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# High-resolution calculation of solar convection zone using K-computer
# 「京」コンピューターを利用した太陽対流層の高解像度計算

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We present the result of a high-resolution numerical calculation about the solar global convection zone especially for the near-surface shear layer (NSSL) using K-computer. Since the solar convection zone is highly stratified, the convective spatial and temporal scale varies significantly from the base of the convection zone to the solar surface. It is thought that the solar NSSL is maintained by small- and large-scale convection generated at the near-surface layer and deep convection zone, respectively. The challenging task for understanding the maintenance mechanism of the NSSL is to cover the broad temporal and spatial scale simultaneously. To this end, the new method, the reduced speed of sound technique (RSST), and K-computer are used. Then the NSSL is reproduced for the first time and the detailed mechanism is revealed.

## 1. Introduction

The solar convection zone is filled with the turbulent thermal convection. The anisotropic convection transports the angular momentum as well as the energy. This causes large-scale flows such as the differential rotation and the meridional flow.

Although there is number of challenges to understand the physical maintenance mechanism of solar differential rotation [1,2,3], the mechanism especially for the near-surface shear layer (NSSL) is still unknown. The solar near-surface layer is known as a transition layer from rotation dominated to convection dominated regime. From the base of the convection to the solar surface, the pressure scale height, which determines the typical convection size, decreases drastically as the temperature decreases. In addition, as the density decreases, the convective velocity increases in order to transport solar luminosity. As a result, the rotation effect on the convection changes drastically at the near-surface layer. It is thought that this change would be a key factor for understanding the NSSL. The reproduction of the NSSL by the numerical simulation is useful to understand its maintenance mechanism, since we can directly compare the character of turbulence and reproduced differential rotation and meridional flow. The reproduction of the NSSL, however, in the numerical simulation is a challenging task, since large number of grid points and time integration are required to cover the broad range of the spatial and temporal scale. This is achieved with the new efficient method RSST and the K-computer.

## 2. Model

We solve three-dimensional hydrodynamic equations in the spherical geometry with Yin-Yang grid [4]. The background stratification is adopted from the solar standard model. About 1 billion grid point is used to resolve the solar convection zone.

## 3. Result

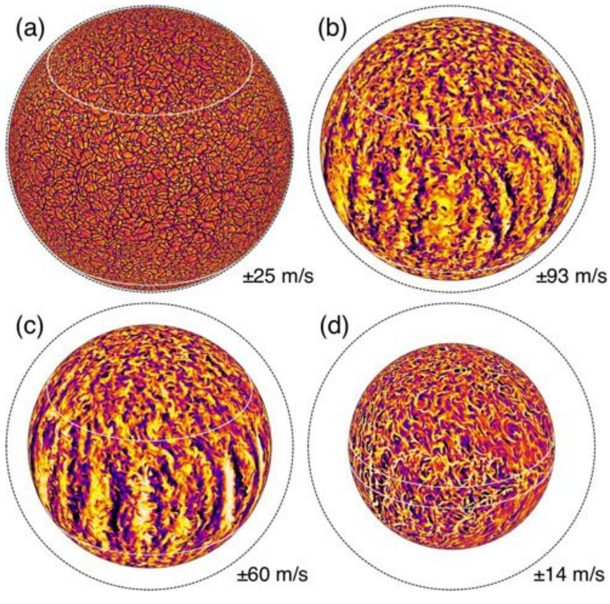


Fig.1. Distribution of radial velocity at (a) r=0.99$R_{sun}$, (b) r=0.92$R_{sun}$, (c) r=0.85$R_{sun}$, and (d) r=0.72$R_{sun}$, where $R_{sun}$ is the solar radius. The white lines show the tangential cylinder

Fig. 1 shows the distribution of radial velocity at different depths. In the deeper region, north-south aligned convective cell (banana cell) is seen, while almost isotropic convection cell exists with small rotation influence. Fig. 2 shows the reproduced differential rotation. In the high latitude the NSSL is partially reproduced. Fig. 3 shows the distribution of meridional flow, i.e., $\rho_0\langle v_r\rangle$ and $\rho_0\langle v_\theta\rangle$ on the meridional plane, where $\rho_0$ is the background density. In the near-surface region, the poleward meridional flow, which is also observed in the real sun, is reproduced. Deep in the convection zone, multi-cell structure is generated.

