

## Earth's Magnetic Field Is Decaying Steadily— with a Little Rhythm

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### Abstract

A new curve fit to a new compilation of data shows with new clarity that from 1900 to 2010, the main “dipole” part of the earth’s magnetic field decayed exponentially (constant percent loss per year) with a small sine-wave variation. The time constant of the exponential part is 1611 ( $\pm 10$ ) years. The sinusoidal part has a period of 66.1 ( $\pm 1.3$ ) years and an amplitude of 0.29 ( $\pm 0.02$ ) % of the main part today. The fit is very good, with most points within 0.05% of the curve. The distinctness of the exponential part gives new strength to the creationary model of the field, that losses in the earth’s core today are steadily decreasing the electric current producing the dipole field, thus supporting a young earth. A simple electric circuit clarifies the decay model. The small sine-wave part, apparently not noticed in the dipole moment data before now, may be due to an east-west torsional oscillation between core and mantle. This corresponds to an approximately 60-year cycle observed in the rate of earth’s rotation.

### Introduction

Early in the nineteenth century, the German mathematician Karl Friedrich Gauss (1777, 1855) used many measurements from all over the world to characterize the earth’s magnetic field. Using what is now called “spherical harmonic analysis,” he mathematically divided the field into *dipole* and *non-dipole* parts. The dipole part, the main part, is the familiar two-pole (north and south) field shown in Figure 1. The earth’s field deviates from that shape by a few percent in many locations. These deviations are due to the non-dipole part of the field, which I discussed in an earlier paper (Humphreys, 2001). This paper will concentrate on the dipole. The strength of its source is called the magnetic *dipole moment*. That number is (roughly) the electric current that causes the field multiplied by the area

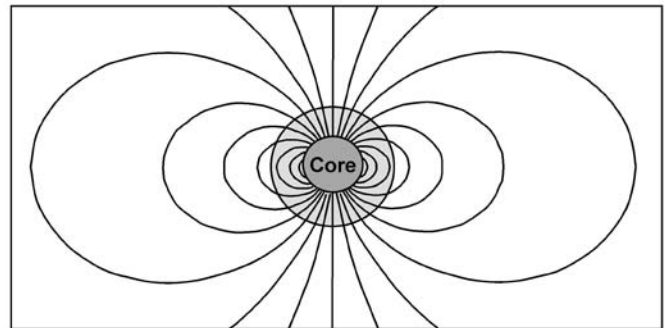


Figure 1. Dipole part of earth’s magnetic field. The magnetic lines of force originate in the earth’s electrically conductive core (fluid outer part, solid inner part), penetrate the earth’s mantle of solid rock above the core, and extend far out into space.

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of the circle in which the current moves, so the dipole moment has units of Ampere square-meters ( $A\ m^2$ ).

Following Gauss, scientists continued to make global measurements of the field. Four decades ago, Keith McDonald and Robert Gunst (1967, 1968) compiled the results of such measurements from 1835 to 1965. They drew a startling conclusion: during those 130 years, the earth's magnetic dipole moment had steadily decreased by over 8 percent! Such a fast change is astonishing for something as big as a planetary magnetic field. Nevertheless, the rapid decline remained relatively unknown to the public, a "trade secret" known mainly to researchers and students of geomagnetism.

A few years later, Thomas Barnes (1971), a creation physicist, began publicizing the trade secret. He showed how the decay of the dipole moment is consistent with simple electromagnetic theory (Barnes, 1973). A six-billion ampere electric current circulating in the earth's core would produce the field. By natural processes, the current would settle into a particular doughnut-shaped distribution, producing a dipolar field. The electrical resistance of the core would steadily diminish the current, thus diminishing the field. Dr. Barnes's fit to the dipole decay data he had then gave a half-life of 1365 years (time constant  $\tau$  of 1970 years; see Appendix B). Using that value in his equations gave a value of core conductivity (inverse of resistivity) of 40,400 Siemens (inverse Ohms) per meter. That is consistent with laboratory-derived estimates (Stacey, 1969). The decay rate is so fast that if extrapolated smoothly more than a dozen or so millennia into the past, the earth's magnetic field then would have been unreasonably strong. These points taken together make a good case for the youth of the field and consequently for a young earth. Since then, I have been adding to Barnes's work, closing loopholes in it (such as explaining reversals of direction during the Genesis Flood) and extending it to other planets (Humphreys, 1983, 1984, 1986, 1988, 1990, 2001, 2008).

After Dr. Barnes fitted the dipole moment decay to MacDonald and Gunst's compilation of data, I added newer data from the geomagnetic literature and made a somewhat more extensive fit, shown in Figure 2 (Humphreys, 1983). However, even more recent and systematic data are now available, so in this paper I present a new curve fit to the new data.

