The origin of the Earth's magnetic field: fundamental or environmental research?

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The origin of the Earth's magnetic field is a long-standing issue, which has captured the attention of many renowned scientists. If William Gilbert, André-Marie Ampère, René Descartes, Edmond Halley, Karl-Friedrich Gauss, Lord Blackett, and many others who contributed to the development of science, have worked on this problem, it is mainly because it was related to a very practical issue of critical importance: navigation at sea. This is not so true anymore, now that satellites provide the precise latitude and longitude without the need for us to rely on the Earth's internal magnetism. Yet the question of the origin of the Earth's magnetic field is so natural that it is still the object of very competitive research. Nobody can ignore that the compass needle points toward the north, and it is a bit irritating that we still cannot offer a complete physical understanding of why it is so. The problem has therefore become an active field of fundamental research in which significant progress has been made in the last few years using combined theoretical, experimental and numerical approaches. By its very nature, the problem is interdisciplinary and lies at the interface of physics, geophysics and applied mathematics. This problem has recently received considerable attention in the press because of the concern of a possible reversal of polarity of the Earth's magnetic field in the near future. Considering that we risk seeing our planet unshielded from the solar wind, understanding the field generation mechanism again appears to be a societal concern and a legitimate goal of environmental research.

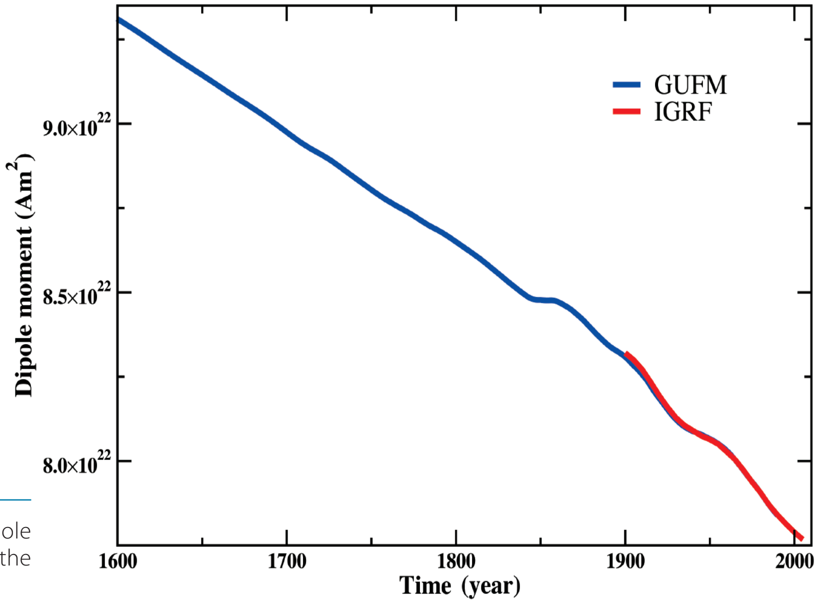
I will summarise here the basics of our present understanding of the generation of the Earth's magnetic field and then ponder on the scientific clues supporting the possibility of an approaching or imminent polarity reversal.

The origin of the Earth's magnetic field

When the Earth formed some 4.5 billion years ago, heavy elements concentrated at the centre, as a result 3000 km below our feet lies the largest of our planet's oceans: the core of liquid iron (mixed with traces of lighter elements), a sphere of 3400 km in radius. As the pressure increases towards the heart of the Earth, the iron solidifies and we find a solid inner-core, which occupies a volume of 1200 km in radius. It is in this metallic core that the magnetic field of the Earth originates. Temperatures at such a depth are above 3000°K and thus well above the Curie point (at which metals lose their ferromagnetic properties). A magnetic field can therefore only be sustained if electrical currents circulate in this ocean of liquid iron. However, Ohmic dissipation would suppress any unsustained electrical current in the Earth's core within some 20 kyr, yet there has been a magnetic field on Earth for millions of years. This is attested by the study of the ancient field recorded in sediments and lavas (known as paleomagnetic records). This means that there must be a process that regenerates electrical currents in the Earth's core against Ohmic dissipation.

