



PLANETARY MAGNETIC DYNAMO THEORIES: A CENTURY OF FAILURE

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ABSTRACT

For nearly a century, geoscientists who believe the earth is billions of years old have been striving to develop a successful "dynamo" theory to explain how the earth's magnetic field might maintain itself over that long time. After reviewing analytic theories, computer simulations, and laboratory experiments, I have concluded that all those efforts have fallen short of proving the geomagnetic field could be maintained by a dynamo. To contrast with this apparent failure, I touch upon the remarkable success of creationist theories in explaining magnetic fields in our Solar system, especially the planet Mercury. This contrast supports the young Biblical age of the world, about 6,000 years.

INTRODUCTION

Can the earth's magnetic field maintain itself? "The terrestrial globe is magnetic and is a loadstone," wrote Queen Elizabeth's personal physician over four centuries ago (Gilbert, 1600). He was right about the magnetic field, but wrong about its cause. What he called "loadstone" is magnetite, an iron oxide mineral that is permanently magnetized by the oriented spinning electric charges of electrons in its iron atoms. But below a few dozen km, the earth is too hot for any material, even pure iron, to remain magnetized; the thermal collisions of the atoms are too vigorous to allow the spins to remain oriented. That leaves a large-scale electric current in the interior as the only possible cause of the magnetic field.

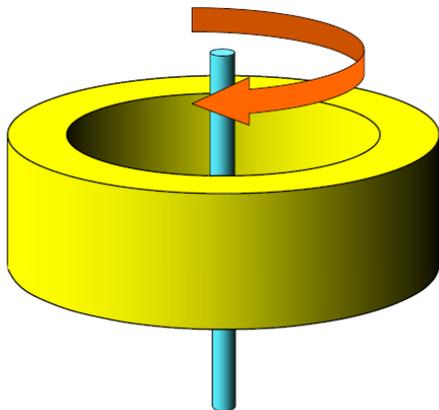


Figure 1. Electric current in the earth's core is like a spinning flywheel.

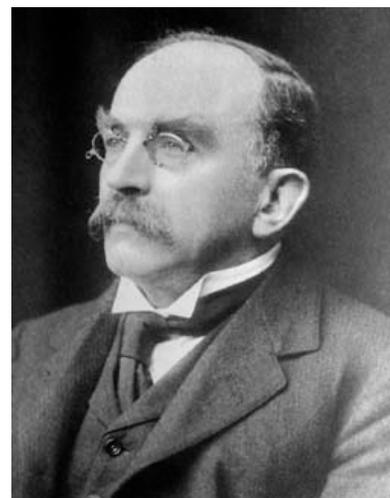


Figure 2. Sir Joseph Larmor, 1857-1942. Photo: Wikipedia

Left to itself, such a current would die away in less than a few dozen millennia, because the electrical resistance of any conceivable material in the interior would wear down the current, just as friction slows down a freely-spinning flywheel (Fig. 1). For creationists who are convinced by both the Bible and much scientific evidence that the earth is only about 6,000 years old, such decay is no problem. In fact, it explains very nicely the steady weakening of the earth's magnetic field for the past few centuries (Barnes, 1971, 1973; Humphreys, 2002, 2011). Creationists theorize that God started the electric current when He created the earth, doing likewise for the heavenly bodies (Humphreys, 1983, 1984, 2008).

But uniformitarians,¹ who believe the earth is billions of years old, assume that some natural process started the electric current and then maintained it for eons. Nearly a century ago, Sir Joseph Larmor (Fig. 2), a well-known Irish-British physicist, was the first to suggest such a scheme. It was in an article trying to answer the question, "How could a rotating body such as the sun become a magnet?" (Larmor, 1919a). He rejected several ingenious but implausible possibilities. Then he outlined a possible solution, the first in a long series of "dynamo" (the British word for an electric generator) theories:

In the case of the sun ... internal motion [of the conducting hot gas in a magnetic field] induces an electric field acting on the moving matter; and if any conducting path around the solar axis happens to be open, an electric current will flow round it, which may in turn increase the inducing magnetic field. In this way it is possible for the internal cyclic motion to act after the manner of the cycle of a self-exciting dynamo, and maintain a permanent magnetic field from insignificant beginnings, at the expense of some of the energy of the internal circulation.

"Self-exciting" alludes to the type of generator that makes its own magnetic field without any need for an externally-applied current or field. Later the same year, Larmor specifically included the earth in his hypothesis (Larmor, 1919b). Ever since then, hundreds of geoscientists have worked hard on developing the hypothesis into a theory that works. They have done theoretical analysis, numerical simulations with large computers, and laboratory experiments. Here I outline the history of those efforts, showing that, astonishingly, they still have fallen short of proving that a dynamo is working, or even could work, in the case nearest us, the earth's core.

The importance of that apparent failure is that it leaves only one alternative explanation for the earth's magnetic field: free decay of the electric current in the core. Free decay is only feasible over a period of thousands of years, not millions or billions of years. So the absence of a dynamo in the core supports the idea that the earth is as young as a straightforward reading of Scripture says it is.

THE "ANTI-DYNAMO" THEOREMS

After Larmor introduced the idea of a self-excited dynamo in the earth, there was little comment in the science literature for over a decade. But in 1933, a young English astronomer with good

¹ Uniformitarianism is the skeptical belief that "all continues just as it was from the beginning" of the universe (2 Peter 3:4) without any large-scale interventions by God. It is the basic assumption behind long-age interpretations of geological, nuclear, and astronomical data.

training in mathematics, Thomas George Cowling (Fig. 3), threw a big monkey wrench into the machinery of dynamos. With straightforward mathematics, applied first to the magnetic fields of sunspots, Cowling showed that simple forms of the dynamo idea couldn't work. Considering steady magnetic fields, he wrote (Cowling, 1933),

... a field which resembles an axially symmetric field in certain respects cannot, in general, be maintained by the currents it itself sets up ... we are led to conclude that the magnetic field of a sunspot is not self-maintained. For the same reason the general magnetic fields of the Sun and the Earth cannot be self-maintained, as was suggested by Larmor.



Figure 3. Thomas George Cowling, FRS, 1906-1990. Photo: Royal Astronomical Society / Photo Researchers, Inc.

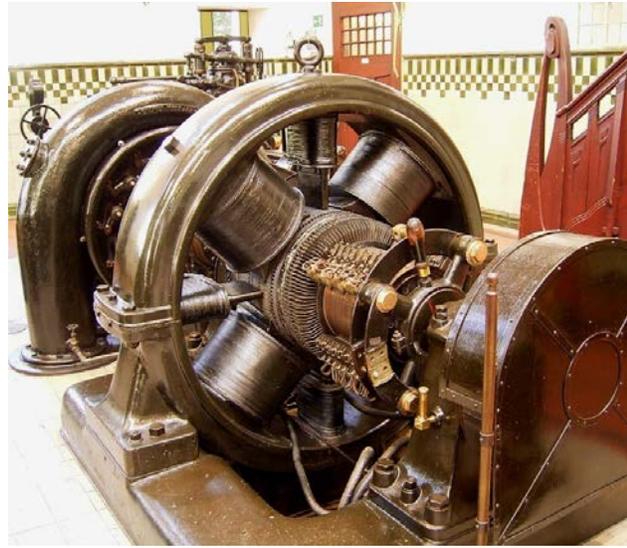


Figure 4. Self-excited electric generator, foreground. Driving steam engine, background. Photo: Wikipedia.

For planets, "axially symmetric field" means that as you rotate azimuthally (east or west) around the magnetic axis (a line through the north and south magnetic poles), keeping your altitude and latitude constant, the field will remain constant. The magnetic field outside the earth deviates from axial symmetry by less than 10% at any point.

Cowling's result spurred a great deal of theoretical work to check it, generalize it, and look for loopholes. It was not only found valid, but over several decades theorists found a series of "anti-dynamo" theorems that made Cowling's result more rigorous and more general. In 1956, they removed the restriction that the fluid velocity and the magnetic field direction must be in meridian planes² (Backus and Chandrasekhar, 1956). The following year, one of those theorists removed the restriction that the field must be steady (Backus, 1957). He showed that the fluid motion

² A (magnetic) meridian plane is any plane that includes the magnetic axis, intersecting the earth's surface in a great circle that runs through the north and south magnetic poles.

... cannot prevent the decay of the external dipole moment, and cannot lengthen the decay time of the dipole moment over a factor of about 4 over its decay time in the absence of fluid motions.

