SEARCH AND DISCOVERY

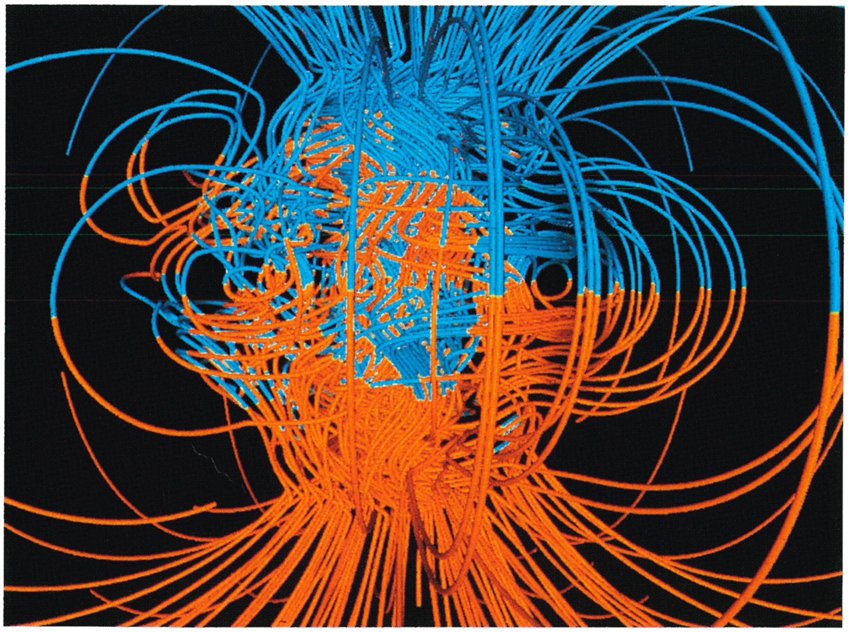
Geodynamo Turns Toward a Stable Magnetic Field

Supercomputer simulation shows that fluid motions in Earth's core could sustain the geomagnetic field. Geophysicists are excited—and also a little relieved; such a "geodynamo" has been the only plausible explanation for geomagnetism for more than 40 years.

Earth's magnetic field has been a subject of curiosity for at least 3000 years and of quantitative study for more than 400 years. Geologic samples now extend our knowledge of geomagnetism back billions of years, and satellites and observatories log the tiniest changes in the strength and direction of the geomagnetic field. These investigations have revealed many intriguing characteristics of geomagnetism that any successful model of the phenomenon must explain—such as the stability of the geomagnetic field on time scales of 10^5 years, the field's predominantly dipole nature, the offset of its dipole axis from Earth's rotational axis, its temporal variability and so on. All these geomagnetic observations, however, have done little to suggest what a model of geomagnetism should look like.

It is only in the last century, and particularly in the last 40 years, that knowledge of Earth's structure and composition has progressed enough to suggest a plausible generating mechanism for geomagnetism. In this mechanism—called the geodynamo—Earth's fluid, electrically conducting outer core acts like a dynamo or generator. As the outer-core fluid rotates (relative to the rotating Earth as a whole) and convects, it cuts across already existing magnetic lines of force, thereby regenerating the geomagnetic field at the expense of the fluid's kinetic energy. (See the cover illustration of this issue.)

Unfortunately, in trying to convert this qualitative mechanism into quantitative understanding, one encounters a number of difficulties. The complicated, nonlinear magnetohydrodynamic equations that govern the geodynamo cannot be solved exactly. Simplified geodynamo models, which linearize or parametrize nonlinear effects, have yielded important insights into the behavior of the geodynamo. However, the results from such models are suspect, in part because the nonlinear effects from the magnetic and other terms in the equations are too large to be neglected. The low viscosity of the outer-core fluid creates further difficulty, causing computer simulations to evolve too quickly for even the most powerful supercomputers. Viscous effects also preclude experimental realization of self-sustaining laboratory-scale dynamos because viscosity dominates the magnetohydrodynamics at these scales. And yet, despite these difficulties, the geodynamo is the only plausible mechanism for geomagnetism. As Peter Olson of the Johns Hopkins University says, "The convection-driven geodynamo was rapidly becoming gospel without anyone actually demonstrating that it could work."