### What Form Should We Expect the Decay to Follow?

Clarifying nineteenth-century calculations by Horace Lamb (1883), Barnes (1973) re-derived the solution of Maxwell's equations of electricity and magnetism that is relevant to the decay of electric current in the earth's core. According to his solution, a few thousand years after any disturbance (Humphreys, 1986), the total electric current  $I$  circulating

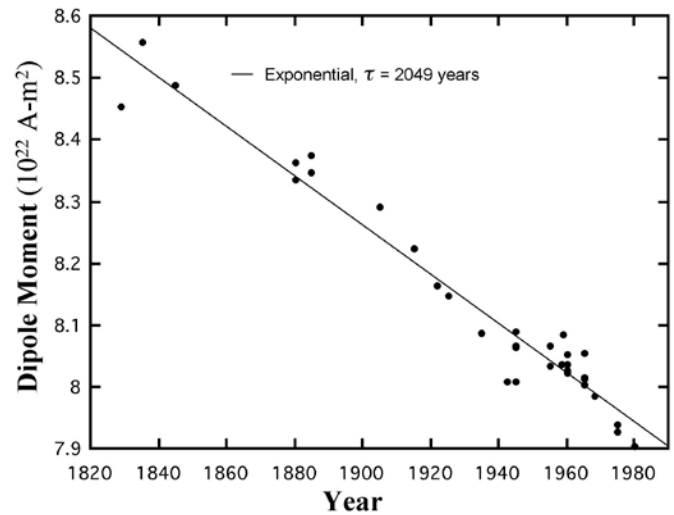


Figure 2. Previous compilation and fit (Humphreys, 1983) of 34 analyses of earth's magnetic dipole moment from 1829 to 1980. Large scatter mainly due to different methods of analysis. Time constant was 2049 ( $\pm 79$ ) years (half-life of 1420 years).

in the core should settle into a steady *exponential* (see Appendix B) decay:

$$I(t) = I_0 e^{-t/\tau}, \text{ where } \tau = \frac{\mu_0 \sigma R_c^2}{\pi^2}, \quad (1a,b)$$

The magnetic permeability  $\mu_0$  is  $4\pi \times 10^{-7}$  Henry per meter, where  $\sigma$  is the electrical conductivity in Siemens ( $\text{ohm}^{-1}$ ) per meter,  $R_c$  is the radius of the earth's core in meters,  $t$  is the time in seconds elapsed from a reference time defined as zero,  $I_0$  is the current in Amperes at time zero, and  $\tau$  is the *time constant* (see Appendix B) of the decay, in seconds.

Barnes showed that the electric current would have a particular distribution (Figure 3) throughout the core. Each oval contour in the cross-section marks off a ten-percentile of current density (Amperes per square meter). For example, the smallest oval contains all the current densities higher than 90% of the peak value, which is in the brightest region at the center of the oval. Extending the ovals westward around the axis in the direction of the arrow (the direction of the current) would form a set of nested toroids that carry the electric current.

This ideal distribution of current would make a magnetic field with the perfect dipole shape shown in Figure 1. The magnetic field  $\mathbf{B}$  at any given point on the earth, and the magnetic dipole moment  $M$ , would be directly proportional to the

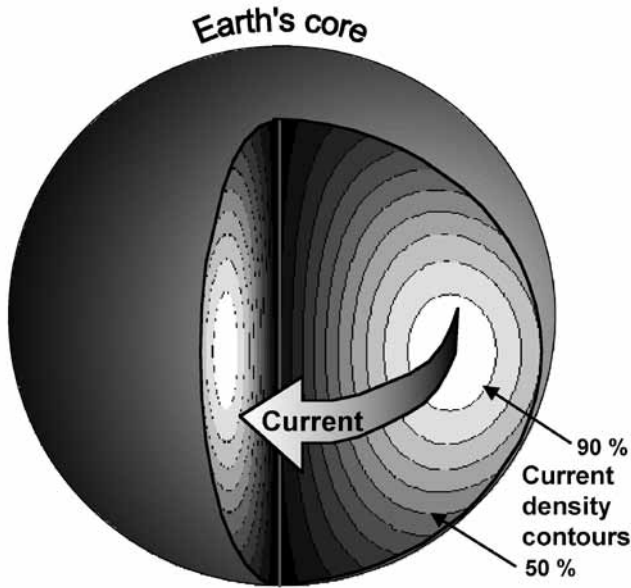


Figure 3. Electric current in the earth's core as calculated from Barnes's 1973 solution.

