A SELF-CONSISTENT MODEL FOR TURBULENT MAGNETIC RECONNECTION

Nobumitsu Yokoi[1], Katsuaki Higashimori [2] & Masahiro Hoshino [2]
[1]*Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan*
[2]*Department of Earth Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*

Abstract Turbulent magnetic reconnection is investigated with the aid of a self-consistent turbulence model. In this framework, turbulence is not injected externally but is generated by the mean-field inhomogeneities. Dynamics of the mean-field and turbulence are treated simultaneously. It is shown that turbulence contributes to the fast reconnection only if the dynamic balance between the transport enhancement and suppression both due to turbulence works. The turbulent cross helicity (velocity–magnetic-field correlation) plays an essential role in the realization of fast reconnection through confining the enhanced magnetic diffusivity to a narrow region.

INTRODUCTION

Magnetic reconnection is an important concept to elucidate several phenomena appearing in the astrophysical, space physical, fusion plasma phenomena in a unified manner. In the classical picture of the magnetic reconnection the reconnection rate is scaled as $M \propto S^{-1/2}$ where $S(= V_{\mathrm{A}} L/\eta)$ is the Lundkist number, the magnetic Reynolds number defined by using the Alfvén speed V_{A} (L: characteristic length, η: molecular magnetic diffusivity). Since S is usually huge in astrophysical and space physical situation ($S \gg 10^6$), the reconnection rate is estimated very small, which can not explain the fast reconnection appearing e.g. in solar flares. In order to alleviate this difficulty, several mechanisms that effectively enhance the magnetic diffusivity have been considered in the history of magnetic-reconnection studies.Turbulence is one of such candidates. Primary effect of turbulence is to enhance the transport (eddy viscosity and diffusivity, turbulent magnetic diffusivity, etc). At the same time, if we have a breakage of symmetry in turbulence, we also have some other turbulence effects that contribute to field generation or transport suppression. The α effect is a typical one in dynamo process [1]. In addition to the α effect, some other effects have also been considered. The cross-cross helicity effect may play a very important role in the presence of large-scale flows [2, 3].

PROPOSED CONTRIBUTION

Recently the turbulent magnetic reconnection has been treated in the context of the interaction between the mean fields and turbulence [4]. In this framework, turbulence is not externally injected or imposed but self-generated and sustained through the mechanisms arising from the mean-field inhomogeneities, which in turn are determined by turbulence. It is predicted that the fast reconnection is realized not only by the turbulent magnetic diffusivity but by the dynamic balance between the transport enhancement and suppression both due to turbulence. In order to confirm this scenario, we construct a system of model equations, which consists of the equations for the mean fields (density, momentum, energy, magnetic field) and for the turbulence (turbulent MHD energy, cross helicity, and dissipation rates). The turbulent effects are incorporated into the mean-field equations through the turbulent electromotive force $\mathbf{E}_{\mathrm{M}} \equiv \langle \mathbf{u}' \times \mathbf{b}' \rangle$ and the Reynolds stress (with the turbulent Maxwell stress) $\mathcal{R}^{\alpha\beta} \equiv \langle u'^{\alpha} u'^{\beta} - b'^{\alpha} b'^{\beta} \rangle$ ($\mathbf{u}'$: velocity fluctuation, $\mathbf{b}'$: magnetic-field fluctuation). At the same time, the transport coefficients should reflect the statistical properties of turbulence, which are represented by the turbulent statistical quantities such as the turbulent MHD energy $K \equiv \langle \mathbf{u}'^2 + \mathbf{b}'^2 \rangle /2$, the turbulent cross helicity $W \equiv \langle \mathbf{u}' \cdot \mathbf{b}' \rangle$, the energy dissipation rate ε, etc. Both the mean-field and turbulence equations are simultaneously solved. In this work, turbulence is generated and sustained dynamically in a consistent manner with the mean-field evolution. This is an entirely new point in considering turbulence effects in the context of magnetic reconnection.

SAMPLE RESULTS

We numerically solved a system of model equations with a typical boundary and initial conditions for the reconnection simulation (the so-called Harris sheets). As the first step for the self-consistent treatment of the turbulence in magnetic reconnection, we consider the effects of turbulent electromotive force in the mean-field evolutions. A small turbulent energy K is initially put homogeneously in space. The initial mean flow and the turbulent cross helicity are set equal zero ($\mathbf{U}_{t=0} = 0, W_{t=0} = 0$). A mean-field configuration corresponding to the fast or Petschek-like configuration was obtained as a steady state. This is entirely new result. The spatial distribution of the mean electric-current is given in Figure 1.
Spatial distributions of the turbulent quantities, the turbulent MHD energy K and the turbulent cross helicity W, around the reconnection are shown in Figures 2 and 3. As predicted by theory [4], the turbulent cross helicity is spatially distributed in a quadruple manner (Figure 2). This is a direct consequence of the asymmetric configurations of the mean electric-current density $\mathbf{J}(= \nabla \times \mathbf{B})$ and the mean vorticity $\mathbf{\Omega}(= \nabla \times \mathbf{U})$. Namely, W is positive (negative) for the region with $\mathbf{J} \cdot \mathbf{\Omega} > 0$ ($\mathbf{J} \cdot \mathbf{\Omega} < 0$).