MAGNETIC FIELD of Glatzmaier and Roberts's model is predominantly dipole with a smooth potential outside the core–mantle boundary, but much more complicated in the core, as indicated by the inward-directed (blue) and outward-directed (orange) magnetic lines of force. The simulated field, shown here about 10 000 years after the polarity reversal, appears to have stabilized in the reversed configuration. Currently the simulated field is slightly more dipolar than Earth's field.

Recently[1] Gary Glatzmaier of Los Alamos National Laboratory and Paul Roberts of the University of California at Los Angeles did just that. The two researchers developed a dynamically self-consistent three-dimensional computer model characterized by Caltech's David Stevenson as "by far the most impressive and complete attempt to construct a dynamic description of the evolution of Earth's magnetic field incorporating more-or-less realistic properties of the core." While their simulation is still in an early state of its evolution, having simulated a mere 40 000 years in 2000 hours of supercomputer time (on a Cray C-90 at the NSF Pittsburgh Supercomputing Center), and while much work remains to be done before we will know how relevant their geodynamo simulation is for terrestrial magnetism, the model has so far exhibited behaviors and characteristics that look encouragingly Earthlike. In fact, some of the behaviors—especially the spontaneous reversal of the field polarity that occurs about 38 000 years into the simulation—look tantalizingly Earthlike.

Simplifying Earth, but not too much

In Glatzmaier and Roberts's model, a heat flux from the solid, electrically conducting inner core drives convection in the outer core. The fluid outer core is bounded above by a smooth, thin, solid, electrically conducting shell at the core–mantle boundary, which is rigidly fixed to the electrically insulating mantle. The entire assemblage rotates about its axis in an initial, arbitrary, nonzero magnetic field. Magnetic, viscous and other torques can cause the inner core, outer core and mantle to rotate at different rates, provided the system's total angular momentum is conserved. Angular and radial dependencies of relevant variables—such as the magnetic field, mass flux and thermodynamic quantities—are expanded in terms of spherical harmonics and Chebyshev polynomials, respectively.

Glatzmaier and Roberts make several simplifying assumptions common to fluid dynamical calculations. They use the Boussinesq approximation, which neglects energy dissipation by viscous forces and ohmic heating in the outer core. They neglect the relatively small inertial term in the MHD equations, because this allows them to use a much longer time step (about 1 week) than would otherwise be possible. They neglect compositional buoyancy—an effect that occurs when iron in the outer-core fluid crystallizes onto the inner core, leaving buoyant lighter elements to drive convection.

To compensate for omitting compositional buoyancy and to achieve a reasonable amount of convection, the model assumes a somewhat greater heat flux from the inner core than is realistic for Earth. As with all geodynamo models so far, they assume a viscosity for the outer core that is many orders of magnitude larger than the geophysical value—an assumption that is necessary to keep the numerical calculation manageable. Glatzmaier and Roberts's model also effectively damps out computer-time-consuming small-scale eddies by increasing the viscosity as the scale of the flow decreases. Nevertheless, in their model the viscous forces are six orders of magnitude smaller than Coriolis and magnetic forces. In the view of many geophysicists, this is one of the features that makes the Glatzmaier–Roberts model of the geodynamo the most realistic to date.

The effects of these seemingly reasonable assumptions can be determined only by observing how the model behaves when they are relaxed, a strategy that will require vast amounts of supercomputer time. Ultimately, however, such studies will determine whether the Earthlike behaviors seen so far are the result of a model that is truly, or at least asymptotically, Earthlike, or rather are coincidental.