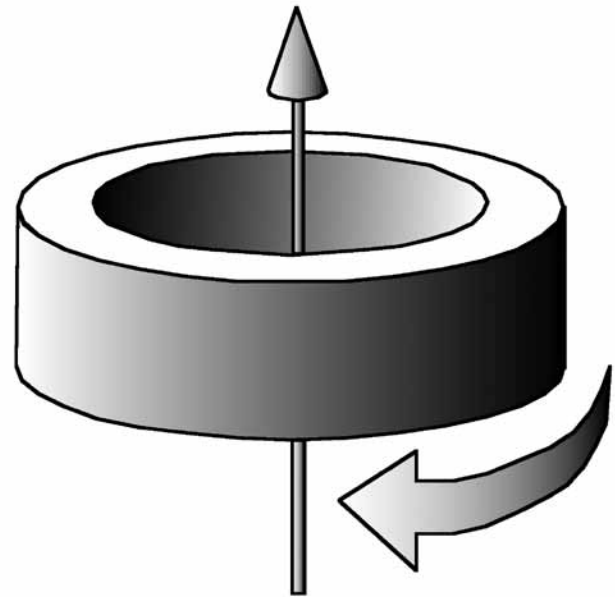


Figure 4. Slowing flywheel is analogous to decay of electric current in core.

exponentially decaying current of eq. (1). So the field and dipole moment also would decay exponentially with the same half-life.

It helps to compare this decay to the slowing down of a spinning flywheel due to fluid friction, as in Figure 4. The angular speed of the moving wheel represents the electric current, its angular kinetic energy represents the electromagnetic energy contained in the magnetic field, and the frictional drag represents the effect of electrical resistance. The angular kinetic energy has to be used up by the frictional drag to slow the wheel down. Frictional drag forces, being proportional to speed, slow the wheel down by a fixed percentage per unit time. That means the speed of the flywheel decays exponentially (Appendix B).

### The Electric Circuit in the Earth's Core

To a physicist, Barnes's derivation is elegant and physically very sensible. This may not be fully appreciated by those lacking adequate physics training. But for those with electronic experience, I can offer a simple electric circuit representation. Figure 5 shows a loop (a torus) of thick wire with dimensions  $a$  and  $b$  carrying an electric current. Engineering handbooks (Knoepfel, 1970; see p. 315, eq. (A1.8), with  $l \rightarrow 2\pi b$  and  $d \rightarrow 2a$ .) show that when  $a$  is significantly smaller than  $b$ , the inductance  $L$  of the loop is approximately:

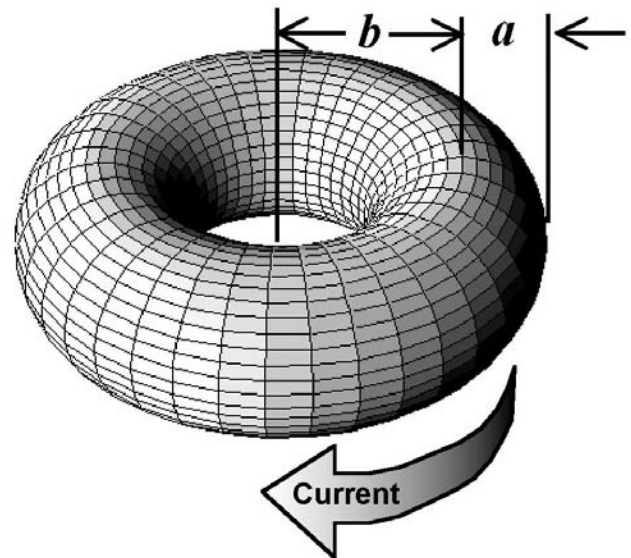


Figure 5. Thick loop of wire with circulating electric current. The cross-sectional radius  $a$  is a large fraction of the loop radius  $b$  to simulate the current distribution in Figure 3.

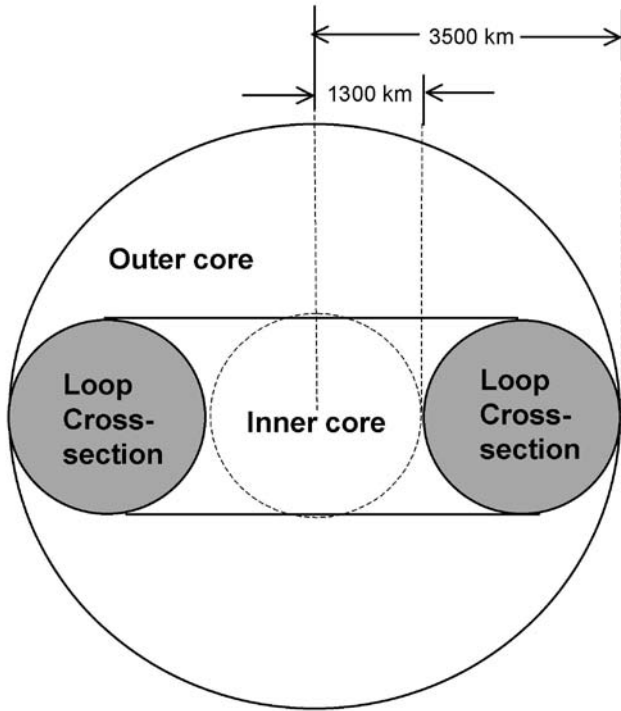


Figure 6. Current loop fitted into the earth's core. Arbitrarily choosing the loop dimensions to make it fit snugly between the inner core and the outer core radii gives it the dimensions shown. Compare to the 50% current density contour in Figure 3.

