§16. Chaotic Reversals of Dipole Moment of Thermally Driven Magnetic Field in a Rotating Spherical Shell

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The origin of generation and sustenance of the geomagnetic field is one of the most intriguing unsolved mysteries in geophysics. One of the possible sources of the magnetic field which is now commonly believed is the convective motion of melted iron in the outer core. There are several interesting features observed in the structure of the magnetic field [1]. It seems to be nearly three-fold symmetric around the rotation axis and to drift westward relative to the Earth. The paleomagnetic observation tells us that the dipole component is dominant and aligned with the rotation axis over most of the time history, and more interestingly that it changes the direction abruptly and irregularly in time.

In order to realize these properties of the geomagnetic field at least qualitatively on a computer and to obtain a hint of the generation mechanism we have performed a series of direct numerical simulations (DNS) of a simple three-dimensional magneto-hydrodynamic (MHD) model [2-4]. Here, we report the chaotic reversals of the polarity of the dipole moment observed in the numerical magnetic field.

The model we consider here is an electrically conducting fluid confined between two concentric spheres which are rotating with a common constant angular velocity in the gravity field pointed to the center of the system. The temperature on each sphere is kept uniform and constant at all the time. It is hotter on the inner sphere than on the outer. This temperature difference drives a thermal convection, which in turn generates the magnetic field. There is an insulator inside the inner sphere and vacuum outside the outer. The no-slip boundary condition is imposed for the velocity field. The magnetic field inside and outside the shell is connected continuously on the boundaries. The evolution equations of the velocity, the magnetic and the temperature fields under the Boussinesq and the MHD approximations are solved numerically by the use of the Chebyshev-spherical harmonics pseudo-spectral method described in Ref. [2].

This system may be characterized by five non-dimensional parameters, that is, the Rayleigh number R_a, the Taylor number T_a, the Roberts number R_o, the Prandtl number P_r, the ratio r_1/r_2 of the radii of the outer and the inner spheres (see Ref. [2] for the definitions of these parameters). The dynamo simulation is performed in two steps. First, a steady thermal convection state is realized in a run without magnetic field with parameters $R_a = 3200$, $T_a = 8000$, $P_r = 1$ and $r_1/r_2 = 0.5$. The initial velocity and temperature fields are generated by uniform random small perturbations superimposed on a stationary thermal conduction state which is linearly unstable. Five pairs of cyclonic and anti-cyclonic vortex columns appear spontaneously, which are aligned with the rotation axis and drift westward steadily [5]. The MHD simulation is then conducted by adding a small random seed of magnetic field to this steady thermal convection state for various values of R_o. It is found that there is a critical Roberts number, below (or above) which the magnetic field is (or not) intensified. This critical Roberts number is 0.122 for the present set of parameters. The magnetic energy excited is at the level of 2% of the kinetic for $R_o = 0.12$ [3], 30% for $R_o = 0.10$ [2] and 40% for $R_o = 0.07$ [4]. The magnetic dipole moment changes either periodically, quasi-periodically or chaotically in time in the respective cases.

In Fig. 1(a), we plot the temporal evolution of the axial (z-) component of the magnetic dipole moment for $R_o = 0.07$. The cross component (perpendicular to the rotation axis) is negligible in magnitude comparaed with the axial component over most of the time. In other words, the dipole moment is almost always aligned nearly with the rotation axis and changes the direction abruptly and irregularly in time. The time-series of the sign of m_z is shown by a band graph in Fig. 1(b). It is positive in black bands and negative in gray. We can see that the polarity changes irregularly in time. The number of intervals longer than the magnetic diffusion time is counted to be 7 after the transient time, while that of shorter interval is 20. This is reminiscent of the behavior of the chaotic reversals of polarity of the dipole moment of the actual geomagnetic field, in which the typical intervals of the reversals are longer than the magnetic diffusion time (cf. Fig. 5.4 in Ref. [1]).

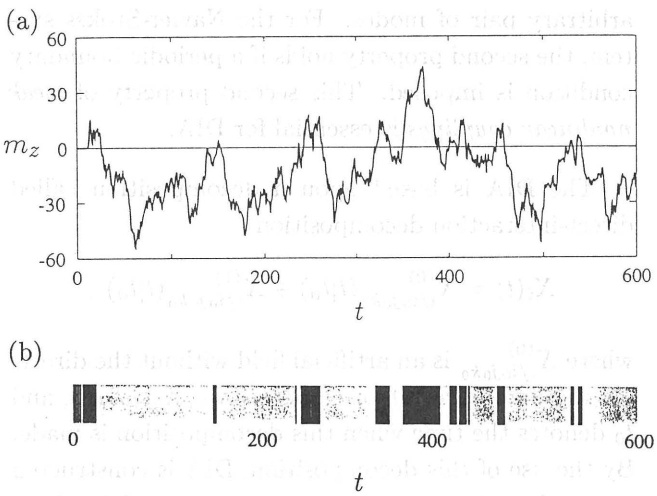

Fig.1. Time-series of (a) the axial component m_z of magnetic dipole moment, and (b) the polarity of it.

References

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