"External dipole moment" is the strength of the electric-current source (in the core) of the externally-observed dipole (two magnetic poles, north and south) part (the main part for earth) of the magnetic field. Earth's dipole moment has been decaying steadily and rapidly over the last few centuries, as I will touch upon in the next section.

Two geoscientists who try to simulate dynamo action in the earth with supercomputers summarized the generalized results of "Cowling's theorem" very simply (Roberts and Glatzmaier, 2000, their italics):

... an axisymmetric \mathbf{B} [magnetic field] cannot be sustained by dynamo action.

Anyone who has seen the complex windings in an electric generator (Fig. 4) can see why a self-excited dynamo in the earth is difficult for theorists to imagine. An engineer designing such a machine must first make an engine (in the figure, perhaps a steam turbine) that converts undirected energy, such as heat, into directed energy in the form of a rotating shaft. The shaft drives a whirling set of "armature" windings in the generator section of the system.

The engineer must then provide a way to extract electric current from the armature windings and connect it to the non-rotating outer world. Often he uses fixed "brush" electric contacts to sweep against contact plates on the rotating shaft. Next, he siphons off some of the current output from the brushes and feeds it back, with insulated wires, into the fixed "field" windings placed around the armature. That applies a magnetic field in the proper orientation to the armature windings. The windings moving through the field generate a current and send it to the brushes. More current goes back to the field windings, making the field stronger, etc. This "self-exciting" feedback process quickly builds up the magnetic field and current from essentially nothing, overcoming losses and providing a steady output from the generator.

But the problems for dynamo theorists are much greater than for the generator designer. The theorist must use only naturally-occurring motions in the core fluid, powered only by natural processes. Without insulation or brushes, he must somehow find a way that electric currents in a conducting ball will travel in the special paths that will produce a magnetic field in the desired orientations and locations. Otherwise the currents will travel in the simplest possible paths, as they would in a "shorted" circuit. He does not have the engineer's freedom to *make* things happen the way he wants. The dynamo theorist can only hope to uncover processes that already happen ... or perhaps don't really happen.

The anti-dynamo theorems have eliminated all the simple possibilities. The author of the most general such theorem above concluded (Backus, 1957):

... if the geomagnetic field is maintained by a self-excited dynamo, the absence of axisymmetry of the field is probably essential to its generation and maintenance.

The magnetic field outside the earth is generally symmetric around its north-south magnetic axis. So Backus's comment means that if a dynamo is going to work, the field *inside* the earth could not have such symmetry. Instead it would have to deviate strongly from symmetry from place to place. That means dynamo theorists have had to abandon grand global explanations and examine specific local phenomena. Their theories have had to become much more complicated.

EARTH'S CORE: THE SCENE OF THE ACTION

Structure and density. Fig. 5 shows a cross-section of the earth. Decades of comparing data from seismic waves and whole-earth oscillations³ with high-pressure and high-temperature experiments have given geoscientists a good picture of what is in the interior. Nearly 3,000 km beneath our feet, below the solid rocky *mantle*, is a dense hot fluid, the *outer core*. At the top its density is 9.9 g/cm^3 , almost twice as dense as the mantle rock (5.5 g/cm^3) just above it. At the bottom, over 2,200 km lower, the fluid's density is 12.2 g/cm^3 . Below that is the somewhat denser solid *inner core* that extends a little more than 1,200 km down to the earth's center.

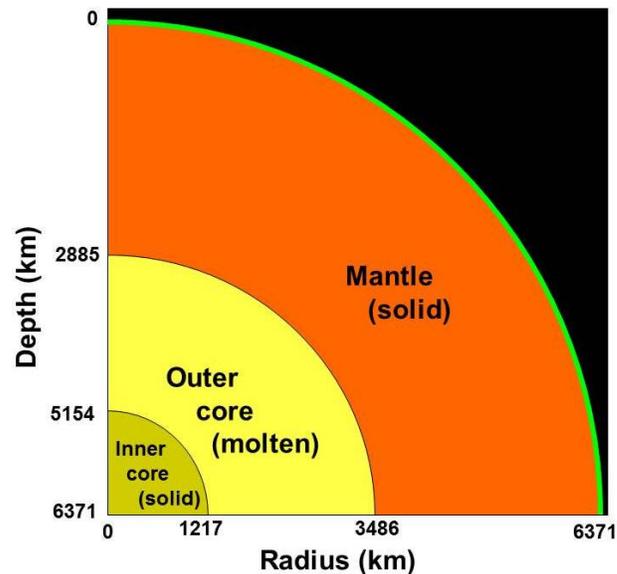


Figure 5. Cross-section of the earth.

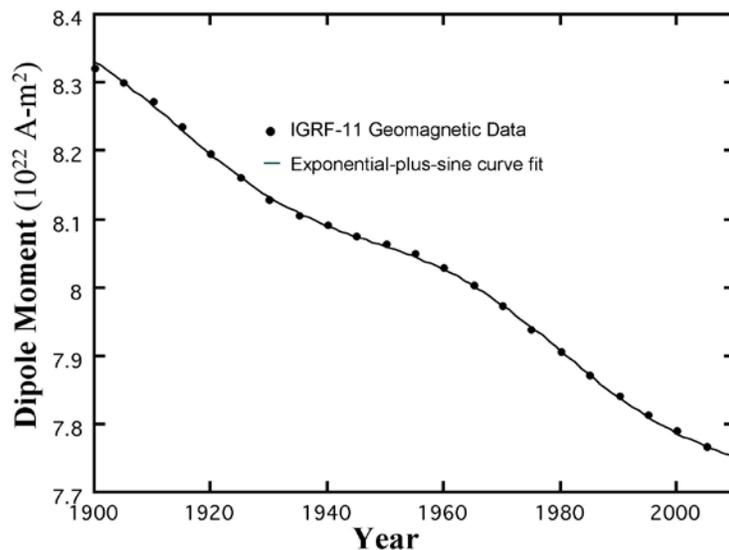
Pressure, temperature, and composition. The weight of the mantle makes the pressure at the top of the core about 1.3 million times atmospheric pressure. At such a high pressure, most materials have to be hotter than several thousand Kelvin to be molten. According to high-pressure, high-temperature experiments on likely materials, most of the atoms in the fluid core have to be iron. No other element appears to fit the geophysical data. Current estimates are zeroing in on a composition of about 80% iron atoms, with the remainder being some mixture of lighter elements, such as silicon and oxygen (Alfè *et al.*, 2000; Pozzo *et al.*, 2012). First-

³ Large earthquakes cause the whole earth to slowly shake like a bowl of jelly. The frequencies (hours or days) of such whole-earth oscillations give much information about the interior.

principles calculations⁴ (Pozzo *et al.*, 2012) on such alloys give a temperature at the top of the outer core of about 4,000 to 4,200 K (6,700 to 6,900°F), making it literally white-hot.

Electrical conductivity. A new first-principles calculation (Pozzo *et al.*, 2012) of the electrical and thermal conductivities of such an iron alloy at core conditions has startled dynamo theorists. The authors say, "We find both conductivities to be two to three times higher than estimates in current use." The higher heat conductivity puts dynamo theorists into a serious dilemma, as I will show later. The electrical conductivity findings, 1.45 to 1.57 million S/m (1 S = 1 Siemens = 1 mho = 1 ohm⁻¹) from top to bottom of the fluid core, are more welcome. However, that is the *Ohmic* conductivity, σ_Ω , the conductivity that would be measured in a motionless fluid. In a later section, I will point out standard dynamo theory calculations showing that *turbulence* in the core fluid should reduce the effective electrical conductivity by more than an order of magnitude. The observed decay rate of the earth's magnetic dipole (Fig. 6) supports that idea, giving an overall *effective* conductivity (including both turbulent and Ohmic parts) σ , of only 33,000 S/m (Humphreys, 2011).

Figure 6. Exponential plus small sine-wave fit to earth's magnetic dipole data since 1900. Exponential part of fit (not shown) is a straight line bisecting all the points. Decay time of exponential part is 1611 (± 10) years, giving an effective core conductivity of 33,000 (± 200) S/m according to the free-decay model (Humphreys, 2011).



Velocity. For over three centuries (Halley, 1692), geoscientists have known that small-scale features in the earth's magnetic field (representing irregularities at the top of the core) drift steadily westward at about 0.2° per year (Bullard, 1950). The most robust feature seems to be a 0.5 mm/s westward drift in a belt at the equator in the Atlantic Hemisphere (Finlay and Jackson, 2003). The cause of the drift appears to be fluid rising (due to convection) at the same rate from the interior of the core (Merrill and McElhinny, 1975, pp. 266-267. Possibly for that reason, many theorists take the above figure, 5×10^{-4} m/s, as the characteristic large-scale velocity of fluid in the core (Roberts and Glatzmaier, 2000, p. 1087). Variations from this average are undoubtedly large, especially at smaller size scales.

