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A Study by Computer Simulation of the Generation and Evolution of the Earth's Magnetic Field

Gary A. Glatzmaier*, Rainer Hollerbach, Paul H. Roberts

Abstract

Until recently very little has been known about the maintenance of the Earth's magnetic field. The general consensus was that some type of convective motion exists in the Earth's liquid iron alloy core that is affected by rotational forces in a way that continually generates new magnetic field to replace that which diffuses away. Magnetic-field reversals and secular variation have long been measured but no theory existed to explain these phenomena. To gain an understanding of the basic physical mechanisms of the "geodynamo," we produced the first self-consistent computer simulation of convection and magnetic field generation in a rotating three-dimensional spherical fluid shell as an analogue to the Earth's convective dynamo. This is a final report of a three-year Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL).

1. Background and Research Objectives

A fundamental goal of geophysics is a coherent understanding of the structure and dynamics of Earth's interior. An integral part of this understanding must be a model of Earth's magnetic field that reproduces its salient features: a field that is maintained for many magnetic diffusion times, is dominantly dipolar at the surface with a dipole axis that on the average lies close to the geographic axis of rotation, and exhibits secular variation with occasional excursions and reversals. The only plausible candidate for such a model is the dynamo model, in which new magnetic field is continually being generated by the shearing and twisting fluid motions within the Earth's liquid, electrically-conducting, outer core.

To gain an understanding of the geodynamo we have produced the first fully self-consistent three-dimensional (3D) numerical simulation of a convective strong-field dynamo by solving the nonlinear magnetohydrodynamic (MHD) equations that describe convection and

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magnetic field generation in a rotating spherical shell of conducting fluid with a conducting solid inner core [1,2]. A magnetic field is maintained for more than 40,000 years (three magnetic diffusion times) and has energy at least three orders of magnitude greater than the kinetic energy of the convection that maintains it. The exciting feature we captured is a reversal of the dipole polarity that occurs near the end of our simulation. Since our simulation is self-consistent and maintains a field that resembles the Earth's in many respects, we believe that it provides a plausible description of the geomagnetic field and the way it reverses.

2. Importance to LANL's Science and Technology Base and National R&D Needs

This project involves a very fundamental problem in basic physics and geophysics while utilizing the Laboratory's state-of-the-art supercomputers. Our effort is internationally recognized as the leading computer modeling study of the generation of the Earth's magnetic field.

3. Scientific Approach and Results to Date

Our numerical model solves the nonlinear MHD equations that govern the 3D structure and evolution of an electrically-conducting fluid undergoing thermal convection in a rapidly-rotating spherical shell. A specified heat flux at the inner core boundary (ICB) drives thermal convection in the fluid outer core. This convection, influenced by the rotation of the core, twists and shears magnetic field, generating new magnetic field to replace that which diffuses away. The field diffuses into a solid, electrically-conducting, inner core providing magnetic torque between the inner and outer cores. Magnetic torque also exists between the outer fluid core and a solid mantle above via a thin conducting layer at the core-mantle boundary (CMB). The rest of the mantle is assumed an insulator; so the field above this layer is a source-free potential field. Time-dependent rotation rates of the solid inner core and solid mantle are determined by the net torques at the ICB and CMB, respectively.

With Earth-like parameters, our solution spans over 40,000 years, more than three magnetic diffusion times, with no indication that it will decay away, which is convincing evidence that our solution is a self-sustaining convective dynamo. The solution begins with random small-scale temperature perturbations and a seed magnetic field. After an initial period of adjustment (roughly 10,000 years) during which the dipole part of the field gradually becomes dominant, our time-dependent solution maintains its dipole polarity until near the end of the simulation when it reverses in little more than a thousand years and then maintains the

new dipole polarity for roughly the remaining 4000 years of the simulation. The simulation required over 2 million computational time steps that took more than 2,000 cpu hours on a Cray C-90.

