The Earth's Magnetic

By STEFI WEISBURD

In all the thousands of years that people have lived in the aura of the earth's magnetic field, no one has discovered why it exists. People have used the geomagnetic field for centuries to navigate the seas, and more recently to unravel the evolution of the planet, without ever understanding the exact mechanisms of how the field itself is created. It took until the middle of this century for geophysicists to arrive at the idea that the swirling dance of the earth's liquid iron core somehow generates the magnetic field. But the detailed choreography of this motion, what energy sources drive it and how it gives rise to the field, remain stubbornly out of reach.

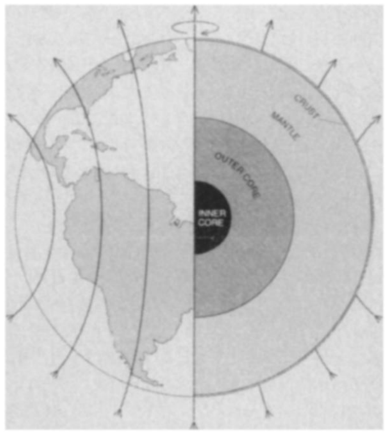
The best way for scientists to catch a glimpse of what is going on 2,900 kilometers below their feet is to study changes in the field. Paleomagnetists know from scrutinizing the magnetic orientation of rocks in the oceanic crust that the field completely reverses direction about every half-million years. But it will be a few hundred thousand years before scientists will be able to observe the next reversal firsthand.

Four hundred years of navigational charts also reveal long-term changes, or "secular variations," of the field. Its intensity, for example, has been slowly decreasing in this century. And because the circulation of the fluid core is unable to keep up with the rotation of the solid mantle and crust, the field gradually drifts westward across the planet's surface at a rate of about 1° of longitude every five years.

These kinds of changes help constrain geomagnetic models, but because they are slow and continuous the information they provide is limited. Sudden changes, on the other hand, would give scientists different footholds for studying the unseen and mysterious core motions.

This is why the "magnetic jerk" has stirred up so much excitement and debate.

The magnetic jerk was first reported in 1978 by a group of researchers at the University of Paris in France. Vincent Courtillot, Joël Ducruix and Jean-Louis Le Mouël discovered that, nine years earlier, there had been a rapid change, or jerk, in the acceleration of the secular variation of the magnetic field in France. This change was evident primarily in the westward drift, which had in general been slowing down until 1969, when over the course of a year or so it began to speed up.



Surrounding the earth's solid inner core is a sea of molten metal. The motion of this fluid outer core is thought to generate electric currents, which in turn create the geomagnetic field.

Such rapid fluctuations in the measured magnetic field are not unknown. There are all sorts of sources outside of the earth — ionospheric currents and magnetic storms, for example — that induce currents to flow in the mantle, setting up magnetic fields that merge with that generated by the core. In order for proponents of the jerk to show that it was indeed something special, they had to demonstrate that it was not generated by these external sources but instead originated in the core.

So Stuart Malin of the National Maritime Museum in London, England, and Barbara Hodder of the Institute of Geological Sciences in Edinburgh, Scotland, examined the data of 83 observatories. Using a mathematical method called spherical harmonics, they separated the internal and external contributions to the field and concluded in a 1982 paper that most of the jerk was indeed created within the earth. Spherical harmonics was developed in the 1800s by the German mathematician Karl Friedrich Gauss, who showed that 95 percent of the geomagnetic field originates within the earth's interior.

After the French paper appeared in 1978, a number of researchers began to hunt for the jerk in data from other parts of the world. According to Le Mouël it has turned up in field measurements taken in other European countries, the Soviet Union, parts of North America and a few sites, including India, in the Southern Hemisphere, where there are far fewer observatories. Le Mouël and his colleagues have also laid out the data on world maps to demonstrate the worldwide scale of the jerk. "In some very remote places the jerk has the same character, so in my opinion, it's rather global," he says.

While everyone involved agrees that the field in Europe "jerked," one researcher in particular challenges the idea that the jerk was a global event. Leroy Alldredge of the U.S. Geological Survey in Denver notes many sites in the world where the jerk is not at all evident. He also contends that some proponents of the jerk have biased their analyses by assuming *a priori* that a worldwide jerk occurred in 1969. In addition, Alldredge claims that the apparent rapidity of the field change is an artifact of the mathematical assumptions used.

Instead, Alldredge thinks that the secular variation is typically upset in many unrelated events over the globe. "There are lots of *localized* sources that are not coordinated with time or place, which are the result of turbulence or some such thing in the core," he says. "They're like weather patterns, like tornadoes — they don't perturb the worldwide picture but have a strong local impact."