⁴ Starting with observed and quantum-theoretical properties of individual atoms, large computers can now extrapolate to find the properties of large groups of atoms. These first-principles (or *ab initio*) numerical simulations have been checked with laboratory measurements of various materials at non-core conditions.

Viscosity and turbulence. The kinematic viscosity⁵ ν of the core fluid is difficult to measure by observation. But first-principles calculations on molten iron under core conditions give a ν of about $1.5 \times 10^{-6} \text{ m}^2/\text{s}$ (de Wijs *et al.*, 1998). This is a very low viscosity, quite comparable to that of liquid water at room temperature and atmospheric pressure. This low value makes it very difficult for even very large computers to properly simulate the motions of the core fluid. That is because the low viscosity gives very high values for the fluid-dynamic Reynolds number, R , defined as

$$R \equiv \frac{u \ell}{\nu}, \quad (1)$$

where u and ℓ are the characteristic velocity and length scale of the system, and ν is the viscosity. Using the above values for velocity and viscosity, and $2.2 \times 10^6 \text{ m}$ (the thickness of the outer core) for the length scale gives $R = 7 \times 10^8$. When the Reynolds number exceeds a certain threshold, say about 100, a flow becomes turbulent (Landau and Lifshitz, 2000, p. 96). With such a large R in the core, nearly a billion, the flow is very turbulent. That does not imply high velocities. The slow rise and breakup into turbulence of cigarette smoke (Fig. 7) is a good way to visualize the turbulence in the core.

Using the above numbers, a plume rising up, say from a hot spot on the surface of the solid inner core, will become turbulent in less than 10 minutes, after travelling less than 0.3 meter. The high Reynolds number for the whole core means there will be many swirls and eddies of all sizes throughout the core (Landau and Lifshitz, 2000, p. 130). That is, the fluid flow is chaotic. Whatever dynamo action may take place must depend on general statistical features of the flow, and part of the analysis must be statistical. Yet turbulence is one of the few areas of fluid dynamics that remains relatively unexplored. In a later section I show that even the small eddies in the core are very important to dynamo action. As yet, even the largest computers are not able to simulate any but the largest eddies while at the same time looking at the whole core.

CURRENTS AND FIELDS IN THE CORE

Current. In any theory, from simple considerations of electromagnetism, the electric current in the core causing the dipole part of the field must be similar to the toroidal current for a freely-decaying dipole field. Starting from Maxwell's equations, Thomas G. Barnes, a creationist physicist, calculated the field and current distribution for free decay (Barnes, 1973). For convenience to readers, I reproduce his results here, using the same spherical coordinates



Figure 7. Cigarette smoke breaks into turbulence within a few centimeters. Photo: Diane Hirsch @ Fundamental Photographs, NYC.

⁵ Kinematic viscosity indicates the resistance a fluid makes to objects moving through it. It has units of m^2/s . A similar quantity, dynamic viscosity, is the product of the fluid density and kinematic viscosity.

(r, θ, φ) .⁶ All of the current is in the azimuthal (east-west) direction. Its density (in amperes per square meter) is:

$$J_{\varphi} = -\frac{3a_0}{\mu_0 r} \left(\frac{\sin x}{x} - \cos x \right) \sin \theta, \quad (2)$$

where μ_0 is the magnetic permeability of free space, $4\pi \times 10^{-7}$ Tesla-meter/Ampere,

$$a_0 \equiv \frac{\pi^2}{6} \left(\frac{R_e}{R_c} \right)^3 B_0, \quad x \equiv \pi \frac{r}{R_c}, \quad (3a,b)$$

and where R_e , R_c , and B_0 are, respectively, the radius of the earth, the radius of the core, and the magnitude of the magnetic field at the surface at the North Pole, presently about $60 \mu\text{T}$ (0.6 Gauss). Fig. 8 shows contours of the current density. The peak current density is at about 65% of the core radius with a magnitude of about 0.6 mA/m^2 . We can take the average as about half of the peak, 0.3 mA/m^2 . The total current for the dipole is about 6 billion amperes, going westward around the magnetic axis. Other parts of the field, such as the non-dipole components, and the toroidal components (see below), will have currents in addition to this as their sources.

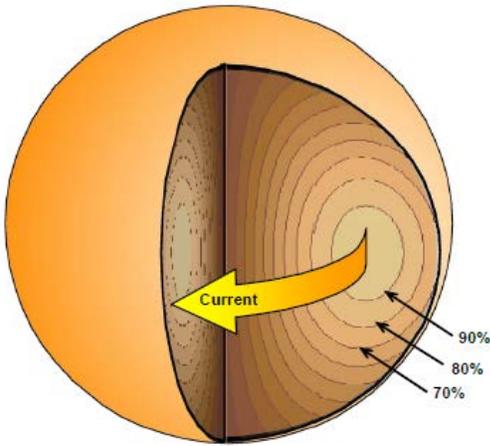


Figure 8. Contours of current density in earth's core for dipole part of field, according to eq. (2). Each contour line represents a 10% step of current density.

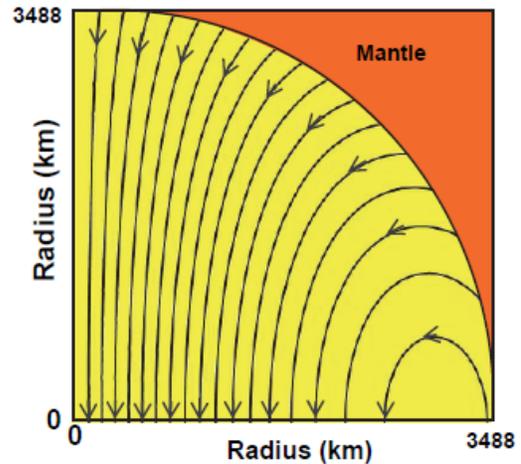


Figure 9. Dipole magnetic flux lines in the core, according to eq. (4a,b). Effects of the solid inner core and continuation of flux lines through mantle not shown.

Dipole Field. Again, for any theory, the field in the core produced by the above toroidal current must be similar to Barnes' solution for the dipole field within the core. It has a radial component, B_r , and a component in the θ -direction, B_{θ} :

⁶ r is the radial distance from the center, θ is the co-latitude ($\pi/2$ radians minus latitude), and φ is the longitude, or azimuth. To match the actual field of the earth more accurately, relate the co-latitude and azimuth to the magnetic poles, which are tilted about 11.5° away from the geographic poles.

$$B_r = -\frac{6a_0}{x^2} \left(\frac{\sin x}{x} - \cos x \right) \cos \theta, \quad B_\theta = \frac{3a_0}{x^3} (x \cos x - \sin x + x^2 \sin x) \sin \theta \quad (4a,b)$$

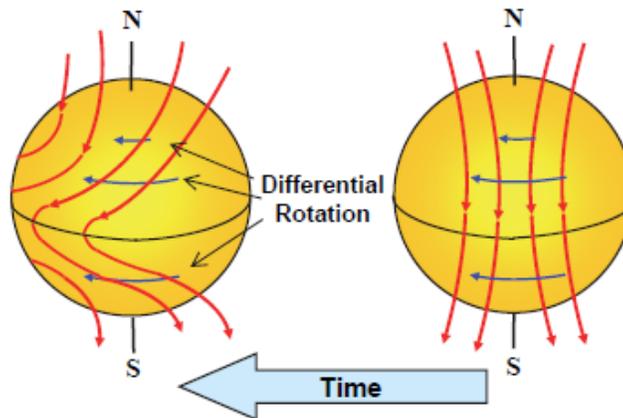
Fig. 9 shows the dipole field lines (magnetic flux, lines of force) inside the core according to eqs. (4a,b). The maximum field, 1870 μT (18.7 Gauss), is right at the center. The average field, halfway out along the equatorial plane, is about 750 μT (7.5 Gauss). There will be other magnetic flux from other types of currents, but the flux in the core that is related to the externally-observed dipole field will be generally like the figure shows. Barnes' solution says that the dipole current and field will decay exponentially (constant % per year) with a time constant T given by:

$$T = \frac{\mu_0 \sigma R_c^2}{\pi^2} \quad (5)$$

As will become clear in a later section, the electrical conductivity σ above is the overall effective conductivity. It includes both the turbulent conductivity σ_t and the Ohmic conductivity σ_Ω . As I mentioned above, for the earth's core the effective conductivity appears to be more than an order of magnitude lower than the Ohmic conductivity that would apply in a motionless, non-turbulent conductor. Eq. (5) is a result that appears often in geomagnetic literature. It is useful for estimating the decay times of current loops even in non-spherical situations.

