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Multiple-scale analysis of turbulent transport in highly compressible magnetohydrodynamic plasma flows

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In space-physics and astrophysical phenomena as well as in laboratory plasma experiments, variable density and density fluctuations often play essential roles on turbulent transport. In strongly compressible turbulence, where the fluctuation dilatation $\nabla \cdot \mathbf{u}'$ is large ($\mathbf{u}'$: velocity fluctuation), the effects of density fluctuation ρ' represented by the density variance $\langle \rho'^2 \rangle$ as well as the mean density stratification $\nabla\langle\rho\rangle$ should be properly taken into account in the evaluation of the turbulent transport ($\langle \cdot \rangle$: ensemble average, ρ: instantaneous density).

In the present work, turbulence correlations in strongly compressible magnetohydrodynamic (MHD) flows, such as the Reynolds and turbulent Maxwell stresses, $\langle \mathbf{u}'\mathbf{u}' \rangle$ and $\langle \mathbf{b}'\mathbf{b}' \rangle$, respectively, turbulent electromotive force $\langle \mathbf{u}' \times \mathbf{b}' \rangle$, turbulent mass flux $\langle \rho'\mathbf{u}' \rangle$, turbulent heat flux $\langle q'\mathbf{u}' \rangle$, etc., are explored with the aid of a multiple-scale analysis coupled with a renormalized perturbation closure theory of turbulence ($\mathbf{b}'$: magnetic fluctuation, q': internal energy fluctuation). By introducing slow and fast variables with a scale-parameter expansion, the fundamental equations are analytically investigated in a perturbative manner. As for the lowest-order turbulence fields, we assume homogeneous isotropic statistical properties, and all the inhomogeneity and anisotropic effects are systematically taken into account through the higher-order turbulence fields.

According to the theoretical analysis, the turbulent electromotive force (EMF), for instance, is expressed as

$$\begin{aligned}\langle \mathbf{u}' \times \mathbf{b}' \rangle = &-(\beta+\zeta)\nabla\times\mathbf{B} + \alpha\mathbf{B} \\ &-(\nabla\zeta)\times\mathbf{B} + \gamma\nabla\times\mathbf{U} - \chi_\rho\nabla\langle\rho\rangle\times\mathbf{B} \\ &-\chi_Q\nabla Q\times\mathbf{B} - \chi_D(D\mathbf{U}/Dt)\times\mathbf{B}\end{aligned} \tag{1}$$

($\mathbf{B}$: mean magnetic field, $\mathbf{U}$: mean velocity, Q: mean internal energy, $D/Dt=\partial/\partial t+\mathbf{U}\cdot\nabla$). Here, the transport coefficients β, ζ, α, γ, χ_ρ, χ_Q, and χ_D are expressed in terms of the spectral and response functions of the turbulence in the present framework. In addition to the usual dynamo terms (from the first to the fourth terms) [1], we have new χ-related terms intrinsically arising from the density variance [2]. For instance, the transport coefficient for the mean-density stratification, χ_ρ, is expressed as

$$\begin{aligned}\chi_\rho = &\frac{1}{3}(\gamma_s-1)^2\frac{Q}{\overline{\rho}}\int d\mathbf{k}\, k^2 \int_{-\infty}^{\tau} d\tau_1 \int_{-\infty}^{\tau_1} d\tau_2 \int_{-\infty}^{\tau_2} d\tau_3 \\ &\times [G_{u\mathrm{S}}(k;\tau,\tau_1) + G_{u\mathrm{C}}(k;\tau,\tau_1)] \\ &\times G_q(k;\tau,\tau_2) G_b(k;\tau,\tau_3) Q_{u\mathrm{C}}(k;\tau_2,\tau_3),\end{aligned} \tag{2}$$

where γ_S is the ratio of the specific heats for constant pressure to constant volume, G_{uS}, G_{uC}, etc. are the Green's functions of turbulence (the index C denotes the compressible parts while S denotes the solenoidal ones), and Q_{uC} is the spectral function of the compressible turbulent energy. Following this analytical result, χ_ρ can be modeled as

$$\chi_\rho = (\gamma_s-1)^2\frac{\tau_u\tau_q\tau_b}{\tau_\rho^2}\frac{Q}{\overline{\rho}}\frac{\langle\rho'^2\rangle}{\overline{\rho}^2}, \tag{3}$$

where τ_u, τ_q, etc. are the timescales of turbulence linked with the Green's functions. A similar analysis was done for several important turbulence correlations such as the turbulent mass flux, Reynolds and Maxwell stresses, turbulent heat flux, etc.

Physical pictures of those effects arising from strong compressibility are discussed, including the role of density variance in turbulent dynamo and that of compressional Alfven wave in turbulent mass and heat fluxes along the mean magnetic field.

The χ_ρ-related term in Eq. (1) indicates that, in the presence of the density variance, an obliqueness between the mean density gradient and the mean magnetic field may contribute to the electromotive force. A possible application of these density-variance dynamo effects on the shock–turbulence interaction and turbulent magnetic reconnection in the astrophysical context will be also presented.

References

[1] Yokoi, N. "Cross helicity and related dynamo," Geophys. Astrophys. Fluid Dyn. **107**, 114-184 (2013).

[2] Yokoi, N. "Electromotive force in strongly compressible magnetohydrodynamic turbulence," J. Plasma Phys. (2018) in press.