ELECTROMAGNETICS OF THE EARTH'S FIELD AND EVALUATION OF ELECTRIC CONDUCTIVITY, CURRENT, AND JOULE HEATING IN THE EARTH'S CORE

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Evidence of decay in the earth's main magnetic field and the fact that Sir Horace Lamb's "model" of the earth's magnetic field indicated that it should decay, have aroused renewed interest in his famous work. However Lamb's original treatises[1, 2] are difficult to follow because they are cast in outmoded terminology and draw upon additional papers[3, 4, 5, 6, 7] that are not well referenced.

Because of the great importance of the phenomenon this paper begins with first principles and derives the relevant equations in the terminology of our day and in a more convenient coordinate system. In light of seismic knowledge the earth is assumed to contain a conducting core[8] of known radius and also assumed to have electric currents. Solutions for the internal and external magnetic fields are derived and show as did Lamb's solutions that the currents and magnetic fields decay exponentially with time.

After evaluating the time constant from existing data the conductivity of the core material is evaluated (assuming a uniform core). A solution is also obtained for the distribution of the current density in the core. Then the total current and Joule heating are solved. The time constant is 1970 years; total current is six billion amperes; and the Joule heating is two hundred million calories per second.

Introduction

The most remarkable geophysical phenomenon observed on a world-wide scale in modern times is the rapid decay of the earth's main magnetic field[9, 10]. Taking the real time observations of this decay and assuming that it will continue, it is known that the earth's main magnetic field will be gone in a few thousand years[11]. The author's analysis shows that this is not a periodic electromagnetic oscillation but is an aperiodic phenomenon with so much damping that no reversal of the magnetic field can take place before the magnetic field is completely gone. Extrapolating the phenomenon backwards and ruling out implausibly large values for the initial current and magnetic field shows that the earth's magnetic field is of recent origin, and does not have the so-called "geologic age" of billions of years[12].

Because of its great importance a detailed study of this electromagnetic phenomenon is developed in this paper. It is a reinvestigation of the problem first studied theoretically by Horace Lamb[13, 14]. Maxwell's field equations are applied and solved for the appropriate boundary conditions associated with the earth's magnetism.

Existing data on the earth and its magnetic dipole field are used to evaluate the time constant (time to decay to 1/eth of its value), the conductivity of the core, and the current density distribution in the core. Using the value of conductivity and integrating the square of the current density over the core volume yields the Joule heating. Integrating the current density over the appropriate cross section yields the total current in the core.

All data were processed on a CDC 3100 electronic computer. A least square exponential fit was employed on the existing magnetic dipole data to evaluate the time constant. As a separate check it was noted that the variability was smaller for this exponential fit than for a straight line fit, as one would expect from the exponential solutions obtained from Maxwell's equations.

The SI system of units is employed and the symbols for the physical quantities are:

- E electric field (volt/meter)
- B magnetic induction (tesla)
- H magnetic field
- D displacement
- J current density (ampere/meter^2)
- σ conductivity (mho/meter)
- μ permeability
- A vector potential
- P power (watt)
- t time (second)
- T time constant (second)

I. Derivation of Solutions in the Core

Beginning with the Maxwell's equation:

$$\nabla \times \underset{\sim}{E} + \frac{\partial \underset{\sim}{B}}{\partial t} = 0, \tag{1}$$

$$\nabla \times \underset{\sim}{H} - \frac{\partial \underset{\sim}{D}}{\partial t} = \underset{\sim}{J}, \tag{2}$$

$$\nabla \cdot \underset{\sim}{B} = 0, \tag{3}$$

the constituent equations;

$$\underset{\sim}{B} = \mu \underset{\sim}{H}, \tag{4}$$

$$\underset{\sim}{J} = \sigma \underset{\sim}{E}, \tag{5}$$

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and the defining equation for vector potential A;

$$\underset{\sim}{B} = \nabla x \underset{\sim}{A}, \tag{6}$$

one obtains in the conducting spherical core, after neglecting the displacement current, imposing the Coulomb gauge, and assuming that E is derivable from the vector potential alone (A much used device; see, for example, Lawson[15]), the wave equation

$$\nabla^2 \underset{\sim}{A} = \sigma\mu \frac{\partial \underset{\sim}{A}}{\partial t} . \tag{7}$$