Toroidal field, theory. It is likely that the 0.2°/year westward drift mentioned in the "Velocity" subsection above decreases with depth, and is roughly proportional to the distance from earth's rotation axis. This means that parts of the core fluid with different depths or different latitudes will rotate westward with different speeds relative to the solid mantle above the core.

Figure 10. Omega effect in earth's core. Different rotation speeds of fluid twist poloidal flux lines (right-hand side), giving them a toroidal component.



This "differential rotation" has a significant effect on the magnetic fields in the core. Alfvén's "frozen-flux" theorem, well-known in magnetohydrodynamics (MHD), says that flows in an electrically conductive fluid will tend to carry lines of magnetic flux along with it, just as if the lines were streaks of dye in the fluid (Shercliff, 1965). Flows parallel to the lines have no effect, but flows perpendicular to the lines do move them. So the differential rotation in the core will shear *poloidal* flux (north-south lines lying in a meridian plane as do the dipole flux lines) in the

east-west, or azimuthal direction, as Fig. 10 shows. The shearing stretches the lines of force, as if they were rubber bands with some tension, adding to their intensity and energy. The result of continued shearing is a set of *toroidal* lines of force, magnetic flux in the azimuthal direction. Dynamo theorists call this the *omega* effect (Ω -effect). It is a robust phenomenon, verified by laboratory experiments and observation⁷ of the Sun's surface magnetic fields.⁸

For later discussion it is important to notice that because earth's rotation generates this toroidal flux, it is necessarily symmetric around the rotation axis of the earth, not around the magnetic axis, which tilts 11.5° away from it.

So there is probably some toroidal magnetic field in the core, and it is very important to dynamo theory. We can make a rough estimate of its strength as follows: First notice that the westward drift of small magnetic features at the surface of the core will make one full revolution in $(360^\circ/0.2^\circ \text{ per year}) = 1,800$ years. Each revolution will add at most one turn to the toroidal flux (less for the interior, which has a slower drift). Second, note that toroidal flux, left to itself, will decay freely, just as earth's dipole flux appears to do. It turns out that the slowest decay mode for toroidal flux is about twice as fast as the slowest dipole decay mode (Moffatt, 1978). The ratio of decay times is:

$$\frac{T_{toroidal}}{T_{dipole}} = \left(\frac{\pi}{4.493} \right)^2 = 0.4889 \quad (6)$$

Using the observed dipole decay time for earth of 1611 years (caption of Fig. 6) gives us a toroidal decay time of 788 years. So while it takes at least 1,800 years to wind up the toroidal flux by one turn, in the same period the toroidal flux has gone through several exponential decay times' worth of decay, taking away from the effect of the winding. The number of "turns" that remain in effect in the toroidal flux roughly indicates the enhancement factor over the poloidal field intensity. So an upper limit on the ratio of toroidal (east-west) field to poloidal (north-south) field is:

$$\frac{B_{toroidal}}{B_{poloidal}} < \frac{788 \text{ years}}{1800 \text{ years}} = 0.44 \quad (7)$$

The dipole (poloidal) field is highest near the center, but the differential rotation there is low. The shear increases with radius as we move outward, but the field also decreases. The two are both at significant levels near the middle of the fluid core. Using the dipole field in that region (see previous subsection), about 750 μT , we can say that the toroidal field is probably less than

⁷ Observatories use such effects as the Zeeman splitting (proportional to magnetic field at the source) of spectral lines to measure the Sun's magnetic fields in great detail. The toroidal lines of force emerge from and re-enter the Sun's surface to make pairs of sunspots, which drift eastward with the solar plasma.

⁸ There is another way, called the *alpha* effect, that fluid motions can generate east-west fields from north-south fields. However, as I will show in the next section, it is a much weaker effect, so it is unlikely to contribute significantly to toroidal fields in the core.

300 μT (3 Gauss) throughout the core. Near the top of the core the toroidal field, which should diminish with radius, is probably less than 100 μT (1 Gauss).

Toroidal field, observation. According to straightforward electromagnetic theory, the toroidal field must be nearly zero outside the core. But the electric currents that maintain the field circulate in the core around the toroidal flux in meridian planes, and the currents penetrate into the mantle, which according to theory and observations is somewhat conductive. Unless there is a mantle layer which is a good insulator (very unlikely⁹), some of those currents should reach the earth's surface. Several decades ago, scientists at Bell Laboratories used a newly-laid transatlantic telecommunications cable to measure such currents (Lanzerotti *et al.*, 1985). Using estimates of lower mantle conductivity inferred from short variations in the earth's field, they concluded the toroidal field at the top of the core is between 100 μT (1 Gauss) and 1,000 μT (10 Gauss). This range of values is at least an order of magnitude less than the value desired by dynamo theorists and computer simulations. As the authors put it, the observation "places some severe constraints" on dynamo theory. But it is quite consistent with my rough estimate above.

THE TURBULENT HEART OF DYNAMO THEORY

Kinematic dynamos. Responding to the proofs that axisymmetric dynamos can't work, theorists began trying models without such symmetry. One broad class of those were the "kinematic dynamos". Theorists tried to find specific large-scale core fluid flows that would produce the observed field. Bullard and Gellman (1954) used an infinite series of spherical harmonic functions to describe the motions. The motions, though mathematically regular, were very complex. The series appeared to give a solution for the fields when truncated at the 12th harmonic. Because it was the first dynamo model to produce numerical results, it became very influential. However, later examination showed that the infinite series does not converge, invalidating the solution (Gibson and Roberts, 1969). Other variations using different initial flows have failed to get around this problem (Merrill and McElhinny, 1983, p. 250). The only kinematic dynamos that appear to work (on paper, at least) are existence theorems that have unrealistic geometries, such as an infinitely-large conducting medium. Apparently none have been found for spherical geometries like the earth's core (Merrill and McElhinny, 1983, p. 253).¹⁰

Turbulent dynamos. Nearly fifty years after publishing the first anti-dynamo theorem, Thomas Cowling published a concise and useful review of the status of dynamo theory (Cowling, 1981). His review boils down to the status of *mean-field electrodynamics*. This approach divides fields and velocities into mean (average) and fluctuating (turbulent) parts. Then the theorist puts that equation "template" into the foundational equation of dynamo theory, the magnetic induction equation. Making the reasonable assumption that the turbulence is the same in all directions (isotropic), Cowling repeats the demonstration that throughout the fluid, the mean electric field **E** (bold font means vector) depends on the mean magnetic field **B**:

⁹ Most solids are somewhat conductive at the high temperatures of the mantle (Stacey, 1969).

¹⁰ Another class of dynamos uses the assumption of "geostrophic" balance between Coriolis force and pressure gradients. But the assumption appears to be unrealistic for the earth, and the model appears to have other serious problems (Merrill and McElhinny, 1975, pp. 260-263).

$$\mathbf{E} = \alpha \mathbf{B} - \beta \nabla \times \mathbf{B}, \quad (8)$$

where α and β depend on the fluctuating (turbulent) part \mathbf{u} of the fluid velocity that lasts for a limited time τ :

$$\alpha = -\frac{1}{3}\tau \langle \mathbf{u} \cdot \boldsymbol{\omega} \rangle, \quad \boldsymbol{\omega} \equiv \nabla \times \mathbf{u}, \quad \beta = \frac{1}{3}\tau \langle \mathbf{u} \cdot \mathbf{u} \rangle \quad (9a,b,c)$$

Usually τ is the overturning time of an eddy. The brackets indicate a spatial average over the volume of the eddy. The vector $\boldsymbol{\omega}$ is the fluid-dynamical *vorticity* of the eddy (Landau and Lifshitz, 2000, p. 13). I will explain these quantities further below, but first I would like to show how they affect dynamo theory. Cowling puts eq. (8) into the mean-field version of the induction equation to get the mean-field dynamo equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\alpha \mathbf{B} + \mathbf{v} \times \mathbf{B}) - \nabla \times [(\eta + \beta) \nabla \times \mathbf{B}] \quad (10)$$

where \mathbf{v} is the mean (not fluctuating) flow velocity, and η is the *Ohmic diffusivity*, inversely proportional to the Ohmic conductivity σ_Ω :

$$\eta \equiv \frac{1}{\mu_0 \sigma_\Omega} \quad (11)$$

Eq. (10) appears to be at the center of whatever may be viable in dynamo theory today. We can clarify it by making use of the mean magnetic vector potential \mathbf{A} and one of Maxwell's equations¹¹ that relates the curl of \mathbf{B} to the mean electric current density \mathbf{J} :

$$\mathbf{B} \equiv \nabla \times \mathbf{A}, \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad (12a,b)$$

