulence.

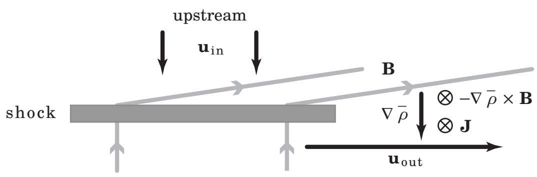

Figure 2. Slow mode MHD shock configuration and contribution of the oblique mean magnetic field and density gradient, $\mathbf{B} \times \nabla \overline{\rho}$, to the turbulent electromotive force (EMF). $\mathbf{u}_{\rm in}$ and $\mathbf{u}_{\rm out}$ are the in- and out-flow velocities, respectively.

MAJOR CONCLUSIONS

In the slow mode of the MHD shocks in magnetic reconnection, the EMF due to the mean density variation is expected to enhance the turbulence generation in the foreshock (upstream) region but no effects in the aftershock (downstream) region. This effect is mediated by the density variance $\langle \rho'^2 \rangle$, and serves itself as an interesting shock–turbulence interaction associated with the fast turbulent reconnection.

FURTHER RESULTS IN THE FINAL PAPER

The density variance effects can be implemented to the turbulence model for the explosive reconnection. The turbulence energy is expected to be enhanced by the shock–turbulence interaction. In addition to the turbulent energy, the turbulent cross helicity may be also enhanced near the shock region. The nonlinear dynamics, in particular, the balance between the transport enhancement and suppression both due to turbulence is an interesting subject to explore further. These points will be discussed more in the final paper with the aid of turbulence model simulation.

References

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