Numerical simulations of the geodynamo at low Ekman numbers

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Dynamo action and its secular variation, with particular reference to the Earth's core, are examined through three-dimensional, self-consistent numerical simulation of magnetohydrodynamic (MHD) dynamo. In order to model the Earth's outer core, a rapidly rotating spherical shell filled with an electrically conducting Boussinesq fluid is considered. Spherical harmonic expansion in the angular direction and a finite difference method in the radial direction are used. The spectral transform method is used to evaluate the non-linear interaction terms. For more Earth-like numerical geodynamo models, numerical simulations are run on the ``Earth Simulator'' (ES), and a highly optimized and parallelized numerical code is developed to gain a good performance on the ES.

Throughout this study, we fix the Prandtl number, Pr, and the radius ratio, ri/ro, at 1 and 0.35. The Ekman number, E, is 10^{-5} or less. The magnetic Prandtl number, Pm, is the order of 1 or smaller. The Rayleigh number, Ra, is from 2.5 to 50 times supercritical.

We then examine the results of simulations at the low Ekman number. At moderate Rayleigh numbers, convective vigor is moderate and convection rolls concentrate near the inner-core boundary (ICB). The field advection works so that the magnetic field is advected into anti-cyclones near the equatorial plane and into cyclones near the core-mantle boundary (CMB). At mid-latitudes, the magnetic field is generated by the stretching process acting between a pair of cyclone and anti-cyclone.

We can observe dipole field reversals in the simulations for a highly supercritical Rayleigh number, in which the magnetic energy is lower than the kinetic energy. This fact indicates inefficient magnetic field generation by convection rolls. The flow structure is cylindrically multi-cellular and asymmetric about the equatorial plane. These highly three-dimensional flow patterns can generate a localized small-scale magnetic field and even the reversed field. The dipole reversal occurs from the deep portion of the shell at low-latitudes and grows towards higher latitudes at the CMB. When the magnetic pole is unstable, high-latitude flux patches disappear, which suggests the possibility to detect signals associated with reversals or excursions from observations. Thus, the magnetic field at the CMB is characterized by the intense equatorial patches during the unstable polarity period. Disappearance of high-latitude flux patches is caused by the inefficient field advection into cyclones near the CMB. Such a weak field advection is due to the relatively short life-time of each convection roll. It also indicates that convection rolls govern the dynamo action and its secular variations.