THE EARTH MAGNETIC FIELD : AN UNSTABLE DYNAMO

Ph. Nozières

JOURNAL DE PHYSIQUE
Colloque C1, supplément au n° 1, Tome 45, janvier 1984

THE EARTH MAGNETIC FIELD : AN UNSTABLE DYNAMO

Ph. Nozières

Institut Laue-Langevin, B.P. 156 X, 38042 Grenoble Cedex, France

Résumé : L'origine du champ magnétique terrestre semble ressortir d'un mécanisme de dynamo auto excité. Cette brève revue est plus particulièrement consacrée à des considérations qualitatives et à des ordres de grandeur significatifs.

Abstract : The earth magnetic field is supposed to arise through a self-excited dynamo mechanism. In this very sketchy survey we emphasize some qualitative questions and relevant orders of magnitude.

The earth magnetic field has been studied for centuries -- mostly for practical navigation purposes. It is now widely accepted that the field results from a dynamo instability inside the earth metallic liquid core, driven by an appropriate convection flow. There exists an extensive literature on the subject which could not be summarized here: we only quote a few important facts and problems : the interested reader is referred to more extensives reviews (1).

Observational facts

On the earth surface the field, a fraction of a gauss, is mostly dipolar, with an axis close, but not identical to the geographical pole axis. It slowly decreases in time (approx. .03%/year); it displays small irregular eddies, which drift westward(.2°/year).

Rock magnetization provides a fossil record of B through geological ages. "Recent"data (back to a few 10^6 years) are obtained from volcanic lavas. Using mediooceanic ridges, one can go back much further ($\sim 10^9$ years). It is found that the field B flips irregularly, the north pole becoming the south pole. The time τ_1 between flips is $\sim 10^5 - 10^6$ years, quite irregular (in an extreme case, the field stayed quiet for 6.10^6 years!). The duration of a reversal, τ_2, is sharp, less than 10^3 years. It seems that the field first decreases, then goes through 0 toward its new value. In either polarity, the magnetic poles are close to the geographical poles.

Dynamo model

From seismological evidence, the earth is supposed to contain a liquid metallic core, between radii ~ 1200 and 3500 Km. The inner core ($r < 1200$) is solid, while the mantle ($r > 3500$) is an insulating liquid. In this metallic liquid, a convection flow pattern with velocity $u(r)$ can set up. If u is large enough, an electric instability develops spontaneously, driven by the induction emf according to the usual sequence

$$\boxed{\text{Field } B} \longrightarrow \boxed{\text{emf } u \wedge B} \longrightarrow \boxed{\text{current } J = \sigma E}$$

Once the instability is started, it produces a magnetic force $J \wedge B$, which reacts on the convection flow and provides saturation. In a time dependent situation, it is essential to study the coupled motion of electrical and mechanical degrees of freedom.

Characteristic time scales

Electrical currents decay on an inductive time scale, $t_1 \sim \mu_0 \sigma R^2$ where σ is the core conductivity and R a characteristic size . Typically $t_1 \sim 10^5$ years is comparable to the time τ_1 between flips.

Exchange between magnetic and kinetic energies is controlled by $t_2 = \frac{R}{v_A} = \frac{R}{B}\sqrt{\mu_o \rho}$ where v_A is the velocity of Alfven MHD waves in the core (ρ is the specific mass). Estimates of t_2 depend on the field B inside the core, which is unknown experimentally (a conjectured toroidal field $\sim$100 gauss would not show up at the earth surface). As a result, $t_2 \sim 1$ - 100 years, in any case much faster than t_1. Other time scales involve viscous relaxation (negligible), and mostly the Coriolis force due to the earth rotation : the corresponding characteristic time t_3 = 1 day clearly shows the Coriolis force is a primary feature.

Geometry on the convection and nature of dynamo instability

The problem is extremely difficult, involving a combination of Magnetic forces, Archimedian buoyancy and Coriolis forces ("MAC" theories). In zero field B, recent work shows that the convection pattern is an array of slowly spinning rollers, with a N-S axis ; the helicity of these rollers is responsible for the magnetic instability.What happens when B≠0 is still controversial, despite substancial progress in recent years.

Driving force of the convection flow

The simplest explanation is a Rayleigh Benard instability due to the outward flow of heat. Figures are however not totally convincing. The net heat flow through the earth surface is 4.10^{13} watts, out of which 10^{13} w only come from the core. This is to be compared with the dissipated Joule heat in the dynamo, ranging from 10^9 to 10^{12} watts. Since the Carnot thermodynamic efficiency is small(<5%),it is not clear whether the "heat engine" can work or not.

The question actually goes one step further : where does the heat come from ? Radioactivity of ^{40}K is possible, but unlikely. A low cooling of the earth would do it, releasing the latent heat of melting as the core grows (as well as the cooling specific heat). (A cooling of 100°K in 10^9 years would be enough).

It has been noted recently that a growth of the solid core could provide a more direct source of convection (not limited by thermodynamic efficiency). It seems that the solid is denser than the liquid ($\sim$20%?): freezing then releases an excess of light elements, which float up to the surface, starting the convection mechanism.

These are only examples:there exists other theories of convection involving differential rotation of the liquid and solid cores,inverted turbulences of the MHD flow,etc.

Reversals : a relaxation model

An exact solution of Maxwell and Navier stokes equations is hopeless. One may instead use truncated models, retaining the non linear nature of the problem.

The simplest choice is to assume a fixed geometry : the problem involves one flow velocity u and one electrical variable x. The problem is equivalent to the well known Faraday unipolar self excited disk dynamo. Past a characteristic driving torque, a magnetic field appears; the system evolves toward a fixed point at which nothing changes.

The situation is much richer if two electrical variables are retained : u, x_1, x_2.An example is the coupled disk dynamo studied by Rikitake. In general, the resulting equations must be solved numerically. Here, however, an analytical expansion is possible, in powers of t_2/t_1 (2).Among the various possible regimes, triggered relaxation appears especially interesting: the system slowly evolves on a limit cycle on a time scale t_1. At a critical point, the cycle becomes unstable, and the field jumps "suddenly" (on a time t_2) to a new configuration, triggering a bunch of fast oscillations around the slow cycle. This occurs twice per cycle; it is an appealing interpretation of the observed reversals.

Of course, such an oversimplified model is in no way a theory of the field reversals. Its only purpose is to show that triggered relaxation is possible, leading to sharp reversals with roughly correct time scales: intervals $t_1 \sim \tau_1$ and durations $t_2 \sim \tau_2$.Many features do not work. The fact oscillations are not observed (are they screened by the skin effect in the mantle?). The reversals are definitely aperiodic (should one invoke more degrees of freedom?). The model only provides a clue for a real theory: rather than splitting the problem into a kinematical step (fixed u) and a dynamical problem (reaction on u), one should separate slow motions (with local mechanical equilibrium) and fast oscillations (whose slow drift is due to Joule dissipation).

Conclusion

The origin and behaviour of the earth magnetic field remains a fascinating physical problem, blending many crucial features (MHD, buoyancy earth rotation). Major progress has been achieved recently - but a detailed understanding is still a long way ahead.

References

(1) See for instance an excellent introduction for the layman in Scientific American: The Source of the Earth Magnetic Field, C.R. CARRIGAN and D. GUBBINS (Scientific American, Feb. 1979).
Magnetic Field in the Cosmos, E.P. PARKER (Scientific American, Aug. 1983).

(2) See for instance P.NOZIERES, Bulletin de la Société Française de Physique, May 1978.