Adopting spherical coordinates and assuming a circular current mode one writes

$$\underset{\sim}{J} = \underset{\sim}{e}_\phi J_\phi . \tag{8}$$

By looking at the form of equation (7) along with expectations about the physical behavior of the system, one assumes that the time solution is a *real* exponential with negative argument. Hence, the solution has the form

$$\underset{\sim}{A}(\underset{\sim}{r},t) = \underset{\sim}{A}(\underset{\sim}{r})e^{-t/T} , \tag{9}$$

where T is the time constant. Equation (7) reduces to

$$\nabla^2 \underset{\sim}{A} = \frac{-\sigma\mu}{T} \underset{\sim}{A} . \tag{10}$$

Expanding the Laplacian of vector A in spherical coordinates[16] and noting that A, like J in equation (8), has only the azimuthal component and depends only on r and θ, equation (10) reduces to the scalar form

$$\nabla^2 A_\phi - \frac{A_\phi}{r^2 \sin\theta} = \frac{-A_\phi}{L^2} \tag{11}$$

where there has been the substitution

$$\frac{\sigma\mu}{T} = \frac{1}{L^2} . \tag{12}$$

In order to show the relation between J and A, the expression

$$\underset{\sim}{E} = \frac{-\partial \underset{\sim}{A}}{\partial t} \tag{13}$$

is obtained from equations (1) and (6) subject to the previously noted restriction that E is derivable from A alone. In view of equation (5) one may write equation (13) in the form

$$\underset{\sim}{J} = -\sigma \frac{\partial \underset{\sim}{A}}{\partial t} , \tag{14}$$

and then reduce it to the scalar form

$$J_\phi = \frac{\sigma}{T} A_\phi \tag{15}$$

by carrying out the partial derivative with respect to time.

Equation (11) is now solved by the separation of variables technique. One assumes that $A\phi$ may be written as

$$A_\phi = A(\theta)A(r). \tag{16}$$

Equation (11) is now expanded into the form

$$\frac{1}{r^2}\frac{\partial}{\partial r} r^2\left(\frac{\partial A_\phi}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial A_\phi}{\partial \theta}\right) + \left(\frac{1}{L^2} - \frac{1}{r^2 \sin^2\theta}\right) A_\phi = 0. \tag{17}$$

By utilizing the differential equation for the associated Legendre polynomial, namely

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta \frac{\partial}{\partial\theta} P_\ell^m (\cos\theta)\right] + \left[\ell(\ell+1) - \frac{m^2}{\sin^2\theta}\right] P_\ell^m(\cos\theta) = 0$$

where l and m are integers, l being positive and $-l \leq m \leq l$, one may now substitute equation (16) into (17) and obtain the separated equations. It is observed that

$$A\ (\theta) = P_{\ell}^{1}\ (\cos\ \theta). \tag{18}$$

The differential equation for A(r) is

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2\,\frac{dA(r)}{dr}\right] - \frac{\ell(\ell+1)}{r^2}\,A(r) + \frac{1}{L^2}\,A(r) = 0\,. \tag{19}$$

The smallest value for l is 1, since m is 1 in this case. By making the substitution

$$A(r) = \frac{u(r)}{r}\,, \tag{20}$$

equation (19) reduces to

$$\frac{d^2u(r)}{dr^2} - \left(\frac{2}{r^2} - \frac{1}{L^2}\right)u(r) = 0 \tag{21}$$

for $l = 1$, the lowest mode. It is realized that the lowest mode solution is not the most general solution, but as Lamb pointed out, the higher modes decay more rapidly. The lowest mode should give the most physically reasonable results. Examining equation (21), one sees that it has a non-essential singularity at $r = 0$. Hence the series solution technique may be employed and one finally obtains the solution, for convergence at the origin,

$$u(r) = 3a_0 L^2 \left(\frac{L}{r}\right)\sum_{n=1} (-1)^{n-1}\,\frac{\left(\frac{r}{L}\right)^{2n+1}}{(2n-1)!\,(2n+1)}\,. \tag{22}$$