Stability and reversal

After settling into statistical equilibrium from its initial state, Glatzmaier and Roberts's model produced a magnetic field with a strength, radial dependence and angular dependence much like that of Earth's magnetic field (although in Earth's present field the dipole term is much more dominant). Magnetic north was displaced slightly from the axis of rotation, just as on Earth. The interplay of viscous and magnetic torques caused the inner core's rotation to speed up and that of the mantle to slow down relative to the outer core in a manner that may be analogous to the decadal variation of the length of Earth's day.

Perhaps the most remarkable characteristic of the model's field was its stability. Throughout most of the simulated 40 000 years (equivalent to about three times the 13 000-year magnetic diffusion time, the time scale on which a static field would decay), the model's field remained strong, with an average magnetic energy about 4000 times the kinetic energy of the outer core.

The only exception to the model's stability occurred during another extremely Earthlike behavior: From 33 000–38 000 years into the simulation, the field became less dipolar, the magnetic energy decreased fourfold, the outer-core kinetic energy doubled, and ultimately the polarity of the field suddenly reversed. Although a single event, however intriguing, cannot reliably illuminate the mechanism of magnetic reversals, the behavior of Glatzmaier and Roberts's model reinforces results from previous studies of a two-dimensional model[2] by two researchers in the United Kingdom, Rainer Hollerbach, now at the University of Glasgow, and Chris Jones of the University of Exeter, that indicated the importance of the electrically conducting inner core in maintaining the stability of the geodynamo.

Glatzmaier and Roberts's simulated field has one dipole polarity in the outer core (and mantle) and an opposite, induced polarity in the inner core. Because the outer core is fluid, it evolves rapidly, and its magnetic-field polarity would flip on a time scale of a few hundred years were it not for the restraining influence of the solid core's magnetic field, which evolves on the inner-core diffusion time scale—about 1600 years. The model field can successfully reverse only when the outer-core magnetohydrodynamics is favorable long enough for the inner-core field to decay away. Although, given the limited statistics, it is impossible to make quantitative comparisons with the time scale of geomagnetic reversals seen in the paleomagnetic record (on the order of 10^5–10^6 years), qualitatively the stabilizing effect of the conducting inner core is clearly evident. The conducting shell at the core–mantle boundary seems to exercise much less of a stabilizing effect.

Refinements

The work of Glatzmaier and Roberts opens up many more avenues for future progress than it closes. Harvard University's Jeremy Bloxham suggests, "Now that we know the geodynamo is feasible, we need to run several different models to find out what factors are most important." Olson hopes detailed observations of the model and laboratory experiments on the convection of conducting fluids in magnetic fields will illuminate the actual physical mechanisms of the geodynamo.

Glatzmaier and Roberts are currently monitoring the evolution of a more realistic and non-Boussinesq version of their model in its reversed-field configuration. They have added compositional convection, reduced the heat flux from the inner core to its geophysical value and are also studying the influence of a horizontally dependent heat flux at the core–mantle boundary. More than 10 000 years after the reversal the model appears stable in its reversed configuration, and its field is currently slightly *more* dipolar than Earth's field. (See the figure on page 17.) At some point, the researchers hope to develop a version of their model that would allow them to take full advantage of the extra speed and power of a massively parallel supercomputer and observe the model's evolution more rapidly.

Still, those hoping for a quick solution to the origin of geomagnetism are likely to continue to live in frustration. Caltech's Stevenson hopes that in three to five years it may be possible to observe a million-year evolution of a model that includes compositional buoyancy and relaxes the Boussinesq approximations. Such a model would allow one to investigate whether the field amplitude is determined by energy limitations or by the balance of Coriolis and Lorentz forces. After ten years the parameter space of variables in the model may be sufficiently explored to judge the adequacy of current geodynamo models. Stevenson suggests, "We have to look at this as a long-term project."

RAY LADBURY

References

1. G. A. Glatzmaier, P. H. Roberts, Phys. Earth Planet. Inter. **91**, 63 (1995). G. A. Glatzmaier, P. H. Roberts, Nature **377**, 203 (1995).
2. R. Hollerbach, C. A. Jones, Nature **365**, 541 (1993).