The study of paleomagnetic records of the Earth's magnetic field also revealed a most puzzling feature: the Earth's magnetic field has reversed its polarity several times during its history in an apparently chaotic manner. The self-excited dynamo mechanism was first proposed by Sir Joseph Larmor in 1919 to account for the magnetic field of sunspots. This theory, called the *dynamo theory* for short, proposes that the non-magnetic solution ($\boldsymbol{B} = \boldsymbol{0}$) in a magnetohydrodynamic flow can become unstable if the flow is vigorous enough. This sort of instability can easily be introduced using a simple mechanical disk device (see the box), it is not as straightforward when it concerns a uniform volume of conducting fluid. A major cause of concern was first identified by Thomas Cowling, as early as 1934. Cowling found that an axially symmetric field cannot be maintained by dynamo action. This result suppresses the hope for any simple axially symmetric description of the dynamo process (a tempting approach considering the strong symmetry of the Earth field). In fact an even more general result came afterwards, and is known as Zeldovich's theorem: no two-dimensional solution can be sought. The problem has to be envisaged directly in three-dimensions of space, without the hope of a first simplified spatial approach.

The problem was formalised just after World War II by Walter Elsasser. Despite the early bad news of Cowling's theorem, it is the only theory that can account for the observational constraints. Besides, a remarkably nice feature of the resulting equations is their invariance under a change of sign of $\boldsymbol{B}$. If a velocity field of space and time $\boldsymbol{u}(\boldsymbol{x},t)$, a temperature field $T(\boldsymbol{x},t)$, and a magnetic



▶ **Fig. 1:** The strong decrease of the magnetic dipole moment over the last four centuries as revealed by the GUFM and the IGRF field models.

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field $\boldsymbol{B}(\boldsymbol{x},t)$, can be identified that satisfy the governing equations; then the same velocity and temperature fields together with the opposite magnetic field $-\boldsymbol{B}(\boldsymbol{x},t)$ also satisfy the equations. This property (resulting from a linear equation governing the evolution of $\boldsymbol{B}$ and a Lorentz force quadratic in $\boldsymbol{B}$ in the momentum equation) does remarkably well in accounting for reversals. The two polarities do not need to correspond to two different hydrodynamic states and reversals can be thought of as transitions from one magnetic solution to another.

Another critical issue concerns the properties of liquid iron. Like all liquid metals, liquid iron dissipates electrical currents much more efficiently than heat and momentum. In other words, the ratios of the kinematic viscosity or thermal diffusivity to the magnetic diffusivity (these ratios are known respectively as the *magnetic Prandtl number* and the *Roberts number*) are exceedingly small (of the order of 10^{-6}). Since dynamo action requires motions to be vigorous enough to counteract magnetic diffusion, it means that they are extremely vigorous in comparison, say, to viscous effects. The ratio of these two effects is known as the *Reynolds number*. A large Reynolds number means a strong connection with the difficult problem of hydrodynamic turbulence. In the case of Earth core dynamics, this issue is made even more challenging by the rapid rotation of our planet. The Coriolis force, as well as the magnetic Lorentz force, strongly affects the turbulent flow, reducing turbulence, but also making it very anisotropic. The properties of this rapidly rotating magnetohydrodynamic turbulence are, as yet, far from understood.

Significant progress has been achieved over the last few years. Numerical models succeeded in solving the proper set of equations in the relevant geometry. Yet models are restricted so far to a very remote parameter regime, dominated by viscous forces. Efforts are underway to try to push models to the right force balance. Experimental fluid dynamos were also created simultaneously in 1999 in Riga (Latvia) and Karlsruhe (Germany), but the flows in these first experiments were extremely confined (guided by well established analytical dynamo flows). The first objective of the new generation of experiments is to reduce the constraints on the flow and thus gain insight into the dynamo solution.

Why is the Earth field dominated by an axial dipole? How does it reverse? What is the role of turbulence in the dynamo process? How does the system dissipate the energy at small scales? These are some of the open questions that researchers are trying to address.