Putting eqs. (12a,b) into eq. (10) results in an expression that begins with the curl operation for every term. "Uncurling" the expression (i.e., equating the expressions that were being "curled") gives us,

$$\frac{\partial \mathbf{A}}{\partial t} = \alpha \mathbf{B} + \mathbf{v} \times \mathbf{B} - (\eta + \beta) \mu_0 \mathbf{J} \quad (13)$$

Each term in this equation has the units of electric field, volts per meter. That means the factor $(\eta + \beta) \mu_0$ has the units of resistivity, Ohm-meters. So let us define an overall *effective resistivity* ρ as the sum of an *Ohmic resistivity* ρ_Ω and a *turbulent resistivity* ρ_t as follows:

¹¹ In eq. (12b) I have neglected a term proportional to the rate of change of electric field. That is usual in MHD because the term is very small at the low frequencies we are concerned with (Shercliff, 1965, p. 21). That makes the equation identical to Ampere's law.

$$\rho \equiv \rho_\Omega + \rho_t, \quad \text{where} \quad \rho_\Omega \equiv \eta \mu_0 \quad \text{and} \quad \rho_t \equiv \beta \mu_0 \quad (14a,b,c)$$

The inverses of ρ , ρ_Ω , and ρ_t are, respectively, σ , σ_Ω , and σ_t , which are the effective, Ohmic, and turbulent conductivities I mentioned previously. With these definitions, eq. (13) becomes simpler:

$$\frac{\partial \mathbf{A}}{\partial t} = \alpha \mathbf{B} + \mathbf{v} \times \mathbf{B} - \rho \mathbf{J} \quad (15)$$

The left-hand side is the mean electromotive force (e. m. f.) on a charged particle at any given location in the core. If positive, the e. m. f. would increase the core current and the magnetic field. If negative, it would decrease them. If zero, they would remain steady. The first term on the right-hand side represents the *alpha effect*. It is a new feature brought in by mean-field theory. The second term is the Lorentz force¹² on a charged particle when it moves through a magnetic field. That term has been in dynamo theory since its beginning. The third term is the voltage drop per meter for the current moving through the electrical resistance, both Ohmic and turbulent. If α and \mathbf{v} , but not β , were to become zero, the solution to eq. (15) would have a decay time given by eq. (5), with σ being the effective conductivity.

Alpha-omega dynamos. At this point, dynamo theory breaks into two branches. One, the *alpha-omega*¹³ class of theories, depends on the omega effect (see previous section) to twist poloidal field lines into toroidal ones. Then it uses the alpha effect (subsection above) to generate poloidal field from toroidal field. The other class, the *alpha-alpha* dynamos, tries to use the alpha effect twice, first to make toroidal field from poloidal field, and then a second time to do the reverse. As we will see below, for bodies like the earth, the value of α in eq. (9a) is too small for the alpha effect to be as efficient in making toroidal field as is the omega effect. So here I will discuss only the more robust option, the alpha-omega theories. For that class, we are interested only in the φ (azimuthal, toroidal, east-west) component of eq. (15):

$$\frac{\partial A_\varphi}{\partial t} = \alpha B_\varphi + (\mathbf{v} \times \mathbf{B})_\varphi - \rho J_\varphi \quad (16)$$

This equation is the heart of dynamo theory today. It stands or falls on the magnitude of the right-hand terms, particularly the first and last terms. On the left-hand side, the curl of the toroidal part A_φ of the mean vector potential is the mean poloidal magnetic field. The rate of change of A_φ is the e. m. f. that drives the toroidal current that makes the poloidal field. On the right-hand side, let us discuss the second term first, because we can essentially eliminate its effects relative to the effects of the other two terms. Only the poloidal components of the mean velocity and mean magnetic field, \mathbf{v}_p and \mathbf{B}_p , can contribute to the second term. That is,

¹² This neglects the electrostatic force, which is almost always absent in MHD situations.

¹³ This class might more logically be called "omega-alpha", but the converse became more popular, perhaps because it resonates with the words of God in Revelation 1:8.

$$(\mathbf{v} \times \mathbf{B})_\phi = \mathbf{v}_p \times \mathbf{B}_p \quad (17)$$

Because upflows in \mathbf{v}_p tend to balance downflows, we might expect that this Lorentz force term would zero itself out. This term was the crux of Cowling's 1933 anti-dynamo proof. He pointed out that there is always a radius in the core where the poloidal field is zero, and very low around it. You can see that region in Fig. 9, within the oval (half-oval as shown) line of force on the equatorial plane near the right edge of the figure. In that region, the azimuthal current density sustaining the field is not zero. But in the region the $\mathbf{v}_p \times \mathbf{B}_p$ term cannot provide enough electromotive force to sustain the current, because \mathbf{B}_p is low (and zero at one point) there. This "hole" in the Lorentz force effectiveness makes the current and field decay, and the hole will grow as the field decays. After dozens of millennia, the field would be essentially zero. The gap in coverage makes a dynamo based on the second term impossible.

But as Cowling put it in 1981, the αB_ϕ term in eq. (16) "plugs the gap" and overcomes his early anti-dynamo theorem. The toroidal field \mathbf{B}_ϕ in the gap does not have to be zero. If the first term has the correct sign and is large enough, it could overcome the losses from the third term, the resistive term, ρJ_ϕ — provided the turbulent resistivity based on β , eq. (14c), is not too high.

Here the alpha-omega theories split into many branches. They all seek to understand the turbulence well enough to estimate α . Very few of such papers seem to be concerned with β , even though it is a potential killer of possible gains from α . I haven't been able to find a single paper giving numerical estimates for either parameter in the earth's core. However, it seems to me that rough estimates are possible, and I will supply them below to evaluate the viability of dynamo theories. Let us look at α and β in more detail.

Beta, vorticity, and helicity. We can learn a few things about α and β by looking again at eqs. (9a,b,c). In eq. (9c) for β , the quantity $\langle \mathbf{u} \cdot \mathbf{u} \rangle$ would be the mean-square velocity of the fluid circulating in an eddy, or twice the mean kinetic energy per unit mass. If we use the average large-scale velocity of 5×10^{-4} m/s as an indication of the root-mean-square velocity of an eddy, then eqs. (9c) and (14c) imply a turbulent conductivity of 33,000 S/m (the value in the caption of Fig. 6) when the overturning time τ of an average eddy is 3.3 days. The average radius of such an eddy would be 20 meters.

Now examine eq. 9(b), which defines the vorticity $\boldsymbol{\omega}$ of an eddy. If part of the flow is rotation around an axis, then the vorticity is simply the product of the angular rate of rotation ω (radians/second) of each particle in the eddy and a unit vector along the rotation axis. The right-hand rule determines the direction of the vector. Vorticity tends to be conserved and move along with the fluid (Landau and Lifschitz, 2000, p. 13).

Next, look at eq. (9a) specifying α . The number $\mathbf{u} \cdot \boldsymbol{\omega}$ is called the *helicity* of the flow. Because vorticity $\boldsymbol{\omega}$ persists and moves with the flow, helicity will also persist within an eddy as long as it lasts. A positive (negative) helicity means a right-handed (left-handed) corkscrew motion of particles in the eddy. The vectors \mathbf{u} and $\boldsymbol{\omega}$ can have any angle between them.

How the alpha effect works. Fig. 11(a) illustrates the α -effect. A column of fluid rises with velocity \mathbf{u} upward through a west-pointing flux line of toroidal field \mathbf{B}_ϕ . As it rises, it is slowly

twisting clockwise (as you look down on it) with angular speed ω . (The direction of ω is downward.) Alfvén’s “frozen flux” theorem says the fluid tends to lift the line and twist it clockwise, as if the line were a streak of dye moving with the fluid.

Fig. 11(b), looking down on the flux line in the column after it has been turning for a time τ , shows that the field has a northward component B_n ,

$$B_n = B_\phi \sin \omega\tau \cong \omega \tau B_\phi \quad (18)$$

The approximation applies if the angle $\omega\tau$ is small. Then the rise of fluid at speed u upward through the northward component B_n applies a Lorentz force of magnitude $u B_n = u \omega \tau B_\phi$ to charged particles in the region, a westward e. m. f. that adds to the current flowing westward, sustaining it from the resistive losses. Equating the Lorentz force above to the first right-hand-side term of eq. (15) gives us $\alpha = u \omega \tau$ for that part of the eddy.