Alldredge draws on a recently published, detailed study by Hiroo Mizuno of the Geographical Survey Institute in Tsukuba, Japan. After analyzing 12 years of magnetic data recorded at 40 stations in Japan, Mizuno found abrupt changes in the secular variation pattern at a number of different spots, but these did not appear to be closely related to one another or to the 1969 jerk observed elsewhere.

Le Mouël and many others, however, remain convinced of the jerk's global nature. "The homogeneity of the phenomenon may not be as clear as we originally believed," he says. "But I do not think the jerk itself is a local phenomenon because we see it at many places over the world." The jerk may not be visible at some sites, he adds, because there may be other, local changes in the field at those spots that mask it.

Recently, Ducruix, Le Mouël and C. Gire, also at the University of Paris, have identified what they believe was another jerk in 1912 or 1913 with the same global features as the 1969 jerk. They also suspect that there was yet another jerk in 1978, although their analysis is far from complete.

Hiccup

Something strange happened to the geomagnetic field in 1969: It jerked

If Le Mouël and others are correct in thinking of the jerk as global, it would mean that the circulation of the core fluid was altered within one year all over the surface of the core. "The interest with the jerk is that it was a surprise," says Le Mouël. "Such a rapid and organized change was unexpected because the circulation of the surface of the core was supposed to be more or less random and turbulent. If you admit the jerk...you must say that the circulation is not like that at all."

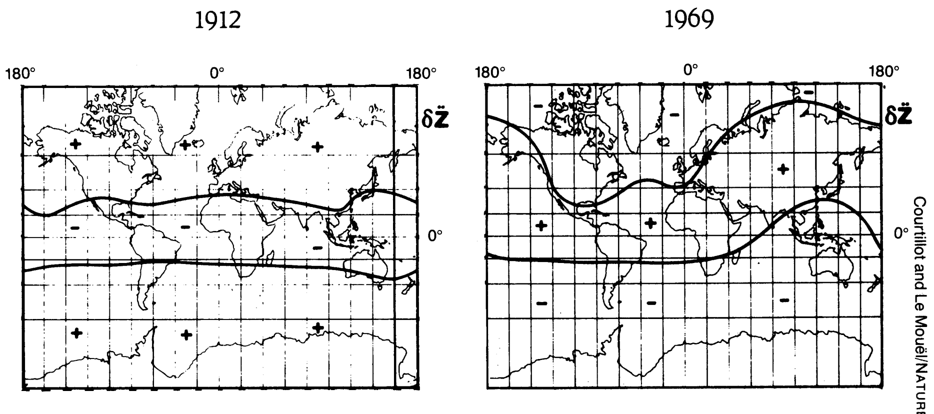
But how might this upset in the circulation have occurred? Theories to explain the cause of the jerk are scant. Some researchers have suggested that a large bubble grows and migrates in the core. Another idea, put forth by Raymond Hide of the Meteorological Office in Bracknell, England, rests on the twisting of the core fluid as it simultaneously rotates and convects toward the surface. In this process, the magnetic field lines carried by the fluid twist as well. Eventually, the field lines, being wound up like a rubber band on a model airplane, would develop a knot or kink, which could spread in waves across the core in very little time. Such "kink instabilities" have been demonstrated in plasma physics.