The self-excited dynamo: a magnetic instability

Dynamo action (the conversion from kinetic to magnetic energy) works so efficiently in a bicycle dynamo that it is not straightforward at first to capture what makes the subject so difficult and interesting! The first critical issue is that an everyday dynamo relies on a permanent magnet. Usually the magnet rotates within a loop and the varying flux will induce an alternating electrical current in the coil. This principle can be slightly modified to produce a continuous current, a process known as the *Faraday Disk Dynamo* (introduced by Faraday in 1831). If a conducting disk revolves while being permeated by an applied magnetic field (as depicted in fig. a), a potential difference will be induced between the axis and the rim of the disk, thus driving an electrical current if these are connected by a wire. The magnetic flux through the disk and the electromotive force (obtained by integrating $\boldsymbol{u} \times \boldsymbol{B}$ across the disk of radius r, assuming a uniform normal field B) are

$$\Phi = B\pi r^2 \qquad \text{and} \qquad \mathcal{E} = \frac{\Omega B r^2}{2} = \frac{\Phi\Omega}{2\pi}$$

This setup is however not a *self-excited dynamo*, since it relies on a permanent magnet. If one now replaces this magnet with a solenoid of inductance L (as in fig. b), one now faces an instability problem. If the rotation rate is small enough, the resistivity will damp any initial magnetic perturbation. If the rotation rate is sufficient, then the system undergoes a *bifurcation* and an initial perturbation of the field will be exponentially amplified by *self-excited dynamo action*. Introducing M, the mutual inductance between the solenoid and the disk, we can use

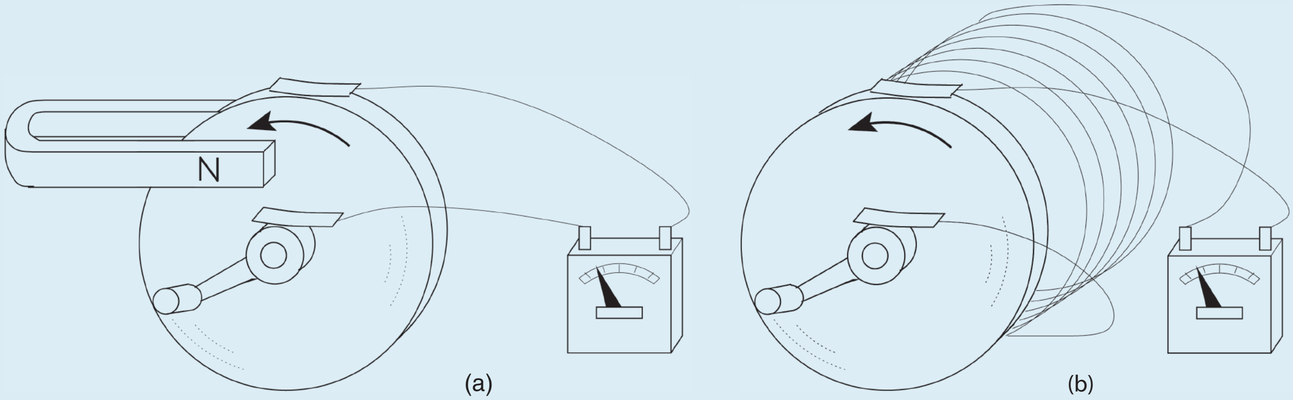
$$\Phi = MI \qquad \text{to rewrite} \qquad \mathcal{E} = \frac{M\Omega I}{2\pi}$$

Then, R being the electrical resistivity of the complete circuit, electrical currents are given by

$$L\frac{dI}{dt} + RI = \frac{M\Omega I}{2\pi}$$

It follows that the system becomes unstable and an electrical current grows in the circuit provided

$$\Omega > \Omega_c = \frac{2\pi R}{M}$$



(a) (b)

The approaching polarity reversal

While this field of research has made significant progress over the last few years, it has also received considerable attention in the press because of the concern of an approaching polarity reversal. Indeed, it has even been proposed that we are currently at the very beginning of such a geomagnetic reversal. Since these concerns are guided by observational facts, we will briefly review them here.

