Core Concerns

The hidden reaches of Earth are starting to reveal some of their secrets

By RICHARD MONASTERSKY

Gary A. Glatzmaier gazed down on the world he had created and decided it was good. Peering deep into the bowels of the planet, he saw vast currents of molten iron alloy swirling at temperatures above 5,000 kelvins, nearly as hot as the surface of the sun. He watched for 40,000 years as the globe's magnetic field pulsated like the beating of a heart. Deeper still, at the center, he beheld a spinning orb made of solid iron almost as large as the moon.

This creation, forged from numbers and equations, is a virtual version of Earth's metallic core. Glatzmaier, a geophysicist at Los Alamos (N.M.) National Laboratory, constructed the extremely sophisticated computer model to simulate the magnetic dynamo that churns away, unseen, far below Earth's crust.

Five years ago, most geophysicists considered such representations poor stand-ins for the real core—the scientific equivalent of a tone-deaf Elvis impersonator. In the last year, however, these models have earned newfound respect by showing striking similarities to the real thing. The simulation by Glatzmaier and his colleague Paul H. Roberts of the University of California, Los Angeles scored a major coup with its prediction that Earth's solid inner core spins out of sync with the rest of the planet—a feature verified 3 months ago by seismologists (SN: 7/20/96, p. 36).

Combined with recent advances in seismology, the computer models are opening windows into Earth's hitherto impenetrable iron heart. This new access gives scientists hope that they can finally tackle what Einstein reputedly called one of the five greatest unsolved problems in physics: the origin of the planet's magnetic field.

Although theorists have made great strides since Einstein offered that challenge, geomagnetists still lack a firm understanding of how the field forms and why it changes direction every few hundred thousand years or so. "The mechanisms behind the magnetic field and behind the reversals are still really mysterious. It's fair to say that this is one of the grand intellectual challenges—not just in the earth sciences, but, I think, in all of the physical sciences," says Raymond Jeanloz, a geophysicist at the University of California, Berkeley.

A soft-spoken scientist most at home among his equations, Glatzmaier declines any comparison with the creator in Genesis. It's interesting to note, however, that Glatzmaier began his modeling work with the sun, only later moving on to model Earth.

Initially, Glatzmaier simulated the sun's magnetic field, which arises from the motion of ionized hydrogen and helium inside that star. The branch of physics governing this realm is called magnetohydrodynamics, a mouthful of a term that researchers often shorten to MHD.

After the sun, Glatzmaier studied Jupiter, the Kuwaiti oil fires, and Earth's rocky mantle before finally turning to Earth's core. The recent model—a variation of the one developed for the sun—simulates in three dimensions the currents of iron alloy flowing within the core.

The planet's nucleus is believed to have formed early in Earth's 4.5-billion-year history, when molten iron and other heavy elements sank deep into the planet. As this metallic soup cooled over the eons, crystals of iron froze at the center, creating a solid iron core inside the surrounding liquid alloy.

Over time, this process built an inner core 2,440 kilometers wide, about one-fifth the diameter of the planet. The outer core of liquid alloy spans 2,260 km from top to bottom and is composed of 90 percent iron and 10 percent lighter elements, possibly oxygen and sulfur.

The slow cooling of the core, which continues today, is critical because it stirs the iron alloy. Heat escaping from the top of the outer core chills the upper layers of the outer core, causing the material to sink. At the same time, iron crystals freeze and adhere to the surface of the inner core, leaving behind material richer in the lighter elements. This alloy floats to the surface of the outer core.

This movement of metallic fluids gave birth to Earth's geomagnetic field, according to MHD theory. Basic physics teaches that moving metals can produce an electric current if they pass through a preexisting magnetic field. This principle underlies most electric generators, which use heat to move turbines that carry wires past magnets.

If magnetic fields were common in the early solar system, as scientists believe, then convective flow in the outer core must have created electric currents in the fluid iron. The process turned into a self-sustaining dynamo, because electric currents produce their own magnetic fields. Once the core started producing a magnetic field, the continuous movement of the iron alloy would have maintained electric currents in the outer core, thereby sustaining the geomagnetic field.