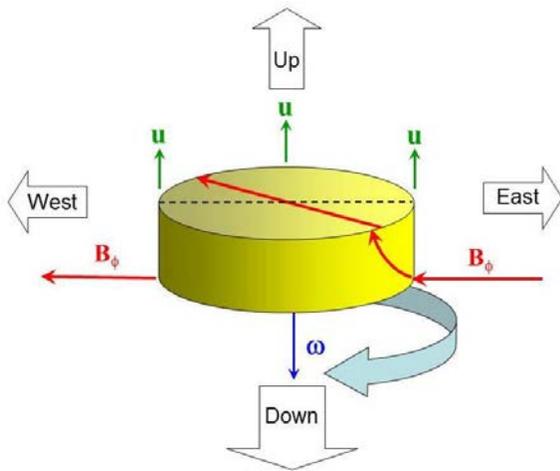


Figure 11(a). Alpha effect, part 1: Rising and rotating column of fluid raises east-west magnetic flux line and twists it clockwise (looking downward).

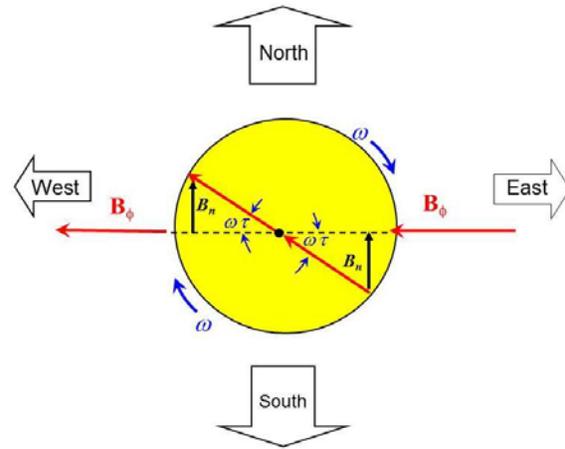


Figure 11(b). Alpha effect, part 2: Looking down on rising column to view flux line after it has rotated for time τ . Notice northward component of field, B_n .

Notice that the e. m. f. would have been eastward if the rotation had been counterclockwise. Then it would have subtracted from the westward electric current. Referring back to eq. (9a), α can be positive only if the average helicity $\langle \mathbf{u} \cdot \boldsymbol{\omega} \rangle$ in the eddy is negative. If there were no general asymmetry, there would be equal amounts of positive and negative helicity, so the cumulative effect of α throughout the core would be zero. The average of alpha can be positive only if, globally, the helicity tends to be negative. A possible cause of such a global preference might be the earth's angular rotation vector $\boldsymbol{\Omega}$. It is northward, meaning the earth's rotation is eastward, and its magnitude is $(2\pi \text{ radians}/24 \text{ hours}) = 7.272 \times 10^{-5} \text{ radian/second}$.

Specific example of alpha effect. I haven't been able to find a visualizable example in the dynamo theory literature that evaluates alpha. However, Eugene Parker (1955) suggested that the Coriolis force¹⁴ would twist updrafts and downdrafts in the core fluid, changing toroidal field into poloidal field. Because he was writing before mean-field electrodynamics was developed, he did not apply his idea to get a specific value for alpha. However, it is the only mechanism I know of that meets the helicity requirements, i.e., that might lead to a working dynamo. So here I will quantitatively develop Parker's qualitative idea in order to get a useful estimate of alpha.

Figure 12 shows a column of fluid that is a vertical part of a large toroidal eddy. This part rises with velocity \mathbf{u} and expands at a rate determined by the volume expansivity ε , which is the fractional increase of specific volume ($= 1/\delta$, where δ is the mass density) per meter of vertical ascent (in the direction of the radial coordinate r):

$$\varepsilon \equiv -\frac{1}{\delta} \frac{d\delta}{dr} \cong \frac{(12.2 - 9.9)\text{g/cm}^3}{\frac{1}{2}(12.2 + 9.9)\text{g/cm}^3 (2.2 \times 10^6 \text{ m})} = 9.5 \times 10^{-8} / \text{meter} \quad (19)$$

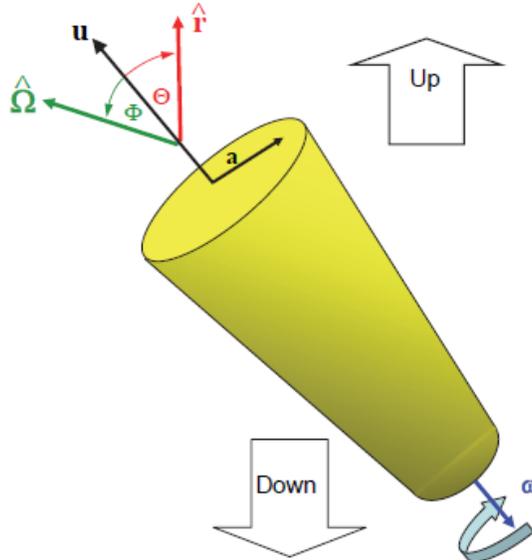


Figure 12. Coriolis force rotates rising and expanding column of fluid clockwise (looking down) around its axis with angular velocity ω .

The expansion will move a particle in the rising column that is a vector distance \mathbf{a} from the axis outward from the axis at a rate $\dot{\mathbf{a}}$ that depends on the expansivity, vertical velocity, and \mathbf{a} :

$$\dot{\mathbf{a}} = \frac{1}{3} \varepsilon (\mathbf{u} \cdot \hat{\mathbf{r}}) \mathbf{a} , \quad (20)$$

where $\hat{\mathbf{r}}$ is a unit vector in the r -direction (vertical). The dot product accounts for the difference in \mathbf{u} from vertical, and allows for it to be downward instead of upward. The factor $\frac{1}{3}$ accounts for the fact that the diameter of the column increases at one-third the rate of the volume expansion.

¹⁴ The Coriolis effect is the force due to the earth's rotation that, for example, twists moving air masses into cyclones (Goldstein, 1959).

The Coriolis force (Goldstein, 1959) on such a moving particle is

$$2 \dot{\mathbf{a}} \times \mathbf{\Omega}_u = 2 \dot{\mathbf{a}} \times (\mathbf{\Omega} \cdot \hat{\mathbf{u}}) \hat{\mathbf{u}} \quad (21)$$

where $\mathbf{\Omega}_u$ is the component of the earth's rotation vector $\mathbf{\Omega}$ along the axis of the column, which is parallel to the velocity \mathbf{u} and its unit vector $\hat{\mathbf{u}}$. This force accelerates the particle clockwise around the axis (as you look down on it). The acceleration of the angular velocity vector $\boldsymbol{\omega}$ (which is in the $-\hat{\mathbf{u}}$ direction) is:

$$\dot{\boldsymbol{\omega}} = -2 \frac{\dot{a}}{a} (\mathbf{\Omega} \cdot \hat{\mathbf{u}}) \hat{\mathbf{u}}, \quad (22)$$

where a is the magnitude of vector \mathbf{a} . Integrate eq. (22) for time τ , use eq. (20) to get an expression for \dot{a}/a , and put the latter into the former. That gives us the angular rotation vector after the column has ascended for a time τ :

$$\boldsymbol{\omega} = -\frac{2}{3} \varepsilon \tau \Omega (\hat{\mathbf{u}} \cdot \hat{\mathbf{r}}) (\hat{\mathbf{\Omega}} \cdot \hat{\mathbf{u}}) \mathbf{u}, \quad (23)$$

in which I have written earth's rotation vector $\mathbf{\Omega}$ as $\Omega \hat{\mathbf{\Omega}}$, and exchanged the positions of \mathbf{u} and $\hat{\mathbf{u}}$. Now put eq. (23) into eq. (9a) to get alpha for this situation:

$$\alpha = \frac{2}{9} \varepsilon \Omega \tau^2 \langle (\hat{\mathbf{u}} \cdot \hat{\mathbf{r}}) (\hat{\mathbf{\Omega}} \cdot \hat{\mathbf{u}}) \mathbf{u} \cdot \mathbf{u} \rangle \quad (24)$$

This gives a positive value for alpha, and so is supportive of a dynamo mechanism. Notice that if we reverse the velocity \mathbf{u} to represent a downdraft, making the replacements $\mathbf{u} \rightarrow -\mathbf{u}$ and $\hat{\mathbf{u}} \rightarrow -\hat{\mathbf{u}}$ in eq. (24), α will remain positive. So, the rising and falling parts of the eddy will each contribute to a positive alpha effect. Horizontal components will contribute less, but none will detract from alpha.