$$L \cong 2 \mu_0 b \left[ \ln \left( 4 \pi \frac{b}{a} \right) - 2.45 \right] \quad (2)$$

Figure 6 shows the loop fitted snugly (and arbitrarily) between the solid inner core, radius 1300 km, and the outer edge of the fluid outer core, radius 3500 km. Having dimensions  $a = 1100$  km and  $b = 2400$  km, the loop has a cross-section similar to the 50% current density contour in Figure 3. Using those values (converted to meters) for  $a$  and  $b$  in eq. (2) gives us an inductance of roughly

$$L \approx 5 \text{ Henry} \quad (3)$$

The electrical resistance  $R$  of the loop would be approximately the product of the resistivity (inverse of the conductivity  $\sigma$ ) of the material and the circumference of the loop, divided by the cross-sectional area of the loop:

$$R \cong \frac{1}{\sigma} \frac{2\pi b}{\pi a^2} = \frac{2b}{\sigma a^2} \quad (4)$$

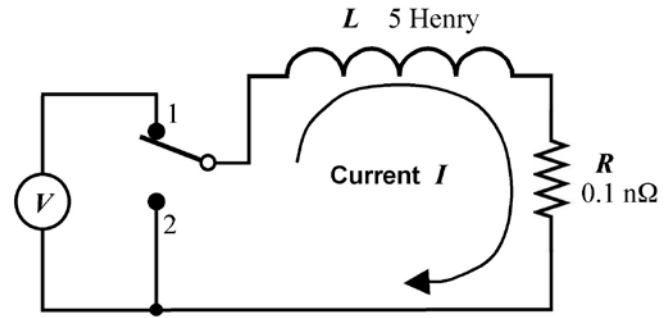


Figure 7. Equivalent circuit for electric current in core.

Geophysicist Frank Stacey (1969) estimated the conductivity of the core based on experimental material properties extrapolated to core temperatures and pressures, getting a  $\sigma$  on the order of 33,000 Siemens per meter. This value has a more realistic foundation than the larger values preferred by “dynamo” theorists (Merrill and McElhinny, 1983). Using that value and the values of  $a$  and  $b$  above in eq. (4) gives us an estimate of the electrical resistance of the current loop:

$$R \approx 10^{-10} \text{ Ohm} \quad (5)$$

This resistance is very small because the cross-sectional area of the loop is very large.

Figure 7 shows the equivalent electric circuit using the values of inductance and resistance from eqs. (3) and (5). Imagine that the switch is in position 1 and that the voltage  $V$  builds up the electric current in the circuit to the initial value  $I_0$ . That represents the creation model I suggested (Humphreys, 1983). Now flip the switch to position 2. Textbooks (e.g., Bitter, 1956; see p. 249, eqs. 6.50, 6.55) show that the current in the circuit will decay exponentially as in equation (1a) with a time constant  $\tau$  given by:

$$\tau = \frac{L}{R} \quad (6)$$

Using the rounded-off values in eqs. (3) and (5) for  $L$  and  $R$  in eq. (6) (and converting seconds to years) gives a time constant of roughly 1600 years. Using the unrounded values gives a time constant of about 1400 years. These circuit-based estimates are on the same order of magnitude as the observed decay time. That means the observed decay rate is consistent with the inductance and resistance to be expected from the dimensions and materials of the earth's core.

I could have used more exact formulas for the inductance and resistance of the simplified loop of current, but my goal here was simply to show that a circuit approximation gives roughly the observed decay rate. For the exact time constant, do not use a circuit approximation at all. Simply use Barnes's exact result, eq. (1b) of this paper.

The current going through the resistance  $R$  dissipates the energy stored in the inductance  $L$  (i.e., in the magnetic field). This "ohmic" power loss is simply the product of the resistance and the square of the total current.

## Accounting for Fluid Motion

The science of magnetohydrodynamics (Jackson, 1975, pp. 469–502) says that motions of the conducting fluid in the core should slowly twist the dipole magnetic lines of force into more complex shapes, subtracting from the dipole field and adding to the non-dipole field. Resistive losses then make the non-dipole field decay more rapidly (Humphreys 1986), so eventually the latter type of losses should prevail (Humphreys, 2001). We can combine the two types of loss by regarding  $R$  in the circuit as an *effective* resistance, including both the purely resistive loss and also the fluid-motion loss.