The dipole moment decay

The usual way to measure the strength and orientation of the dipolar component of the geomagnetic field is to use the dipole moment. It is defined using the first terms of the spherical harmonic expansion. It is a convenient notion, because it can also be recovered in the past using paleomagnetic records (neglecting the averaged effect of higher moment).

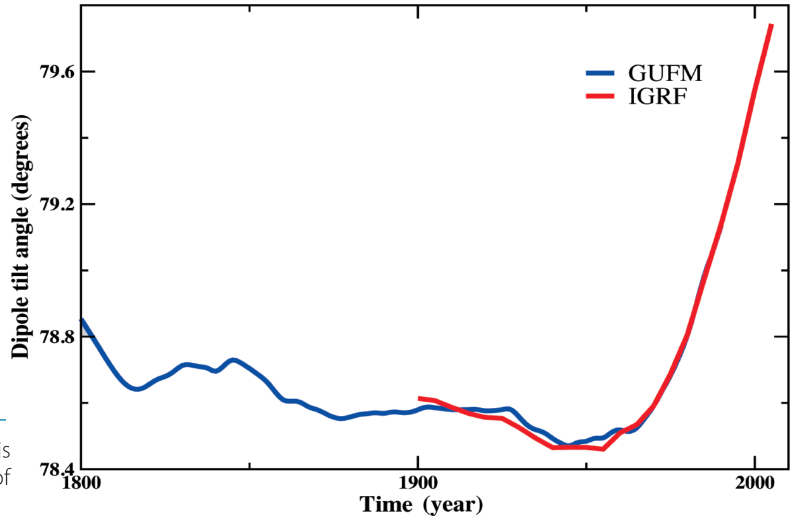
Rather than using brute magnetic observatory data, we rely here on smoothed models based on these measurements. These are the geomagnetic field model GUFM (Jackson *et al.*, 2000) over 1600-1990 or the International Geomagnetic Reference Field –IGRF (Mandea and MacMillan, 2000) going back to 1900. These models differ only slightly and we will use both to highlight the robust features. Both of these clearly reveal (see Figure 1) the rapid and relatively steady decrease of the geomagnetic dipole moment over the last four centuries. This constitutes the original and primary motive for pondering the possibility of an approaching reversal.

As striking as it may be, this decrease is not necessarily meaningful, especially if the present magnitude of the dipole moment is not small compared to that of the past. Indeed paleomagnetism reveals that the geomagnetic field amplitude is a fluctuating quantity and the present decrease could just be part of such fluctuations. In fact it turns out that, the present dipole moment is still significantly higher than its averaged value both over the last polarity interval (800 Ka) and the three preceding ones (0.8-1.2 Ma), see Table 1 (Valet *et al.*, 2005).

Another interesting property of the Earth's dipole moment is its direction, especially its tilt angle, the tangent of which reveals the relative strength of the axial dipole component (i.e. aligned with the axis of rotation) to the equatorial one. This angle is represented versus time in Figure 2. It is noticeable that the angle is presently rapidly increasing toward 90°. In other words, the dipolar component is becoming increasingly axial. This is just the opposite of what is expected for a reversal, simply reflecting the fact that the equatorial dipole is, at the moment, decreasing even more rapidly than the axial dipole.

The magnetic dip pole acceleration

Besides the global spherical harmonic expansion of the field, one can also think about locally defined quantities: the magnetic dip poles. These are the two places on Earth at which a magnetic needle would stand straight up. It is important to capture the distinction between these points and the dipole moment orientation discussed above. While the poles of the large scale dipole field identified in the previous paragraphs, using a spherical harmonic expansion, are naturally antipodal one to the other, the magnetic dip poles are local objects affected by all components in a spectral expansion. As a result, they can move independently of one another.



► **Fig. 2:** Inclination of the geomagnetic dipole. The field is presently becoming increasingly aligned with the axis of rotation (at 90°).