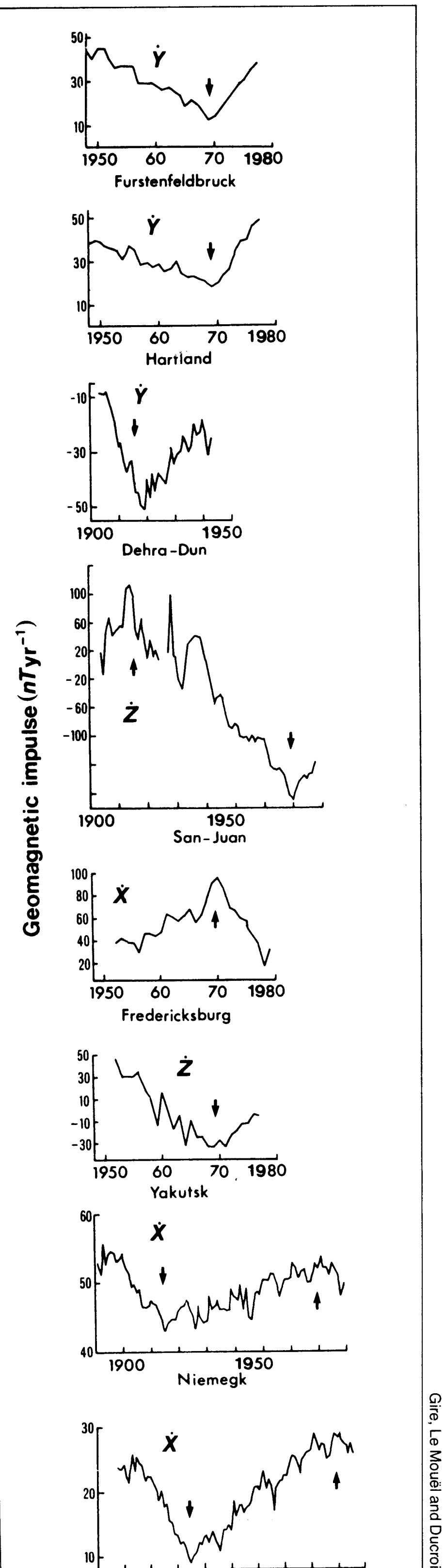
Beyond the spatial extent of the jerk, its one-year duration has consequences for not only the core but also the mantle. Scientists have thought that any change in the magnetic field that took place in less than four years or so would have originated externally because such signals from the core would never survive to reach the surface. The mantle, they believe, is an electrical conductor, albeit a poor one compared with the core, and so screens out the high-frequency core signals.

The exact conductivity of the mantle, however, has never been conclusively determined. If the rapidity of the jerk is a real effect, "then the conductivity of the lower mantle is rather lower than most people thought, because more rapid signals are getting through," says geophysicist George Backus at the University of California at San Diego.

In a paper written in 1983, Backus had noted that if one looked just at one point, it was possible that the different components, or spherical harmonics, of the field might interfere to give the appearance that the jerk lasted only one year. A more recent study using many points on the globe failed to support the year-long jerk, but Backus notes that this may be because the data errors were worse than he assumed or because the conductivity of the mantle changes with geographic location.

"I think there is general agreement that there is an event there, and that it really does contain information about the core and most of the lower mantle," he says. "But it seems to be more complicated





Le Mouël and others believe that the jerk was a global phenomenon. To the far right are examples of data from observatories in Europe, the United States, the Soviet Union, India and Puerto Rico. The graphs show the secular variations (changes in the field from year to year) for different components (X, Y and Z) of the geomagnetic field. The arrows point to possible jerks in about 1912 and 1969. There are other examples where the jerk is far less clear or not seen at all. Above, Le Mouël and his co-workers constructed maps to show that the geographic patterns of the jerks in 1912 and 1969 were similar. The quantity $\delta \ddot{Z}$ is the change in the second time derivative of the Z component of the field.

than we thought, so we just have to work harder."

Some clues to the jerk and the motion of the core may be found by studying the rotation of the earth as expressed in the length of day and the Chandler wobble, or polar motion (SN: 9/21/85, p. 183). For more than 30 years scientists have known that changes in the rotation rate on time scales of a decade are related to variations in the geomagnetic field, because the field mechanically couples the mantle to the core. Researchers have also proposed that when the flow of the core changes, its pressure field changes as well, deforming the mantle and altering its moments of inertia, and, therefore, its angular motion.

As a result, says Le Mouël, "we think that after the jerk, with a time lag of 10 to 15 years, there is an acceleration of the earth." He has suggested that secular variation impulses around 1900, 1913 and 1969 were associated with changes in day length around 1910, 1930 and 1980.

As with most large-scale, complex subjects, study of the jerk is hampered by inadequate data. Scientists lack continuous, detailed and uniform monitoring of the field. The 200 or so magnetic field observing stations are spread unevenly across the globe, leaving big gaps in the ocean and other areas. Debates over the jerk underscore the need for more stations and better coverage. Some scientists have suggested putting magnetometers in the network of digital seismic stations already in place or planned.

"One of the things the jerk has done is to encourage the geomagnetic community to push for a long-term observation program of the field from space" to complement ground stations, says geomagnetist Christopher Harrison at the University of Miami in Florida. Two satellites have measured the magnetic field in the past, but these were short-lived. Magsat, for example, lasted only six months. Geomagnetists at NASA and elsewhere have their sights on a "Magnetic Field Explorer" program, which would launch a trio of three-year satellites, perhaps in conjunction with other countries. The satellites would provide worldwide coverage of the field four times a year.