Flipping the switch in the circuit back to position 1 and making the applied voltage  $V$  vary appropriately with time, we can simulate other effects of fluid motion, such as the electromotive force due to the velocity of the fluid perpendicular to the magnetic field. Fluid motions in the core today appear to be very slow (Merrill and McElhinny, 1983, p. 44), so the voltage should be relatively small.

Summarizing the last three sections, we should expect the dipole field to be decaying exponentially, with only a small variation due to fluid motions. The data in the next section and the curve fit I describe (in the section following that one) show those two features distinctly.

## A Better Compilation of Magnetic Data

McDonald and Gunst (1967, 1968), followed by Barnes (1971, 1973), and then myself (Humphreys, 1990, 2001, 2008), used the results of several analyses from different years to get graphs of the magnetic dipole decay. Each analyst used different methods, adding a degree of "analytical scatter" to the dipole moments from various years, as comparing simultaneous points in Figure 2 will show. But in 1968 the International Association of Geomagnetism and Aeronomy (IAGA) began more systematically measuring, gathering, and analyzing geomagnetic data from all over the world. This group of geomagnetic professionals introduced a "standard spherical harmonic representation" of the field called the International Geomagnetic Reference Field, or IGRF. Every five years, start-

ing in 1970, they have published both dipole and non-dipole components of the field.

Using older data, the IAGA also extended the model back to the beginning of the twentieth century. With the issuance of the latest data set, IGRF-11, we have a standardized set of geomagnetic data from 1900 to 2010. You can download it free of charge as an ASCII file, a table of over 2700 numbers, from the National Geophysical Data Center website (International Association of Geomagnetism and Aeronomy, 2010). One of the IAGA authors estimates accuracies that I have used here (Lowes, 2010). The IGRF is the most consistent set of global geomagnetic data that cover such a long period of time.

The IGRF tables give the "Gauss coefficients"  $g_n^m$  and  $h_n^m$  from which we can construct the total field. For the dipole part,  $n = 1$ . It has three components,  $g_1^0$ ,  $g_1^1$ , and  $h_1^1$ , corresponding to the  $z$ -direction (north along rotation axis),  $x$ -direction (center through equator at  $0^\circ$  longitude), and  $y$ -direction (center through equator at  $90^\circ$  longitude), respectively. We can calculate the dipole magnetic moment  $M$  from those three coefficients as follows (Merrill and McElhinny, 1983, p. 29):

$$M = \frac{4\pi R_e^3}{\mu_0} \sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2} \quad , \quad (7)$$

where  $R_e$  is the average radius of the earth's surface (6371 km) in meters. Converting the three Gauss coefficients from nanotesla to Tesla ( $1 \text{ T} = 10^9 \text{ Gauss}$ ) then gives  $M$  in Ampere meters<sup>2</sup>. Table I shows the Gauss coefficients for the dipole part, and the corresponding dipole moment, every five years from 1900 to 2010.

## Fitting a Curve to the Data

Figure 8 is a log-linear graph (see Appendix B) showing the dipole moments of the new compilation of data in Table I. When these were initially plotted, I determined that I could draw a straight line (corresponding to an exponential decay; see Appendix B) right between the points as shown, dividing the data symmetrically between points above the line and points below it. Unexpectedly, the deviations from the straight line followed a smooth small "S"-shaped curve, contrasting greatly with the random deviations in my 1983 fit (Figure 2). Consequently, I attempted to fit the data with an exponential plus a small sinusoid:

$$M(t) = M_0 e^{-t/\tau} + M_1 \sin\left(2\pi \frac{t - t_0}{T}\right) \quad , \quad (8)$$

where  $t$  is the year AD and the constants the software adjusted to fit the data are:

$M_0$  = Amplitude of the exponential part in the year "zero" (really 1 BC) in A m<sup>2</sup>.

Table I Magnetic dipole moments from the International Geomagnetic Reference Field (IGRF-11) for the years 1900 through 2010 (IAEA, 2010). The  $g$ 's and  $h$  are the Gauss coefficients for the dipole part of the field, in nanoteslas (1 nT =  $10^{-5}$  Gauss). Magnetic dipole moment  $M$  is calculated from eq. (7) and is in units of  $10^{22}$  A m<sup>2</sup>.