Equation (22) is manipulated into closed form by letting

$$S = \sum_{n=1} (-1)^{n-1}\,\frac{\left(\frac{r}{L}\right)^{2n+1}}{(2n-1)!\,(2n+1)}\,. \tag{23}$$

Differentiating,

$$\frac{dS}{d\left(\frac{r}{L}\right)} = \sum_{n=1} (-1)^{n-1}\,\frac{\left(\frac{r}{L}\right)^{2n}}{(2n-1)!} = \frac{r}{L}\sum_{n=1} (-1)^{n-1}\,\frac{\left(\frac{r}{L}\right)^{2n-1}}{(2n-1)!} \tag{24}$$

Hence,

$$\frac{dS}{d(r/L)} = \frac{r}{L}\ \sin\ (r/L)\,. \tag{25}$$

From the fact that

$$\int y \sin y \, dy = \sin y - y \cos y + C,$$

then

$$S = \sin\left(\frac{r}{L}\right) - \frac{r}{L}\cos\left(\frac{r}{L}\right) + C \quad (26)$$

When r is 0, S is 0; hence, C = 0 and

$$S = \sin\left(\frac{r}{L}\right) - \frac{r}{L}\cos\left(\frac{r}{L}\right) \quad (27)$$

From equations (22), (23), and (27) the solution may be written in the following closed form:

$$u(r) = 3\, a_0 L^2 \left[\frac{\sin\left(\frac{r}{L}\right)}{r/L} - \cos\left(\frac{r}{L}\right)\right]. \quad (28)$$

From equations (16), (18), (20), (28) and the fact that $P_1^1(\cos\theta) = -\sin\theta$, thus

$$A_\phi = \frac{-3a_0 L}{(r/L)}\left[\frac{\sin\left(\frac{r}{L}\right)}{r/L} - \cos\frac{r}{L}\right]\sin\theta \, , \quad (29)$$

Then, from equation (15),

$$J_\phi = -\frac{3\sigma a_0 L}{T\,(r/L)}\left[\frac{\sin(r/L)}{r/L} - \cos\left(\frac{r}{L}\right)\right]\sin\theta \, . \quad (30)$$

From equation (6) one notes that B may be obtained by taking the curl of A. Since Aø is the only component of A, it can be shown with the aid of equation (29) and the expansion for the curl in spherical coordinates, that B has the components

$$B_r = -\frac{6a_0}{\left(\frac{r}{L}\right)^2}\left[\frac{\sin\left(\frac{r}{L}\right)}{\frac{r}{L}} - \cos\left(\frac{r}{L}\right)\right]\cos\theta \quad (31)$$

and

$$B_\theta = \frac{3a_0}{\left(\frac{r}{L}\right)}\left[\frac{\frac{r}{L}\cos\left(\frac{r}{L}\right) - \sin\left(\frac{r}{L}\right) + \left(\frac{r}{L}\right)^2\sin\left(\frac{r}{L}\right)}{\left(\frac{r}{L}\right)^2}\right]\sin\theta \, . \quad (32)$$

II. Matching of Field Solutions at the Boundary

It is now desirable to obtain the magnetic field external to the core for the purpose of matching solutions at the boundary. Outside the core, assuming that the permeability for the mantle, crust, atmosphere, and space are approximately the same, one may write

$$\nabla \times \underset{\sim}{H} = 0, \quad \text{and} \quad (33)$$

$$\nabla \cdot \underset{\sim}{H} = 0. \quad (34)$$

Hence, H(r) is derivable from a scalar function of space. Then

$$\underset{\sim}{H} = -\nabla\phi_m \, . \quad (35)$$

Utilizing equation (34),

$$\nabla^2\phi_m = 0. \quad (36)$$

The solution to (36) is well known and for asimuthal symmetry may be written as[17]

$$\phi_m(r,\theta) = \sum_{\ell=0}^{\infty} \left[C_\ell r^\ell + D_\ell r^{-(\ell+1)}\right] P_\ell(\cos\theta) . \tag{37}$$

