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Efficient small-scale dynamo and energy transport in the solar convection zone
太陽対流層での効率的な小スケールダイナモとエネルギー輸送

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We investigate the efficiency of small-scale dynamo in the solar convection zone by using high-resolution magnetohydrodynamics calculations. Recent theoretical and observational studies suggest that the thermal convection reproduced by high-resolution calculation is too high. We expect that the small-scale magnetic field generated by turbulent dynamo have a role to suppress the convection flow. In this study we increase the resolution up to grid spacing of 350 km with using the less diffusive artificial viscosity. In the highest resolution the reproduced magnetic field reaches 95% of the equipartition magnetic field to the kinetic energy at the base of the convection zone. Then the root-mean-square convective velocity is reduced to 50% from the hydrodynamic run. In spite of significant reduction in the convective velocity, the convective energy flux is not reduced much, since the entropy perturbation is increased by magnetic field.

1. Introduction

The solar convection zone is filled with turbulent thermal convection. Since the upflow and downflow is hot and cold, respectively, the thermal convection transports the energy from the bottom of the convection zone to the solar surface. In addition, the chaotic motion of the turbulent convection has an ability to amplify magnetic field, i.e., dynamo.

Although there have been a lot of works to reproduce solar global thermal convection in numerical calculations, recent theoretical and observational studies suggest that the reproduced convection velocity is too high. One study is that in the high-resolution calculation with the solar rotation rate and the solar luminosity, the polar region is accelerated, i.e., an anti-solar differential rotation. The other study is from the helioseismology[1]. The convection velocity reproduced in numerical calculations is more than one order of magnitude larger than that in the result of helioseismology.

Since the global sun is large (circumference is 4400 Mm) compared with the typical convection scale (e.g., pressure scale height is 60 Mm at the base of the convection zone), the typical calculations for global solar convection zone has grid spacing of 6 Mm. This is not enough to resolve the turbulent inertia scale, which is integral factor for the efficient small-scale dynamo.

In this study we significantly increase the resolution with limiting the calculation domain and using a new efficient numerical method.

2. Model

We solve three-dimensional magneto hydrodynamics equations in the Cartesian geometry (x,y,z), where x is the vertical direction, with horizontally periodic boundary in order to avoid the influence from side boundaries. The calculation domain is from the base of the convection zone ($x=0.715R_{sun}$) to the near surface layer ($x=0.96R_{sun}$), where R_{sun} is the solar radius. The horizontal size of the calculation domain is the solar radius. We adopt the solar standard model for the background stratification. The reduced speed of sound technique [2] is adopted in order to overcome sever time step caused by sound wave. In the highest resolution calculation (N_x, N_y, N_z)=(576, 2048, 2048), the grid spacing is smaller than 350 km, where N_x, N_y, and N_z are number of grid points in x, y, and z directions. This is more than one order of magnitude smaller than typical global calculation.

At first we carry out hydrodynamic run, i.e., without magnetic field. Then random weak magnetic field is added to excite small-scale dynamo.

3. Result

Fig. 1 shows the distribution of radial velocity at $x=0.95R_{sun}$ for hydrodynamic case. The typical convection cell is distorted by small-scale turbulence.

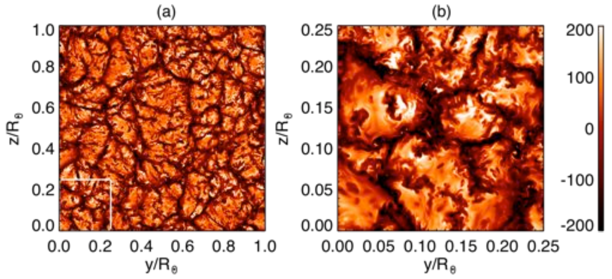

Fig.1. Distribution of vertical velocity at r=0.95R_{sun}. Panel b shows the zoom-in figure of panel a for hydrodynamic case. The white box in panel a shows the area for panel b.

Fig. 2 shows the distribution of radial velocity and radial magnetic field for MHD case at x=0.95R_{sun}. Compared with the hydrodynamic run, small-scale turbulence is smoothed by the Lorentz feedback. Around the base of the convection zone, the root-mean-square (RMS) magnetic field is amplified to 95% of the equipartition magnetic field to kinetic energy. The RMS velocity is reduced to 50% from the hydrodynamic case. While in the typical global calculation, the magnetic energy density in a saturated phase is 3.5×10^{5} erg cm^{-3}, in our calculation the saturated magnetic energy density is 2×10^{6} erg cm^{-3}.

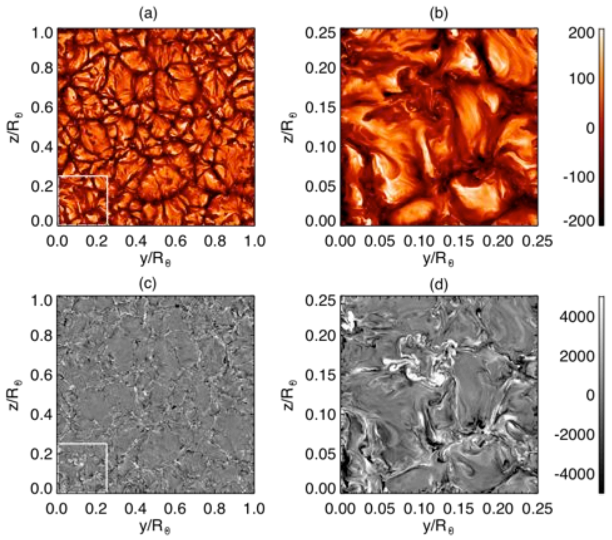

Fig.2. Distribution of vertical velocity (panels a and b) and vertical magnetic field (panels c and d) for magnetohydrodynamic case. Panels b and d shows the zoom in figure of panel a and c, respectively.

In the middle of the convection zone, the reduction of the RMS velocity by the magnetic field is 25%. On the other hand, the reduction of the convective flux is 12%. This reduction in energy flux shows the opposite sense of the previous study[4]. In this study, the strong magnetic field generated by small-scale magnetic field suppresses the mixing of internal energy between up- and downflow. As a result, the up- and downflow become hotter and cooler, respectively. This mechanism is seen in Fig. 3. In the hydrodynamic case (panel a), the small-scale structure mixes the entropy in up- and downflow. As a result overall structure becomes diffuse. In the magnetohydrodynamic case (panel b), the small-scale motion is suppressed by the strong magnetic field. Then the overall structure of the entropy perturbation has compact feature. Consequently the convective energy flux is shifted to the small scale.

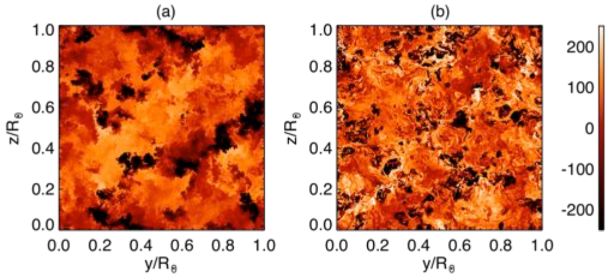

Fig.3. Distribution of entropy perturbation at x=0.8R_{sun} for hydrodynamic (panel a) and magnetohydrodynamic (panel b) cases.

5. Conclusion

We find that in the high-resolution calculation, the Lorentz force from the magnetic field is significant, since the RMS magnetic field is 95% of the equipartition magnetic field at the base of the convection zone. This possibly has a contribution to the recently raised problems about the over excited thermal convection in the solar convection zone calculation.

Acknowledgments

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