As Fig. 12 denotes, the angle between \mathbf{u} and \mathbf{r} is Θ , and the angle between $\mathbf{\Omega}$ and \mathbf{u} is Φ . So in eq. (24) the first dot product is $\hat{\mathbf{u}} \cdot \hat{\mathbf{r}} = \cos \Theta$, and the second is $\hat{\mathbf{\Omega}} \cdot \hat{\mathbf{u}} = \cos \Phi$. Putting these cosines into eq. (24) and separating the average over the eddy volume into two parts gives:

$$\alpha = \frac{2}{9} \varepsilon \Omega \tau^2 \langle \cos \Phi \cos \Theta \rangle \langle \mathbf{u} \cdot \mathbf{u} \rangle \quad (25)$$

Over the whole core, we can regard the two angles as being independent, taking all values which yield a positive product for $\langle \cos \Phi \cos \Theta \rangle$. The average of the positive part of each cosine is $1/\pi$. Average (25) over the whole core, use the average value of $1/\pi^2$ for the product of the cosines, and put the values of ε and Ω into the result. That gives us the following average value for alpha throughout the core:

$$\bar{\alpha} = (1.6 \times 10^{-13} \text{ m}^{-1} \text{ s}^{-1}) \bar{\tau}^2 \bar{u}^2 \quad (26)$$

where $\bar{\tau}$ and \bar{u} are root-mean-square values of lifetime and speed, averaged over all the eddies throughout the core. The units of α are meters per second. If we use nominal values of 3.3 days and 5×10^{-4} m/s (see "Beta, vorticity, and helicity" sub-section above) for $\bar{\tau}$ and \bar{u} here, we get

$$\bar{\alpha} \approx 3.5 \times 10^{-11} \text{ m/s} \quad (27)$$

This speed, 35 picometers per second, seems rather small. Multiplying it by the toroidal field gives a very small e. m. f., one which doesn't seem likely to be able to maintain the poloidal field. Supporters of dynamo theory might suppose that $\bar{\tau}$ and \bar{u} in eq. (26) should be larger than the nominal values I assumed here, thus making alpha larger. The next section compares the effects of alpha and beta in a way that eliminates assumptions about the value of \bar{u} . That clears the way for a discussion about the value of the overturning time $\bar{\tau}$ of average eddies, and about the viability of turbulent dynamo theory in the case of the earth.

THE HEART OF DYNAMO THEORY ISN'T BEATING!

Re-examine what I called "the heart of dynamo theory", eq. (16). As I showed in the paragraphs below it, the second term on the right is negligible compared to the effects of the first and third terms. The first term builds up the poloidal field, and the third term tears it down. It is the relative magnitude of the first and third terms that determines whether the field will increase, stay the same, or decrease. A useful way to compare the two terms is to define the *gain*, G , in an eddy as the ratio of the magnitudes of the two terms:

$$G \equiv \frac{\alpha B_\phi}{\rho J_\phi} \cong \frac{\alpha B_\phi}{\mu_0 \beta J_\phi}, \quad (28a,b)$$

where for the approximation, eq. (28b), I am neglecting the Ohmic resistivity as being small compared to the turbulent resistivity, eq. (14c). Use eqs. (25) and (9c) in eq. (28b) to get

$$G \cong \frac{\frac{2}{9} \varepsilon \Omega \tau^2 \langle \cos \Phi \cos \Theta \rangle \langle \mathbf{u} \cdot \mathbf{u} \rangle B_\phi}{\frac{1}{3} \mu_0 \tau \langle \mathbf{u} \cdot \mathbf{u} \rangle J_\phi} \quad (29)$$

The mean-square velocity, $\langle \mathbf{u} \cdot \mathbf{u} \rangle$, in the eddy cancels out of this expression, reducing it to:

$$G \cong \frac{2}{3} \frac{\varepsilon \Omega \tau \langle \cos \Phi \cos \Theta \rangle B_\phi}{\mu_0 J_\phi} \quad (30)$$

Next, average over all the eddies in the core, again using $1/\pi^2$ for the average value of $\langle \cos \Phi \cos \Theta \rangle$, to get an average gain \bar{G} :

$$\bar{G} \cong \frac{2 \varepsilon \Omega \bar{\tau} \bar{B}_\phi}{3 \mu_0 \pi^2 \bar{J}_\phi} \quad (31)$$

This is a make-or-break equation for the turbulent dynamo theory. If the average gain is equal to or greater than one, the theory will work. If it is less than one, the theory leads to a decaying field that cannot last for eons. We can estimate the average gain in terms of the lifetime of an average eddy, $\bar{\tau}$. From the section "Currents and fields in the core", we get an average toroidal field of 300 μT (3 Gauss), and an average toroidal current of 0.3 mA/m². Using those and the other (well-known) values in eq. (31) gives us

$$\bar{G} \cong (3.7 \times 10^{-7} / \text{second}) \bar{\tau} \quad (32)$$

To get a gain of at least one, the mean lifetime $\bar{\tau}$ of the eddies in the core must be at least 2.7 million seconds, a little over 30 days. That is an order of magnitude greater than the 3.3 days I estimated (from the observed decay rate of the earth's magnetic dipole) in the "Beta, vorticity, and helicity" subsection. If we were instead to use 30 days for τ in eqs. (9c) and (14c), the turbulent conductivity would decrease from 33,000 S/m (consistent with observed decay rate) down to only about 3,500 S/m, a very low value. That suggests that 30 days is too large, as does the following argument:

Using 30 days as the mean time for one revolution (the "overturning time") of fluid in the eddy, with 5×10^{-4} m/s for the root-mean-square velocity, would give a radius of about 850 m for the average eddy. If we use that radius and the high *Ohmic* conductivity, 1.5×10^6 S/m, for σ in eq. (5) to get a rough estimate of field decay time in the eddy, we get 1.4×10^5 seconds, about 1.6 days. So, long before the supposed 30 days would elapse, the distortion of magnetic field produced by the eddy would have died away. That means the basic equations for alpha and beta, eqs. (9a,c), would no longer apply. Again, the 30-day value for $\bar{\tau}$ appears much too large.

In Cowling's derivation of the mean-field equations, he used a form for τ that was limited by the Ohmic decay time in an eddy (Cowling, 1981, p. 118, eq. [9]). If we follow that constraint and put 1.6 days for $\bar{\tau}$ into eq. (32), we get an average gain of **0.05**. That is not really a "gain", but instead a severe loss. It is much less than the break-even gain of one. We would have to adjust the two lesser-known quantities in these considerations, the mean-square velocity of the eddies (giving their size and decay time) and the average toroidal field, by several orders of magnitude to achieve breakeven. Such an adjustment appears to be beyond realistic possibilities. If there exists a threshold for dynamo action, say in rotation speed or mean velocity, the earth's core must fall below it.

In conclusion, with realistic conditions in the earth's core, the central mechanism of turbulent dynamo theory, eq. (16), doesn't work. And yet, in my opinion, that was the only form of dynamo theory that had a chance of success.

MORE PROBLEMS FOR DYNAMOS

Here some additional problems for dynamo theory. Several of them are quite recent developments:

Core heat flow. As I mentioned in the "Electrical conductivity" subsection, the new first-principles calculation of the *thermal* conductivity in the earth's core (Pozzo *et al.*, 2012) has become a problem for dynamos. The factor of three increase in the molten iron's ability to conduct heat "shorts out" most of the heat flow available to drive convection. The only way around that is to increase the heat generated in the core by radioactivity, or to increase the heat flow out of the core and "freeze out" molten iron to form the solid core more rapidly than assumed. Either route makes problems for the billions of years assumed for the earth's age (Buffett, 2012).

Solar convection. New helioseismic observations (Hanasoge *et al.*, 2012) suggest that convection in the Sun is a hundred times slower than previously thought. That makes a dynamo explanation of the observed fields nearly impossible. By implication, this reduces the odds that planetary magnetic fields are produced by dynamos.

Entropy. A new creationist study of energy flow and the second law of thermodynamics (Creager, 2012) suggests to me that the general dynamo system, which is supposed to convert undirected heat energy into the highly-directed energy of the electric current source for the earth's dipole field, is a problem for theorists. It appears to require a decrease in the system's entropy, which does not happen in purely natural processes. I hope to investigate this possibility further.