It turns out that the position of the northern magnetic dip pole is often measured during scientific expeditions, and it was recently found out that its velocity is rapidly increasing, reaching the huge value of 40 km/year over the last few years, whereas its peak-velocity had been of some 15 km/year over the last century. This sudden increase in the northern magnetic dip pole velocity is thought to be a harbinger of a sudden change in the behaviour of the field, which is possibly entering a phase of reversal. This has been the cause of considerable excitement. However, the first striking surprise is that, in the other hemisphere, the southern magnetic pole velocity has kept decreasing over the last few years and is well below 10 km/year! Besides, just as for the global dipole, the north magnetic dip pole is cruising toward the geographic pole and not away from it!

In fact the magnetic dip pole can be understood as the zero of the horizontal component of the field. Plotting isovalues of the horizontal field strength (see Figure 3) it can be shown that the north magnetic dip pole is simply an ill defined quantity, and a minute change in the field can yield a huge shift in the zero position (i.e. in the dip pole position), whereas the south magnetic dip pole is a well constrained quantity (Mioara and Dormy, 2003).

Magnetic flux patches

Another possible sign of an approaching reversal is the evolution of the magnetic field structure at the boundary between the core (where dynamo action takes place) and the mantle (largely insulating). Thanks to the insulating nature of the mantle (the first 300 km below our feet), spherical harmonic models can be continued downward to this depth. The field there is much more complicated than at the surface of the Earth, as the downward continuation reveals finer scale structures. Among these structures, while the globally dipolar nature of the field is still clearly present and the magnetic flux globally reverses its sign at the equator, some patches of reversed flux are present in both hemispheres. It happens that while there were 2 such patches in the northern hemisphere in 1980, this number has increased to 6 in 2000 (meanwhile a merger of two patches has brought their number down from 4 to 3, including a larger one, in the southern hemisphere). Of course, if these patches became so large and numerous that they began to cover the core surface, the polarity would be reversed! In fact it turns out that this is the way some of the numerical dynamo models reversals occur. At the moment, these patches extend over some 15% of the Earth core surface. Besides, we shall, of course, note that this increase in the number of reversed patches is the direct signature in the physical space of the decrease of the dipole moment reported before in the spectral domain.

The overdue reversal

Finally one last element could point toward the possibility of an approaching reversal: the last reversal dates back some 800.000 years ago, while seven reversals have occurred during the last 2 million years, so that… we could be overdue! The reversal rate of the Earth's magnetic field is however far from constant. The long-term average (over hundreds of Myr) is of 1 reversal per million years (the maximum value, when averaged over a few million years, is of some 6 reversals per million years). Some polarity intervals, known as superchrons, even lasted for tens of millions of years! This argument is therefore not very convincing.

