7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Modeling Convection and Transport in the Sun

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What physical mechanism primarily drives the thermal convection in the Sun? Two physical mechanisms are discussed as possible candidate: one is the locally-driven convection, which is fueled by a local (negative) entropy gradient, and the other is cooling-driven convection triggered by surface radiative cooling. The solar interior physics is constructed conventionally based on the mixing-length theory, with assuming the locally-driven convection as the dominant mechanism of momentum and energy transports. However, it has become evident in recent years that a significant disparity exists between theory and observation of the solar convection, known as the "convection conundrum". To address this discrepancy, the concept of cooling-driven convection, characterized by spontaneously-generated downflow plumes at the convection zone (CZ) surface, is being reevaluated.

Which model (cooling- or locally-driven) provides a better description of the Sun's thermal convection? To answer this question, we employ MHD simulations to study distinctions in the physical characteristics of the possible two convection models. From the stability point of view, the only difference between the models lies in a slight difference in the super-adiabaticity. While the cooling-driven model has an adiabatic entropy profile except the CZ surface in the radial direction, the locally-driven one has a radially super-adiabatic profile. Our analysis of the simulation data reveals two primary insights: First, there exist substantial difference in the spectra of the convective kinetic energy between models. Second, there exist a significant difference in 2nd-order correlations of physical parameters, particularly turbulent mass, momentum, and energy fluxes, between models.

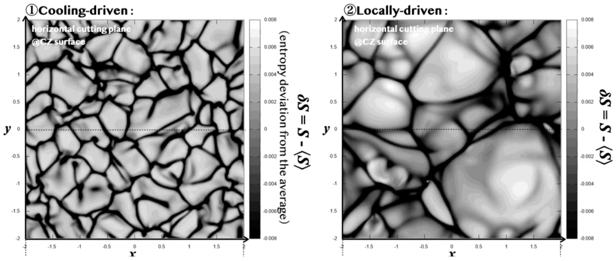

Fig.1. Entropy distributions at the CZ surface for models.

Fig.1 shows the entropy distribution (deviation from the mean value) at the CZ surface for two models. While the black tone denotes the region consisting of cool and fast downflows, white tone is corresponding to hot and slow upflow region. The typical size of the convective cell apparently differs between the models. This dissimilarity in the spatial structure of the convection becomes clearer in the power spectra, as shown in Fig.2. While the cooling-driven model exhibits a remarkable peak at the high-frequency regime ($k \sim 8k_{\mathrm{L}}$) and diminishing its intensity on the low-frequency side, the locally-driven one shows a broad spectrum with a robust intensity even on the low-frequency side.

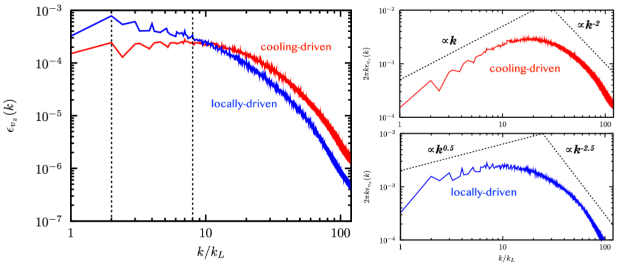

Fig.2. Spectra of convective energy for two models.

The difference that can be found in the turbulent flux is even more pronounced. In Fig.3 (left top), the vertical (radial) distributions of turbulent internal energy fluxes for the cooling-driven (red) and locally-driven (blue) models are shown. The difference is particularly striking near the CZ surface: the cooling-driven model has a sharp peak around the CZ surface. The turbulent energy flux in the locally-driven convection is well-described by a gradient-diffusion model (left bottom in Fig.3), while that in the cooling-driven convection is not, necessitating an alternative theory (model) for its description.

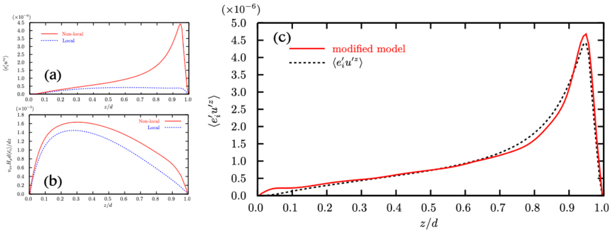

Fig.3. (a)Turbulent energy fluxes for models. (b)Predicted turbulent energy fluxes based on the gradient diffusion model. (c)Fitting of the turbulent flux in the cooling-driven convection by the modified (our developed) gradient-diffusion model with considering a non-equilibrium effect.

In our talk, we show that one of the prominent features of the cooling-driven convection, the enhanced transport of the turbulent energy just below the CZ surface, which cannot be reproduced by the gradient diffusion model, is well reproduced by the (our developed) modified model with considering the non-equilibrium effect. We will also delve into disparities between two convection models through higher-order correlation analysis. Furthermore, the results of analyses using machine learning techniques and a comparison of the numerical model with the actual solar convection will be discussed.

References

[1] Masada & Sano (2022) in review (arXiv:2206.06566)
[2] Yokoi, Masada, Takiawki (2022), MNRAS, 51, 2
[3] Ishikawa et al. (2022), A&A, 658, A142