To illustrate the magnetic field reversal we show in Fig. 1 the longitudinal average of the 3D field at: (a) 9000 years before the end of the simulation, (b) at roughly the middle of the polarity transition as seen at the ICB (about 5000 years before the end), and (c) at the end of our simulation. The right side of each plot shows contours of the east-west (toroidal) part of the field; the left side shows lines of force of the meridional (poloidal) part of the field. There are typically two main toroidal field concentrations, one in each hemisphere, in opposite directions and usually inside the imaginary cylinder tangent to the inner core where large zonal flows shear poloidal field, thereby generating toroidal field. Toroidal field also diffuses into the inner core from the ICB where it is generated when poloidal field is sheared by the inner core as it moves differentially with respect to the fluid just outside the ICB.

The longitudinally-averaged poloidal field (left sides of the figure) typically has two dipolar polarities: one in the outer part of the fluid core, which is also the dipole polarity observed at the surface, and the opposite polarity in the inner part of the fluid core and the inner solid core. Poloidal field is generated by helical flow that twists toroidal field; in the northern hemisphere for example, the time-dependent helicity of the flow (that is, the correlation between velocity and vorticity) is usually right-handed and much larger in magnitude inside the "tangent cylinder" and left-handed outside.

A movie of our simulation shows how the field in the fluid outer core is continually attempting to reverse its axial dipole polarity on a short time scale (roughly 100 years) corresponding to convective overturning but usually fails because the field in the solid inner core, which can only change on a longer diffusive time scale (about 1600 years), usually does not have enough time to diffuse away before it is regenerated at the ICB. It also shows how the axial quadrupole part of the outer field tends to reverse its polarity on roughly a thousand year time scale, causing a hemispheric (non-reversing dipole) oscillation in the structure and intensity of the outer poloidal field since the sum of an axial dipole and an axial quadrupole results in an enhanced axial poloidal field in one hemisphere and a diminished poloidal field in the other. Once in many attempts the 3D configurations of the buoyancy, flow, and magnetic fields in the outer core are right for a long enough period of time for the inner core axial dipole field to diffuse away [Fig. 1(b)], thus allowing the reversed axial dipole polarity in the outer core to diffuse into the inner core. If this one scenario is representative of the Earth, it suggests that the strong nonlinear feedbacks in 3D and the different time scales of the fluid and solid cores are responsible for the Earth's stochastic reversal record.

When the reversal occurs in our simulation, the energy of the total field in the core is about four times less than its typical value. Once the new field polarity has become established, the magnetic energy in the fluid core quickly recovers. During the transition, eastward and westward toroidal field are alternately generated several times in both hemispheres at the ICB before the reversed polarity finally becomes established. Notice how the toroidal field is asymmetric with respect to the equator before [Fig. 1(a)] and after [Fig. 1(c)] the transition but is symmetric mid-way through the transition [Fig. 1(b)]. In our simulation, the toroidal field reverses first, then the inner poloidal field that penetrates the solid core, and finally, somewhat later, the outer poloidal field that appears at the Earth's surface reverses. This entire process takes (depending on how one defines the beginning and end of the reversal) a little more than a thousand years, roughly the characteristic magnetic diffusion time scale for the inner core.

The dipole parts of these fields are nearly axial before and after the transition and equatorial mid-way through the transition. However, the dipole part of the field decreases more during the transition than do the other modes; and therefore the equatorial dipole part of our transitional field is less dominant than the axial dipole part typically is before and after the transition.

Our calculated fields at the surface and at the CMB are qualitatively similar to the Earth's present field, with multimode contributions and several flux concentrations. The maximum intensity of the radial component of our simulated field at the CMB is typically about 3.0 mT, which is a little larger than what it is for the present day Earth; however, like the Earth, the dipole part of the field dominates at the surface. During the reversal the maximum intensity of our field at the CMB drops to about 0.8 mT, with the dipole part dropping more than the other modes, as some paleomagnetic reversal records indicate.

References

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