Another jerk is not, of course, guaranteed to occur during the decade-long NASA program, "but we should see more short-time changes in the field, which may be as useful as the jerk in determining what the conditions in the core are like," says Harrison. The Magnetic Field Explorer did not make it into the fiscal year '87 NASA budget plan as scientists had hoped, so the researchers will try again next year. The earliest possible launch date would be during 1989.

In the meantime, there's more theoretical mileage to be gotten out of the tremor in the geophysical thinking set off by the jerk. □

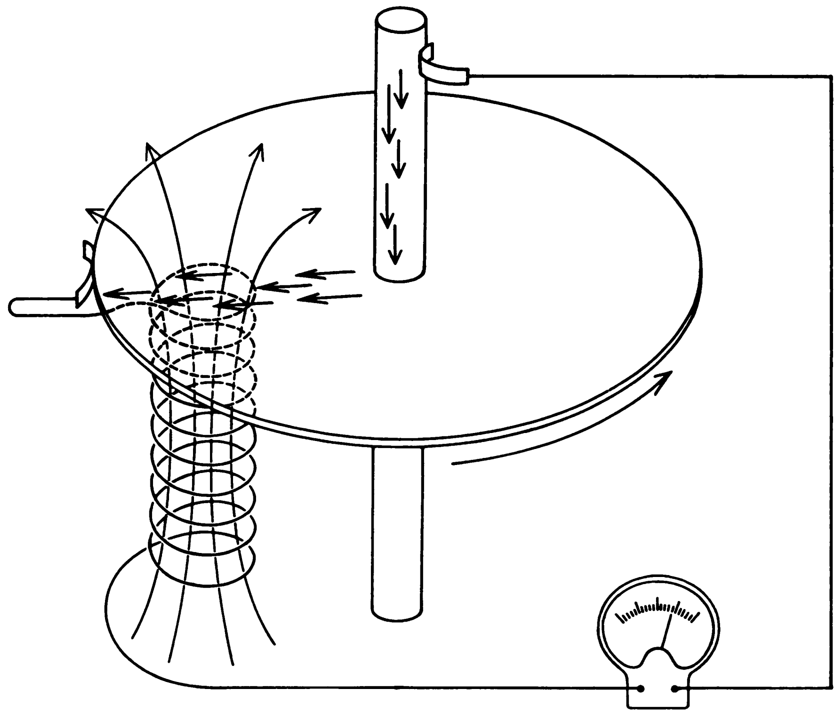
Modeling Magnetism: The earth as a dynamo

In 1600 William Gilbert, the physician of Queen Elizabeth I, published a treatise on magnetism called *De Magnete* in which he dispelled the notion that lodestones are attracted to heavenly bodies. Instead, he concluded from an experiment with a spherical lodestone that the earth itself is a giant magnet.

Centuries passed before scientists developed any reasonable ideas as to what causes this geomagnetism. The main, dipolar part of the earth's field clearly resembles that produced by a bar magnet. But it has become apparent that the field could not arise from permanently magnetized minerals in the earth. Most of the earth is too hot for such materials to retain their magnetism for long, and in order to create all of the changes observed in the magnetic field, solid magnets would have to scurry around within the earth—an impossible feat that would result in massive upheavals of the planet. Moreover, earthquake data indicate that the outer region of the core is a fluid.

Forty years ago Walter M. Elsasser at the University of California at San Diego and Edward C. Bullard of the University of Cambridge in England developed the "self-exciting dynamo" model for the core. The illustration below shows a simple example of a dynamo invented by the 19th-century British scientist Michael Faraday. When the metal disk spins in the initial presence of a magnetic field, currents are generated in the disk. In a self-exciting dynamo, these currents are fed into a solenoid, or coil, which creates a magnetic field of its own.

If the spinning fluids of the earth's outer core act like the disk in the dynamo, the earth could similarly produce a large magnetic field, provided there was a small magnetic field around at the beginning. (The small field that pervades the galaxy would be a good candidate, according to some scientists.) Another provision would be that the core fluids keep moving, and the unanswered question here is what energy



In this self-sustaining Faraday disk dynamo, an electric current (small arrows) in the copper disk reinforces the magnetic field of the coil.

source is responsible for doing just that.

Scientists believe this outer core is a rotating liquid made principally of molten iron and nickel, which conduct electricity. This view of the core has led to the only surviving idea out of many theories (including the notion, once considered and then dropped by Albert Einstein and others, that magnetism is an inherent property of all rotating masses).

Of course, the actual core movements must be considerably different from and much more complex than a spinning disk. So the present focus of research is to devise complicated flow patterns consistent with the magnetic field's behavior — its reversals, secular variations and now possibly the jerk. —*S. Weisburd*