Physicists had sketched out the general picture of this dynamo model by the late 1950s, but the details of what goes on in the outer core remain one of Earth's deepest secrets. What little is known about the outer core comes from the portion of the geomagnetic field that reaches Earth's surface. With its prominent north and south poles, this field is roughly dipolar in orientation, as if it came from a huge bar magnet buried inside the planet.

The simple exterior field—the one that guides Boy and Girl Scouts, airliners, and migrating birds—is but a tiny fraction of the magnetic field writhing within Earth's core. The portion one can sense at Earth's surface comes only from the uppermost layer of the outer core. The much more complex field generated deeper down is trapped inside the outer core and never reaches the planet's exterior.

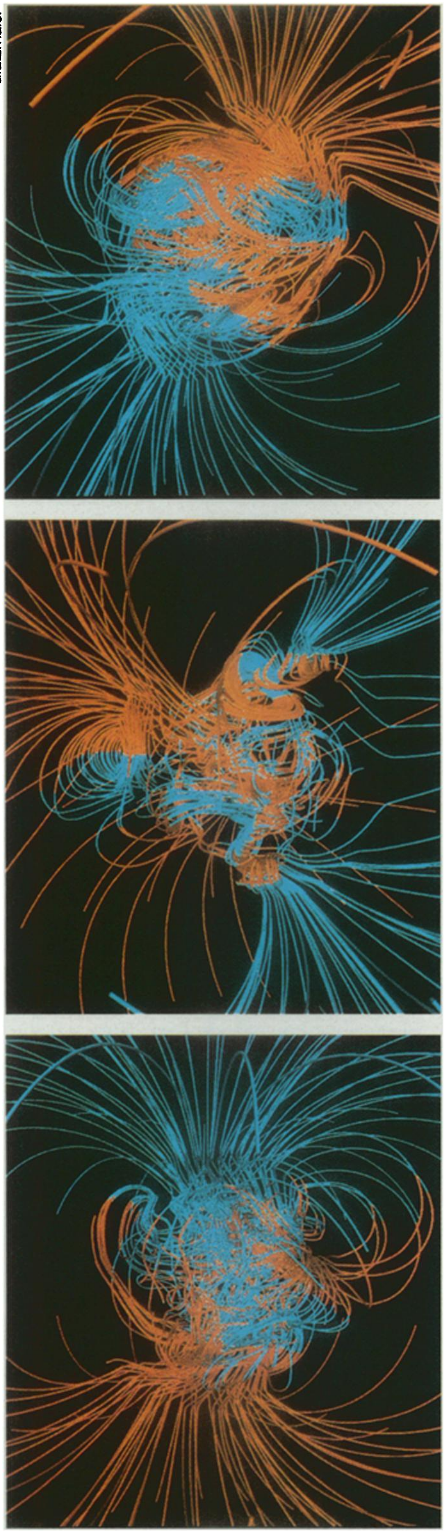
In fact, much of the field created in the upper layer of the outer core also remains hidden. The toroidal portion of the field—which runs in circular east-west bands within the outer core—does not leak outside the core, so scientists cannot measure it. Only the poloidal element—which loops from one pole around to the other pole—extends to the planet's surface and into space.

While Earth conceals most of its field, a computer model is less bashful. That's why Glatzmaier and Roberts have attempted to create a virtual version of the geodynamo, which they run at the Pittsburgh Supercomputing Center and at Los Alamos. They started by specifying how quickly heat leaks out of the core, and then they let the MHD equations govern how the liquid alloy responds. The flow patterns, as they established themselves, generated electric currents and a magnetic field.

"The question I wanted to answer was whether convection in the fluid core could actually maintain the magnetic field—a field that looks like the Earth's magnetic field," says Glatzmaier. "People had assumed it was happening that way, but it was never really demonstrated. What's encouraging is that I'm getting a magnetic field that looks a lot like Earth's in its strength and its structure."

The similarities extend beyond mere

Glatzmaier



As the world turns over: In this computer simulation, the magnetic field emanating from the core flipped upside down. Before the reversal, poloidal magnetic field lines leave the north magnetic pole, curve around the planet, and dive back into the south pole (top). During the transition, the field becomes disorganized (middle) for roughly 1,000 years and then reestablishes itself with the opposite polarity (bottom). Lines wrapping around the core in east-west-directed bands indicate the toroidal magnetic field.

looks. The computer-fabricated field migrates slowly to the west in a manner similar to that of the actual field, whose features shift westward by roughly a degree each decade.