No.	Year	$g_1^0$	$g_1^1$	$h_1^0$	$M$
1	1900	-31543	-2298	5922	8.32146
2	1905	-31464	-2298	5909	8.30081
3	1910	-31354	-2297	5898	8.27238
4	1915	-31212	-2306	5875	8.23545
5	1920	-31060	-2317	5845	8.19570
6	1925	-30926	-2318	5817	8.16042
7	1930	-30805	-2316	5808	8.12928
8	1935	-30715	-2306	5812	8.10647
9	1940	-30654	-2292	5821	8.09118
10	1945	-30594	-2285	5810	8.07531
11	1950	-30554	-2250	5815	8.06476
12	1955	-30500	-2215	5820	8.05067
13	1960	-30421	-2169	5791	8.02841
14	1965	-30334	-2119	5776	8.00474
15	1970	-30220	-2068	5737	7.97307
16	1975	-30100	-2013	5675	7.93873
17	1980	-29992	-1956	5604	7.90700
18	1985	-29873	-1905	5500	7.87107
19	1990	-29775	-1848	5406	7.84091
20	1995	-29692	-1784	5306	7.81425
21	2000	-29619.4	-1728.2	5186.1	7.78956
22	2005	-29554.6	-1669.1	5078.0	7.76745
23	2010	-29496.5	-1585.9	4945.1	7.74574

$\tau$  = Decay time constant of the exponential part, in years.  
 $M_1$  = Amplitude of sinusoid, in A m<sup>2</sup>.  
 $t_0$  = Last year in the nineteenth century the sinusoid was zero  
 $T$  = Period of the sinusoid, in years.

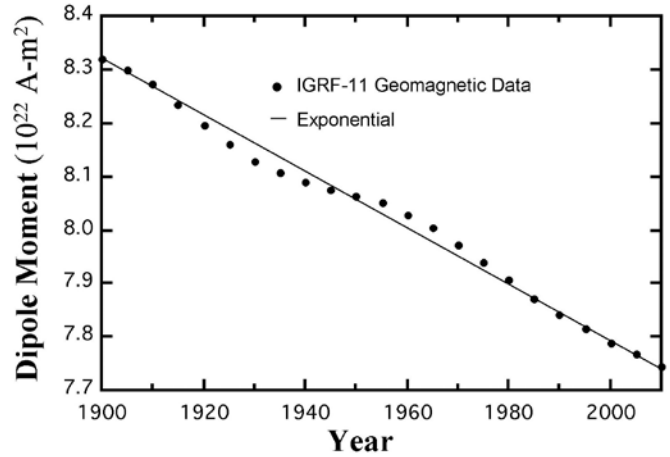


Figure 8. IGRF-11 dipole moments with exponential line only.

The software I used was a general curve-fitting routine in a data-analysis and graphics application for the Macintosh called *KaleidaGraph 3.0* (See Appendix A). It fits any user-supplied equation to a user-supplied set of data. After I gave the software eq. (8), rough starting values for the five coefficients, and equal weight to all 23 data points, it quickly converged on the values in Table II and the curve shown in Figure 9. According to the reference guide, the software's value for  $\chi^2$  is the sum of the squares of the deviations of the fitted curve from the data points (Abelbeck Software, 1994). This gives a root-mean-square deviation of less than 0.05%. The regression coefficient  $r$  (not  $r^2$ ), 0.99976, is very close to one. These numbers indicate a remarkably good fit between the exponential-plus-sine curve and the data, with very little scatter in the data (compared to Figure 2).

Using a linear fit with a sinusoid (instead of an exponential with a sinusoid) gives a slightly better regression coefficient, 0.99981. However, the difference of 0.00005 is probably not statistically significant. Rather, it merely suggests that 110 years of decay is too short a period for us to see a real difference.

Finally, Figure 10 shows the sinusoid that remains after we subtract out the exponential part of the fit. At this scale you can see the deviations of data from the curve, usually less than 0.05% of the total dipole moment. This scatter is consistent with one IGRF author's estimates of their r. m. s. error (Lowes, 2010), about 100 nT up to 1940, and smaller after 1960. Lowes (2010) implies that the error in a dipole coefficient is about a tenth of that, giving us roughly 10 nT error out of about 30,000 nT for the largest dipole component,  $g_1^0$ , or about 0.03%. So the curve fit appears to be about as close as the IGRF data will allow.

Table II. Results of fit to eq. (8).  $\chi^2$ , or chi-squared, in this case is the sum of the squares of differences between the fit and the data;  $r$  is the correlation coefficient.

Parameter	Value	Error
$M_0$ ( $10^{22}$ A m <sup>2</sup> )	27.027	0.197
$\tau$ (years)	1610.9	9.6
$M_1$ ( $10^{22}$ A m <sup>2</sup> )	0.022792	0.00132
$T$ (years)	66.118	1.25
$t_0$ (years)	1881.4	1.61
$\chi^2$ ( $10^{22}$ A m <sup>2</sup> ) <sup>2</sup>	0.00032	—
$r$	0.99976	—

### Possible Cause of the Sinusoid

Since the nineteenth century, geoscientists have noted a periodicity of about 60 years in the length of earth’s day (i.e., in the rotation rate of the mantle), the peak differences being several milliseconds per day (Gross, 2001). They did not find a clear connection to that in the geomagnetic data. But a recent report, confirming a  $62 \pm 3$ -year period in the length of day, found a rough correlation with the inclination and declination (but not with the total dipole moment) of the field (Roberts et al., 2007). Until this year, geomagnetic experts had thought that was due to magneto-hydrodynamic “torsional waves” of fluid in the core, but a new analysis appears to rule that out (Gillet et al., 2010).

