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Weak-field dynamo emerging in a rotating spherical shell with stress-free top and no-slip bottom boundaries

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According to the recent progress of computer resources, three-dimensional numerical simulations of MHD dynamo in rotating spherical shells have been carried out vigorously in order to investigate generation and maintenance mechanisms of magnetic field in celestial bodies. Most of the simulations performed so far use both stress-free or both no-slip conditions at the top and bottom boundaries. However, it seems that the no-slip condition at the bottom boundary and the stress-free condition at the top boundary are suitable for the gas giant interiors, or the solar convection zone, whose internal structure is revealed by recent helio-seismological observations. Under these backgrounds, we have carried out numerical experiments of MHD dynamo in a rotating spherical shell with two kinds of mechanical boundary conditions. One is both no-slip boundary conditions, the other is the stress-free condition at the top and the no-slip condition at the bottom. The Ekman number, the Prandtl number, and the ratio of inner and outer radii are fixed to 10^{-3}, 1, 0.35, respectively. The magnetic Prandtl number is varied from 5 to 50, and the modified Rayleigh number is increased from 1.5 to 10 times critical. For each combination of the parameters and the boundary conditions, time integration of non-magnetic thermal convection is carried out until a quasi-steady state is established. Starting from this quasi-steady state with a small dipole magnetic field, MHD dynamo calculation is performed.
For the cases of both no-slip boundary condition, we obtained alpha-squared type dynamo solutions, which is similar to those obtained by the previous studies. In these dynamo solutions, the magnetic energy is larger than the kinetic energy. On the other hand, for the cases of the stress-free top boundary condition, we obtained dynamo solutions where the magnetic energy is far less than the kinetic energy. These dynamo solutions are characterized by the two-layer spatial structure. The upper layer is governed by prograde strong zonal flows and less-organized prograde propagating spiral convection vortices, while the lower layer is dominated by turbulent retrograde propagating columnar convection vortices. The strong zonal flow in the upper layer prevents the magnetic field generated in the lower layer from penetrating to the surface of the spherical shell.
In order to examine generation and maintenance mechanisms of the magnetic field in these weak-field dynamo solutions, we obtained time-averaged fields on the longitudinally moving coordinate travelling with the same speed as the convection vortices in the upper or the lower layers, and succeeded in extracting typical convective and magnetic structures in the upper and lower layers, respectively. Further, we analyzed kinetic and magnetic energy budget of the dynamo solution, and clarified energy transfer between the toroidal and poloidal components of the kinetic and magnetic energies. Together with these analyses, we identified the regions where conversions from the poloidal and toroidal kinetic energies to the poloidal and toroidal magnetic energies, respectively. In the lower layer of the spherical shell, whirlpool poloidal fields are generated from toroidal fields by the helical poloidal convective vortices through the magnetic field line stretching. These whirlpool magnetic field lines are brought up by the convective motion in the lower layer and they penetrate to the upper layer intermittently. These magnetic field lines are caught by the

toroidal spiral vortices in the upper layer and toroidal magnetic fields are generated. These toroidal fields fall down into the lower layer intermittently, and are caught by the convective vortices, and whirlpool poloidal field generation occurs again. The self-sustained magnetic field is generated by repeating these processes.

Keywords: Convection in rotating spherical shells, MHD Dynamo, Mechanical Boundary Condition