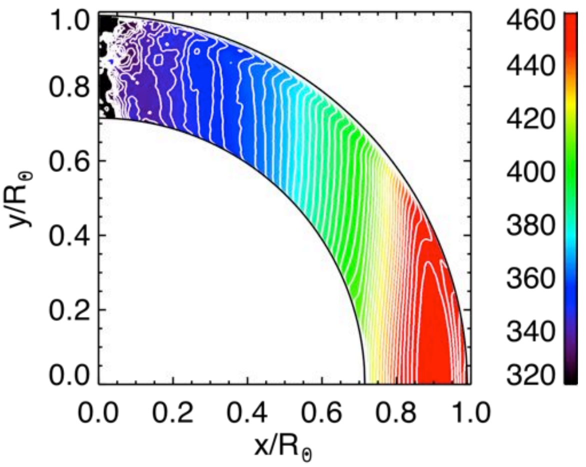


Fig.2. Distribution of mean angular velocity, i.e., differential rotation in the unit of nHz

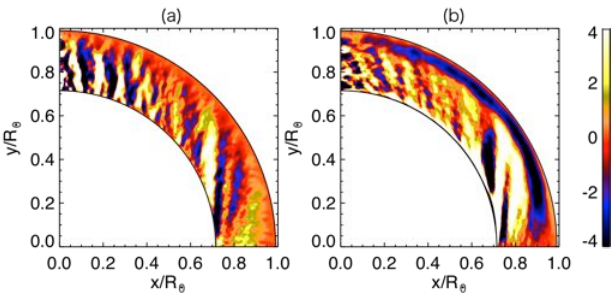


Fig.3. Distribution of meridional flow, i.e., $\rho_0\langle v_r\rangle$ and $\rho_0\langle v_\theta\rangle$ on the meridional plane in the unit of g $cm^{-2}$ $s^{-1}$.

In order to understand the maintenance mechanism, the idea of the Reynolds stress, i.e., the correlation of velocities is useful. Fig. 4 shows the correlations of (a) $\langle v'_r v'_\varphi\rangle$ and (b) $\langle v'_\theta v'_\varphi\rangle$, which show the radial and latitudinal angular momentum transport, respectively. Negative correlation for $\langle v'_r v'_\varphi\rangle$ indicates the inward angular momentum transport by the convection. This inward angular momentum transport is compensated by the angular momentum transport by poleward meridional flow. In the near-surface layer, the amplitude of poleward meridional flow increases along the radius. We find that the small-scale turbulence with small rotational influence acts as a turbulent viscosity on the shear of the meridional flow. The Coriolis force caused by the NSSL balances the resulting viscous stress.

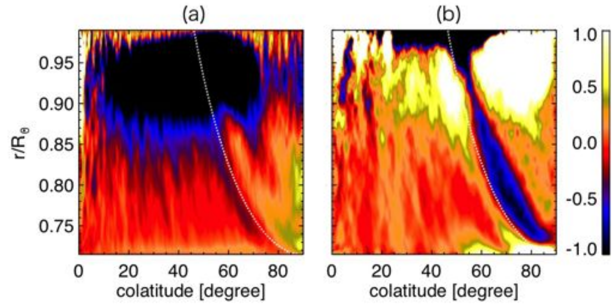


Fig.4. Correlations of (a) $\langle v'_r v'_\phi\rangle$ and (b) $\langle v'_\theta v'_\phi\rangle$ on the meridional plane.

## 4. Conclusion

Using K-computer, we reproduce the solar near-surface shear layer for the first time. The revealed mechanism is summarized that the convection transports angular momentum inward with exciting the poleward meridional flow. The small-scale turbulence acts as turbulent viscosity on the poleward meridional flow compensates the Coriolis force from the NSSL.


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