The model represents a step forward, says Glatzmaier, because in most previous attempts, researchers had prescribed the flow patterns rather than letting them evolve in response to the magnetic field. The earlier techniques used a short-cut that simplified the problem and guaranteed a realistic outcome—as if the tone-deaf Elvis impersonator only lip-synced instead of actually singing.

"The less you specify in the model, the more you are able to learn. If you specify everything, you can get something that looks just like the Earth, but you will not understand why things happen because you have specified the solution," says Glatzmaier.

Glatzmaier and Roberts let their model run through millennia of simulated time, watching the magnetic field wither and then rebound, all the while remaining dipolar. About 35,000 years into the simulation (and after more than a year of real time), the dipolar field nearly disappeared. For 1,000 virtual years the field languished, with a confusing multitude of magnetic poles popping up instead of fixed north and south poles. When the field eventually recuperated, it was pointing in the opposite direction.

Here was a real triumph for Glatzmaier and Roberts. Their MHD model had produced a geomagnetic reversal entirely on its own, without any provocation from the experimenters.

"Our original motivation was not to simulate magnetic field reversals. That seemed too much to hope for. So that was a nice surprise," says Glatzmaier.

The two researchers published their reversal data in the Sept. 21, 1995 NATURE. Although the model simulations have continued, with one now exceeding 200,000 years in duration, Glatzmaier and Roberts have not witnessed a second reversal.

That may be a good sign, since reversals of the actual geomagnetic field usually occur only once every few hundred thousand years and occasionally much less frequently. Still, with only one reversal under their belts, the scientists cannot yet draw many conclusions about what causes the process.

The MHD model garnered even more attention last July, when two seismologists reported that the solid inner core of the actual Earth is spinning faster than the rest of the planet. Xiaodong Song and Paul G. Richards of the Lamont-Doherty Earth Observatory in Palisades, N.Y., who made the discovery, credited the MHD model for stimulating their search.

Glatzmaier and Roberts had predicted the core's quick spin last year, after studying the flow patterns of the iron alloy within their model. The simulation revealed eastward-moving currents of fluid at the bottom of the outer core, roughly analogous to the jet streams in the atmosphere. These currents in the outer core, the scientists realized, would put a magnetic torque on the inner core, forcing it to spin slightly faster than the mantle and crust.

One of Glatzmaier and Roberts' chief competitors, Jeremy Bloxham of Harvard University, has documented a similar torque within his MHD model of the core. In the Harvard simulations, which began more recently than the Los Alamos work, the core spins faster than the rest of the planet on average, but it slows down for brief periods. "I wouldn't be surprised if the rate changes with time," says Bloxham.

There may, however, be explanations besides magnetic torque for the core's fast spin. Berkeley's Jeanloz notes that the rotation rate of the entire Earth is slowing as a result of the friction caused by lunar and solar tides. The deceleration of the inner core, however, may lag behind that of the rest of the planet because the inner core is separated from the mantle and crust by the fluid outer core. According to this theory, the inner core is now rotating as quickly as Earth's surface was spinning 60,000 to 100,000 years ago.

"We may be able to distinguish if one or the other of these ideas is correct over the coming decades, if not years," says Jeanloz. If magnetic torques are causing the discrepancy, seismologists monitoring the inner core should see the rotation rate vary with time. If the slowdown of Earth is to blame, then the rotation rate should change little except for an extremely slow deceleration. Both of these mechanisms may work together, says Jeanloz.

As seismologists continue to refine ways of detecting the inner core's rotation, Glatzmaier, Roberts, and others work on improving the MHD models of the core. At present, the models take shortcuts in simulating fluid flow in the core. Because of computer limitations, MHD models treat the iron alloy as being orders of magnitude more viscous than the actual liquid core, which scientists think flows about as easily as water. "We're hoping we're not doing too much harm by making this approximation," says Glatzmaier.

These and other limitations had led many geophysicists to disregard MHD models. The recent successes, however, have quieted critics and forced them to start taking the models seriously.

"The types of numerical calculations being done today are just beginning to provide us with a set of tools that we need to understand how the geodynamo works," says Bloxham. "There is just an enormous amount of work that we need to do. But I think it's a very exciting time." □