For $r > R_c$, the radius of the core, one has $C_l = 0$ for convergence. Hence,

$$\phi_m(r,\theta) = \sum_{\ell=0}^{\infty} D_\ell r^{-(\ell+1)} P_\ell(\cos\theta). \tag{38}$$

The H components are, therefore,

$$H_r(r,\theta) = \frac{\partial\phi_m}{\partial r} = \sum_{\ell=0}^{\infty} D_\ell(\ell+1)r^{-(\ell+2)}P_\ell(\cos\theta), \tag{39}$$

$$H_\theta(r,\theta) = -\frac{1}{r}\frac{\partial\phi_m}{\partial\theta} = -\sum_{\ell=0}^{\infty} D_\ell r^{-(\ell+2)}\frac{\partial}{\partial\theta}P_\ell(\cos\theta). \tag{40}$$

At the boundary between the core and the mantle

$$B_r(\text{core}) = B_r(\text{mantle})$$

and

$$H_\theta(\text{core}) = H_\theta(\text{mantle}. \tag{41}$$

Hence, by aid of equations (4), (31), (32), (39), (40), and (41), the boundary matching equations may be written as

$$\frac{-6a_0}{\left(\frac{R_c}{L}\right)^2}\left[\frac{\sin\left(\frac{R_c}{L}\right)}{R_c/L} - \cos\left(\frac{R_c}{L}\right)\right]\cos\theta = \mu_m\sum_{\ell=0}^{\infty} D_\ell(\ell+1)R_c^{-(\ell+2)}P_\ell(\cos\theta), \tag{42}$$

and

$$\frac{3a_0}{\mu_c\left(\frac{R_c}{L}\right)}\left[\frac{\frac{R_c}{L}\cos\left(\frac{R_c}{L}\right) - \sin\left(\frac{R_c}{L}\right) + \left(\frac{R_c}{L}\right)^2\sin\frac{R_c}{L}}{\left(\frac{R_c}{L}\right)^2}\right]\sin\theta = -\sum_{\ell=0}^{\infty} D_\ell R_c^{-(\ell+2)}\frac{\partial P_\ell(\cos\theta)}{\partial\theta}, \tag{43}$$

where R_c is the core radius.

By examination of equations (42) and (43), it is seen that $D_l = 0$ for all values of l except $l = 1$. It is also evident that the permeabilities of the core and mantle are equal and

$$L = \frac{R_c}{\pi} \tag{44}$$

for D_1 to have consistent values in equations (42) and (43). Therefore,

$$\frac{-6a_0}{\pi^2}\cos\theta = 2\mu_0 D_1 R_c^{-3}\cos\theta, \tag{45}$$

$$\frac{-3a_0}{\mu_0\pi^2}\sin\theta = D_1 R_c^{-3}\sin\theta. \tag{46}$$

It is clear, therefore, that

$$D_1 = \frac{-3a_0 R_c^3}{\mu_0 \pi^2}. \qquad (47)$$

Hence, the components of the external B field are in the form of

$$B_r = \frac{-6a_0 R_c^3}{\pi^2 r^3} \cos\theta, \qquad (48)$$

$$B_\theta = \frac{-3a_0 R_c^3}{\pi^2 r^3} \sin\theta \,. \qquad (49)$$

By utilizing equation (48), it is seen that at the earth's austral magnetic pole,

$$B_{R_e} = B_0 = \frac{-6a_0 R_c^3}{\pi^2 R_e^3} \qquad (50)$$

where R_e is the radius of the earth and B_0 is the value of the B field at the pole. Hence,