The six-decade sinusoid may come from a magnetically mediated mechanical east-west oscillation between the mantle and the core. In Figure 1, picture the magnetic lines of force as rubber bands having tension (Shercliff, 1965). The high electrical conductivity of the core anchors the lines in the dense fluid, allowing little motion. But the lesser conductivity of the mantle allows the lines to bend and move through it a little, exerting force on the mantle as they do so. If the mantle rotates eastward slightly faster than the core, the tension in the lines of force will slow the mantle and then make it swing slightly westward with respect to the core. The moments of inertia of core and mantle regulate the speed of the swinging. Thus the lines of force can convey a torsional oscillation between the core and the mantle. This would affect the length of the day. The motion of the mantle east or west (with respect to the dipole field lines of force embedded in the core) affects the strength of the field reaching the surface, thus imposing a sinusoidal oscillation on the dipole moment. Rough calculations suggest this model is

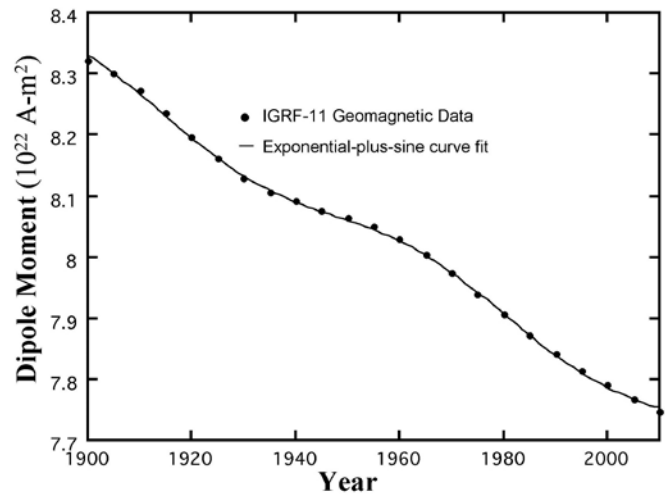


Figure 9. IGRF-11 dipole moments fitted to an exponential decay plus a sinusoid.

feasible. If it is correct, the oscillation may be the remnants of a disturbance in the earth’s rotation in the past. If the “ $Q$ ” (efficiency) of the oscillation (Barnes, 1965) is moderately good, the disturbance could have occurred thousands of years ago—perhaps even during the Genesis Flood.

Whatever the mechanism, the data suggest that some kind of oscillation is at work in the core-mantle-field system. The sinusoid part of the curve fit in this paper appears to be the first clear indication of a 66-year periodicity in the magnetic moment. It is surprising that no one has previously detected this.

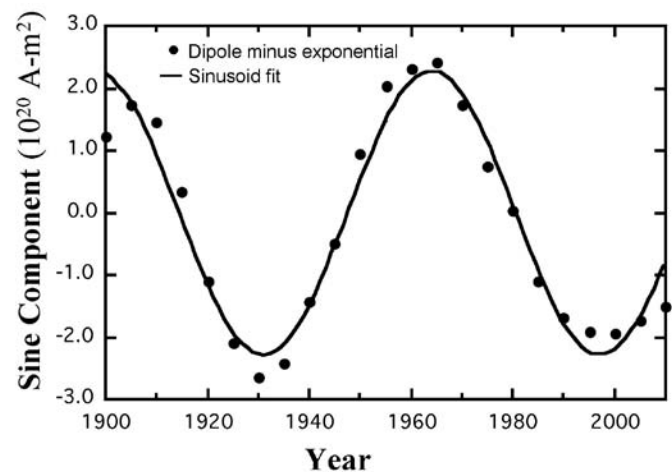


Figure 10. Sinusoidal residual after subtracting exponential from IGRF-11 data.

## Discussion and Conclusion

A linear decay is very unlikely, requiring a precise time variation of voltage  $V$  in the circuit that is hard to generate, as electronic engineers trying to get linear waveforms will attest. That suggests the non-sinusoidal part of the curve is truly exponential. In turn, that implies the cause of the decay is energy dissipation, either directly by ohmic losses in the dipole-generating current, or indirectly by ohmic losses in parts of the current removed from the dipole part by fluid motion, as I mentioned earlier. In support of this, using the new time constant of 1611 ( $\pm 10$ ) years in Barnes's exact eq. (1b)—not in the approximate circuit equations of eqs. (2) through (5)—gives a conductivity of 33,000 ( $\pm 200$ ) Siemens per meter, falling right upon the value preferred by Stacey (1969). The sinusoid neither adds to nor subtracts from the long-term energy loss. These ideas weigh heavily against the idea that there is currently a “dynamo” process at work in the core that would ultimately restore the lost energy back to the field. Without such a restoration mechanism, the field can only have a limited lifetime, in the thousands of years. So the clarity of this new fit, especially the exponential part, is further evidence that the earth's magnetic field is young.