Tilt of earth's field. As I mentioned in the "Toroidal field, theory" subsection, the omega effect should generate a toroidal field that is symmetric around the earth's rotation axis. The alpha effect should then generate a poloidal field in geographic meridian planes, parallel to the rotation axis. However, the earth's dipole field is tilted 11.5° away from its rotation axis. Thus, something is "askew" in the alpha-omega dynamo theories.

NUMERICAL SIMULATIONS AND LABORATORY EXPERIMENTS

Numerical simulations. Turbulent dynamo theory seems to have exhausted itself on many dozens of lines of inquiry which have yielded no conclusive results but instead many difficulties. One recent (very detailed) review says. "However, large-scale dynamos are shown to suffer from resistive slow-down even at intermediate length scales" (Brandenburg *et al.*, 2012). So from the 1990's up to now, theoreticians have turned to large computers to try to simulate dynamos numerically. Several good reviews of these efforts, by the simulators themselves, are available (Glatzmaier and Roberts, 1997; Roberts and Glatzmaier, 2000; Glatzmaier, 2002).

The simulations do not use turbulent mean-field theory explicitly. Instead, they let the flows and fields develop on the basis of first principles. They produce rather complex-looking fields that resemble a dipole and reverse themselves from time to time. The simulations depend implicitly on the same effects that are in turbulent mean-field theory, including the omega effect and the

alpha effect. But, unfortunately, computers are not yet large enough to simulate the low viscosity and small-scale turbulence that the previous sections show are crucial for understanding dynamo action, or non-action. One of the simulators acknowledges:

... the models all have severe deficiencies ... Every geodynamo model completely neglects the actual viscous, thermal, and compositional diffusivities because these are orders of magnitude smaller [than computers can presently model]. However, because they are so small there must be significant energy in small-scale turbulent eddies (Glatzmaier, 2002, p. 241).

In his conclusion, Glatzmaier cautions, "However, we still have a long way to go before we can be confident that these results are robust—they may not be." He gives his colleagues a "grand challenge" to realistically simulate the conditions that must exist in the earth's core, forsaking unrealistic parameters that are tens of thousands of times larger than the real ones. He says, "Reaching this goal will require a significant increase in numerical resolution on a massively parallel computer with improved numerical methods ... the computational costs will be staggering by today's standards ... Because of this, some people feel that this goal will be impossible to achieve within the next decade or so ..." (Glatzmaier, 2002, p. 254).

One indication that the simulations are in error is that they show a much higher toroidal field near the top of the core than observations suggest. For example, one simulation has regions of 6,000 μT (60 Gauss) of eastward field in the northern and southern hemispheres, and a region of 11,000 μT (110 Gauss) of westward field near the equator (Glatzmaier and Roberts, 1997, p. 286, Fig 11a). Yet observations (Lanzerotti *et al.*, 1985) show that the toroidal field at the top of the core is much weaker, between 100 μT (1 Gauss) and 1,000 μT (10 Gauss). (See discussion in the "Toroidal field, observation" subsection.) This discrepancy, two orders of magnitude, indicates a serious problem with the simulations.

I suggest that the simulations fail in this regard because they have no small-scale turbulence, and hence, little turbulent resistivity. Lower turbulent resistivity means the toroidal field can last longer and build up for many more turns of differential rotation than can occur in reality. A higher toroidal field and lower turbulent resistivity gives much more gain, as eqs. (28a,b) show. It is entirely possible that whenever computers can realistically simulate small-scale turbulence, they will show that turbulent resistivity kills the dynamo action.

Laboratory experiments. A recent review (Verhille *et al.*, 2010) describes many laboratory experiments since the turn of this century. While they demonstrate many MHD phenomena, like the omega effect and the alpha effect under complex constraints, it appears that none of them have shown dynamo action under conditions at all like those in a planetary interior.

Figure 13. 3-meter dynamo experiment, with team member Daniel Zimmerman to give size scale. Horizontal tubes around the sphere are a cooling jacket to drive convection flows in molten sodium within. Photo permission: *Nature* Publishing Group.



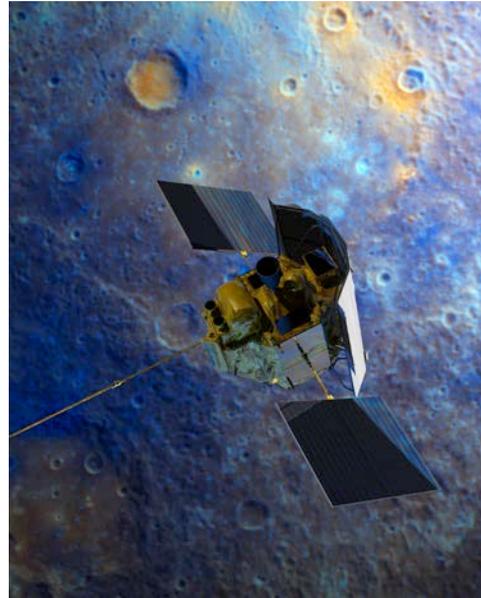
One experiment which may come close to such conditions is the "3-meter" experiment at the University of Maryland in College Park, MD (Fig. 13). It gets its name from the 3-meter diameter steel sphere that contains molten (100°F) sodium metal to simulate the earth's molten iron core (Young, 2011). The outer sphere contains a 1-meter diameter inner sphere to simulate the earth's solid core. The highly conductive liquid sodium is between the two spheres. The outer sphere has a jacket that can be heated or cooled (usually the latter).

Both spheres can rotate independently, either in the same direction or in opposite directions. The rotations are fast for such a ponderous amount of metal (13,000 kg)—four revolutions per second for the outer one and 12 revolutions per second for the inner one. Having a high electrical conductivity, large size, rapid rotation, and large temperature differences to drive convection, this experiment is the most realistic one so far in simulating the MHD effects in the earth's core. It could have a magnetic Reynolds number¹⁵ as high as 680 (Lathrop, 2004). That is high enough to produce some interesting results. Certainly the omega effect should occur. But nobody knows whether actual dynamo action will occur. If that were observed, it would be headline news for science journals, and it certainly would be rushed into print. The experiment has been running with liquid sodium since April, 2012 (Lathrop, 2012). But as of February 26, 2013, nearly a year, there has been no report of dynamo action, either by journal news, technical publication, preprint, or website.

¹⁵ This is a dimensionless number showing how efficiently the fluid moves magnetic lines of force. It is the product of the magnetic decay time and the ratio of the characteristic speed and length of the system.

PLANETARY MAGNETIC FIELD OBSERVATIONS

Figure 14. *MESSENGER* spacecraft orbiting Mercury. Graphic: NASA/Johns Hopkins University Applied Physics Laboratory.



Dynamo theory has fared poorly in the Solar system, particularly with the strong former fields of the Moon and Mars, and the presently fast-decaying field of Mercury. In contrast, the creation science view of planetary magnetic field creation, followed by decay and possible rapid reversals, has been remarkably and quantitatively successful (Humphreys, 1984, 2008). This supports the idea that dynamos are not necessary to explain the magnetic fields of the earth and astronomical bodies.

In particular, the observed field of the planet Mercury seems to support strongly the free-decay theory and weigh against dynamo theory. Mercury rotates nearly 88 times slower than the earth. So because the alpha-effect in earth's core seems to be relatively small, in Mercury's core it should be nearly non-existent. It should exhibit free decay much more clearly.

It does! Spacecraft measurements (Fig. 14) done over the past 36 years show that Mercury's dipole has weakened by 7.8 (± 0.8) percent (Humphreys, 2012a). That decay rate, combined with spacecraft measurements of its core size, implies an effective conductivity of 28,000 S/m, rather close to the 33,000 S/m observed for earth (Humphreys, 2012a, end notes 20 and 21). That suggests the cores of the two planets have similar turbulence. Last, observations of magnetized crust near Mercury's north pole suggest that in the past, its magnetic field was over ten times higher than today, fitting well with the creationist view of decay during 6,000 years (Humphreys 2012b).

CONCLUSION: A WORKING GEODYNAMO IS UNLIKELY

After nearly a century of hard work, scientists have failed to prove that a dynamo is actually working—or even could work—in the earth's core today. Analytic theory, numerical

simulations, laboratory experiments, and planetary observations all weigh against it. In particular, the section above, "The heart of dynamo theory isn't beating", offers quantitative reasons why the most viable form of dynamo theory appears to be dead. It has had some resounding failures in the rest of the solar system, too. In contrast, the creationist free-decay theory has been remarkably successful throughout the solar system. This contrast strongly supports the Biblical age of the earth and the solar system, which is about 6,000 years.

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