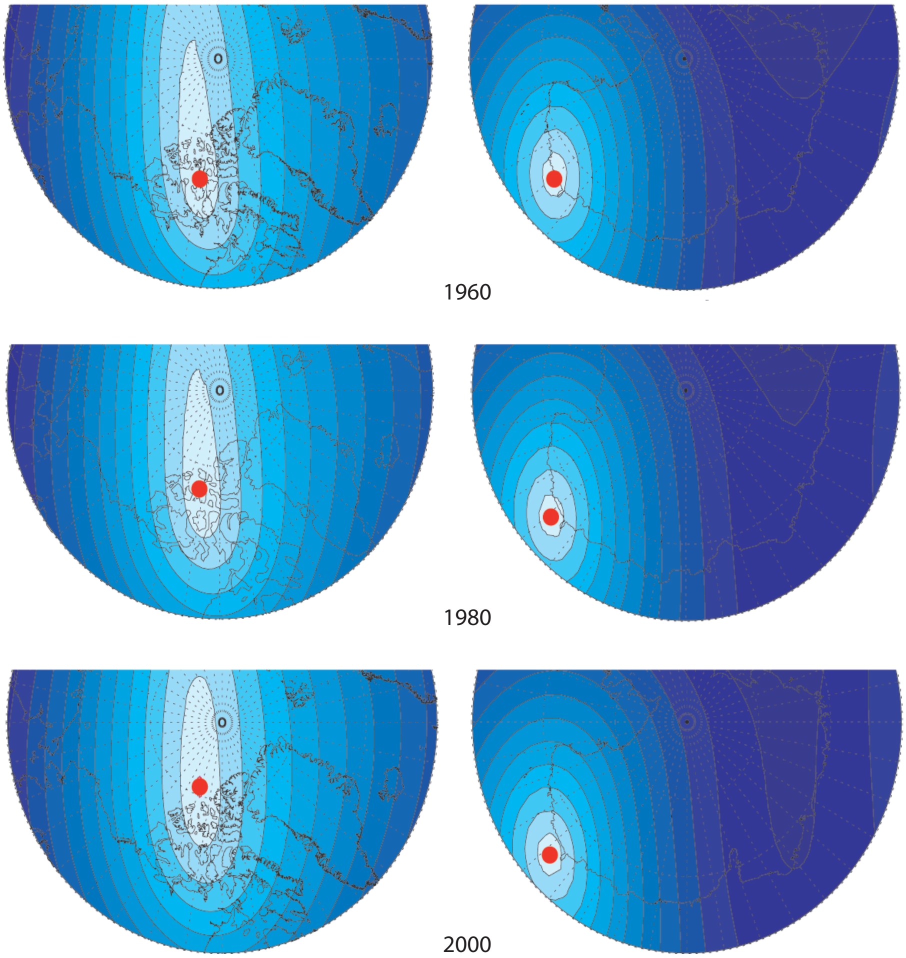
Date/Period	Dipole moment	Source
In 2005	7.776 x 10^{22} A m^2	IGRF
In 2000	7.779 x 10^{22} A m^2	IGRF
Over the last 800 Ka	7.5±1.7 x 10^{22} A m^2	Valet *et al*, 2005
Over 0.8-1.2 Ma	5.3±1.5 x 10^{22} A m^2	Valet *et al*, 2005

▲ **Table 1:** Dipole moment as provided by the International Geomagnetic Reference Field in 2005 and 2000 and the averaged value during the last 800 kyr and the 0.8-1.2 Ma interval. The present dipole moment is significantly stronger than the average over both periods.

Perspectives

A striking property of dynamo action seems to be its ability to work on a large variety of natural bodies. Most planets in the solar system (Venus and Mars excepted) exhibit a magnetic field, but the dynamo instability also occurs on even larger scales. The Sun (100 times the Earth in radius) exhibits a magnetic field, which reverses with a relatively regular period of 22 years. On an even larger kiloparsec ($3x10^{19}$ m) length-scale: galaxies exhibit their own large-scale magnetic field, and there again the only well accepted explanation is self-excited dynamo action. To highlight this amazing range of scales, we should just stress that in the units relevant to the galaxy, the Earth would be a nano-object! Yet a similar process is at work in all these objects (of course, under different parameter regimes).

In conclusion, while dynamo action and the origin of the magnetic fields of planets, stars, and galaxies constitutes an exciting scientific challenge; evidence for an imminent reversal remains rather weak. Moreover, the typical timescale for a reversal is expected to be of the order of 1000 years, so that it should not constitute a major source of urgent social concern. Does that mean that such research, exciting as it may be, should not be supported? Clearly it should. Researchers trying to understand the origin of the geomagnetic field do so for the sake of physical understanding, and for the improvement of our general knowledge; not because they fear an imminent reversal. More and more programmes (both national and international) are emerging to strengthen applied research, directly aimed at environmental concerns. It might be tempting for some fields of research to put forward hypothetical environmental issues and thereby enter the wealthier fields of research that directly address lay concerns, but is this a smart thing to do in the long term? Might it be more valuable to defend the idea that fundamental research is important? Even if -borrowing the words of Jacobi- its only objective is *"l'honneur de l'esprit humain"* (the honour of the human spirit). ■



◀ **Fig. 3:** The Earth's dip poles represented by a red dot for epoch 1960, 1980, 2000. The rapid displacement of the north magnetic dip pole is clearly visible. Isovalues of the magnitude of the horizontal component of the field are also represented with increasing darkness of blue for increasing intensity (Mandea and Dormy, 2003).

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