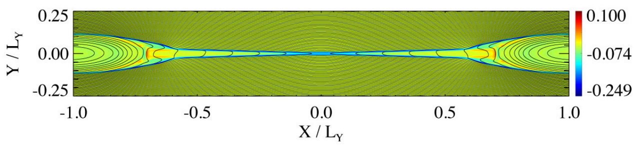

Figure 1. Spatial distribution of the mean electric-current density J^z in a steady state.

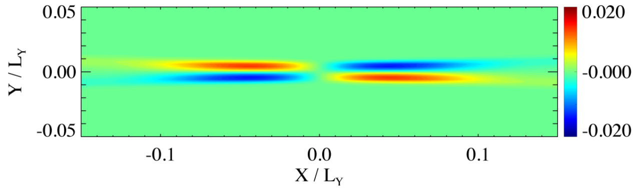

Figure 2. Spatial distribution of the turbulent cross helicity W.

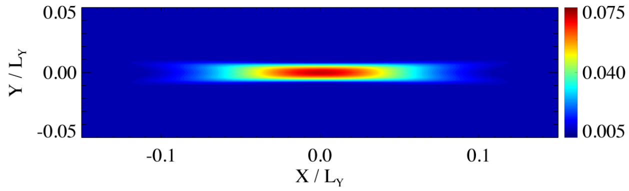

Figure 3. Spatial distribution of the turbulent MHD energy K with the evolution of the cross helicity $W \neq 0$.

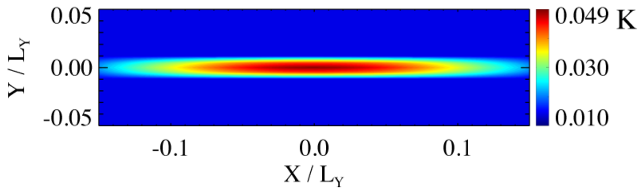

Figure 4. Spatial distribution of the turbulent MHD energy K without the turbulent cross helicity $W \equiv 0$.

Turbulence enhances the transports, but if the effective magnetic diffusivity is enhanced everywhere, the magnetic field will be just diffused everywhere. The basic role of the turbulence cross helicity is suppressing the enhanced transport due to turbulence. It is this effect that makes the enhanced magnetic diffusivity be confined to a narrow region and contributes to the fast reconnection. If we artificially put $W = 0$ everywhere and every time step in the numerical simulation, the region of a strong turbulent magnetic diffusivity represented by K (Figure 4) becomes much larger than the case with the evolving turbulent cross helicity ($W \neq 0$) (Figure 3). This suggests the the turbulent cross helicity certainly plays a role in realizing the fast reconnection.

MAJOR CONCLUSIONS

- Turbulence enhances the effective magnetic diffusivity, which does not directly contribute to the fast magnetic reconnection of the mean magnetic field. It sometimes just gives the diffusion of the magnetic field everywhere.
- Just because of the symmetry of the mean-field configuration in reconnection, the turbulent cross helicity is spatially distributed in a quadrupole manner around the reconnection point.
- Through the balancing due to the turbulent cross helicity against the turbulent magnetic diffusivity, the reconnection region is confined to the vicinity of the symmetry surface or point.
- This confinement of the reconnection region is favorable for the fast reconnection.
- The above scenario was confirmed by a series of numerical simulations with a self-consistent turbulence model.
- In the present simulation, turbulence is self-generated and sustained by the mean-field inhomogeneities. Mean fields and turbulence are dynamically evolved in a nonlinear interactions.

FURTHER RESULTS IN THE FINAL PAPER

In the present calculations, the dissipation rates of the turbulent energy and cross helicity, ε and ε_W, are treated in an algebraic manner with time scale of turbulence being a parameter. This point should be improved by solving the dissipation equations as the full form of the present turbulence model suggested. Also effects of the Reynolds (and turbulent Maxwell) stress should be included in more elaborated form. In the final paper, these points will be improved.

References

[1] E. N. Parker. Hydromagnetic dynamo models. *Astrophysical Jpurnal* **122**: 293-314.
[2] A. Yoshizawa, A. Self-consistent turbulent dynamo modelling of reversed field pinches and planetary magnetic fields. *Physics of Fluids B* **2**: 1589-1600.
[3] N. Yokoi. Cross helicity and related dynamos. *Geophysical and Astrophysical Fluid Dynamics* **107**: Issue 1, 1–71, 2013.
[4] N. Yokoi and M. Hoshino. Flow–turbulence interaction in magnetic reconnection. *Physics of Plasmas* **18**: 111208-1–14, 2011.