**Acknowledgment:** In the early 1990s, a former student of Dr. Barnes, working in California, telephoned me to discuss the decay of the earth's magnetic field. Unfortunately, I don't remember his name. But I recall he suggested there might be a small sinusoid in the decay. At that time we only had the data of Figure 2 to work with, and I was not convinced. Now that the data suggests he was right, I hope he will write a letter to this journal so he can claim the credit he deserves for the idea.

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## Appendix A

1. See Barnes (1965) p. 239, eq. (11–45) for the relation of  $Q$  to losses in an electric circuit analogous to the torsional oscillation. The Biblically-suggested (note dates and times in Genesis 7 and 8) acceleration of the earth's rotation rate from 360 days per year to 365 days per year during the Genesis Flood (about 4350 years ago) would be a decrease of 20 minutes per day. That would probably produce a similarly large decades-long oscillation in the length of day. Assuming a 66-year period in the oscillation, an amplitude of 20 minutes then would diminish to the 4 milliseconds observed in the last few centuries if the  $Q$  of the oscillation were about 16. That would mean the amplitude of the oscillation would decrease by a factor of  $1/e$  every 16 cycles.
2. See the *KaleidaGraph Reference Guide* (Abelbeck Software, 1994). Section 11.2.3, "General curve fits," pp. 227–232. On their usage of  $\chi^2$ , see p. 232, eq. (12), which divides the square of each ( $i^{\text{th}}$ ) deviation by a number  $\sigma_i$ , which they call the "weight." Because I gave each point equal weight, I assume that  $\sigma_i = 1$ .
3. In Humphreys (1986), Table 1 on p. 120 shows non-dipole decay times, much shorter than the dipole decay time.
4. In Humphreys (1983), depolarization of spins of hydrogen nuclei in the originally-created material, water, initiates the electric current, thereby preserving the created magnetic field due to the created spin orientation.
5. For published article on the previous ( $10^{\text{th}}$ ) generation of the IGRF, see (Mandea et al., 2000).
6. For Mandea et al. (2000), the authors are also listed elsewhere (*Pure and Applied Geophysics* 157:1797–1802) as:

International Association of Geomagnetism and Aeronomy (IAGA), Division V, Working Group 8.

7. McDonald and Gunst (1968) provides a summary of their ESSA report of 1967.
8. Dynamo theorists assume a rather high core conductivity (usually 300,000 S/m), because that makes losses lower (e.g., Merrill and McElhinny, 1983, p. 213). In so doing, this eases the difficulty of imagining dynamo mechanisms that might make up for the losses.
9. The tension is  $B^2/\mu_0$ , where  $B$  is the magnetic field intensity (Shercliff, 1965, p. 65).
10. Stacey (1969) gives a reference to his 1967 paper, where he uses a resistivity of approximately  $3 \times 10^6$  emu. He comments that this is his preferred value, which is "10 times higher than the value usually assumed." Using Stacey's Appendix D, p. 277, his preferred value converts to  $3 \times 10^{-5}$  ohm-meter. Inverting that gives a conductivity of 33,000 Siemens per meter. Also on p. 150, Stacey derives circuit values for the core similar to mine, though he uses a somewhat different empirical formula for the inductance.

## Appendix B: Handy Things to Know about Exponentials

- $e$**  A symbol for the very important but irrational number 2.71828 ...
- $e^x$**   $e$  raised to the power of  $x$ , the exponential function of variable  $x$ ,  $\text{Exp}(x)$ .
- Time constant** Often written as the lowercase Greek letter tau,  $\tau$ , as for decays (negative exponents) with time  $t$ ,  $e^{-t/\tau}$ . After one period of time  $\tau$  elapses, the quantity decreases to  $1/e$  (36.8 %) of its value at the beginning of the period. If  $\tau$  has units of years, dividing it into 100 gives the percentage decrease per year. All exponential decays have a constant percentage decrease per unit time.
- Natural logarithm of  $x$**  The (usually non-integer) power of  $e$  which gives  $x$ , or the logarithm to the base  $e$  of  $x$ , or  $\log_e x$ , or  $\ln x$ .
- Half-life** The time needed for something to decay to half its starting value. Multiply the decay time constant  $\tau$  by the natural logarithm of two (0.693) to get the half-life.
- Log-linear graph** Graph with logarithmic vertical scale (so that each factor of ten occupies the same vertical distance) versus (for example) time horizontally on an ordinary linear scale. The logarithmic vertical scale compresses a curved exponential decay line into a straight line. All graphs in this article are log-linear.