$$a_0 = \frac{-\pi^2}{6} \left(\frac{R_e}{R_c}\right)^3 B_0 \,. \qquad (51)$$

III. Reduced Solutions for the Field Components and the Time Constant

Now the internal and external field may be expressed in terms of B_0. *Inside* of the earth's core,

$$B_r = \frac{\pi^2 \left(\frac{R_e}{R_c}\right)^3 B_0}{\left(\frac{\pi r}{R_c}\right)^2} \left[\frac{\sin\left(\frac{\pi r}{R_c}\right)}{\pi r / R_c} - \cos\left(\frac{\pi r}{R_c}\right) \right] \cos\theta \qquad (52)$$

and

$$B_\theta = \frac{-\pi^2 \left(\frac{R_e}{R_c}\right)^3 B_0}{2\left(\frac{\pi r}{R_c}\right)} \left[\frac{\frac{\pi r}{R_c} \cos\frac{\pi r}{R_c} - \sin\frac{\pi r}{R_c} + \left(\frac{\pi r}{R_c}\right)^2 \sin\frac{\pi r}{R_c}}{\left(\frac{\pi r}{R_c}\right)^2} \right] \sin\theta \,. \qquad (53)$$

Outside of the earth's core,

$$B_r = \frac{B_0 R_e^3 \cos\theta}{r^3} \qquad (54)$$

and

$$B_\theta = \frac{B_0 R_e^3 \sin\theta}{2r^3} \,. \qquad (55)$$

The time constant (time for the field to decay to 1/e of its initial value) is found from (12) and (44) to be

$$T = \frac{\sigma \mu_0 R_c^2}{\pi^2} . \tag{56}$$

IV. Evaluation of Time Constant and Conductivity

Table 1 contains the historical values of the earth's magnetic dipole moment, the corresponding values of the B field at the poles, the date (epoch), and the scientists who made the determinations[11]. A least squares curve fit to these data yields a time constant $T = 6.21 \times 10^{10}$ sec (1970 years). Substituting this value of the time constant into equation (56) and using the value for earth's core radius, $R_c = 3.473 \times 10^6$ meters, one obtains a conductivity $\sigma = 4.04 \times 10^4$ mho/meter.

Table 1. Magnetic Dipole Moment M and B_0 at the Poles. 1835 to 1965*

Scientist	Epoch	M (amp meter²) x 10^{22}	Bo (tesla) x 10^{-5}
Gauss	1835	8.558	6.618
Adams	1845	8.488	6.564
Adams	1880	8.363	6.468
Neumayer	1880	8.336	6.448
Fritsche	1885	8.347	6.456
Schmidt	1885	8.375	6.478
Vestine, et al	1905	8.291	6.412
Vestine, et al	1915	8.225	6.362
Dyson-Furner	1922	8.165	6.314
Vestine, et al	1925	8.149	6.302
Vestine, et al	1935	8.088	6.256
Jones-Melotte	1942.5	8.009	6.194
Vestine, et al	1945	8.065	6.238
Afanasieva	1945	8.010	6.194
U.S.C. & G.S.	1945	8.066	6.238
Fanselau-Kautzleben	1945	8.090	6.256
U.S.C. & G.S.	1955	8.035	6.214
Finch-Leaton	1955	8.067	6.240
Nagata-Oguti	1958.5	8.038	6.216
Cain, et al	1959	8.086	6.254
Fougere	1960	8.053	6.228
Adam, et al	1960	8.037	6.216
Jensen-Cain	1960	8.025	6.206
Leaton, et al	1965	8.013	6.198
Hurwitz, et al	1965	8.017	6.200

*The table is constructed utilizing data from a ESSA Technical Report [11]. The B_0 values are obtained from the far field approximation.

V. Current in the Earth's Core

The current density inside of the earth's core is found from (30) and (51) to be

$$J_\phi = \frac{\pi^3}{2\mu_0 R_c}\left(\frac{R_e}{R_c}\right)^3 \frac{B_0}{\left(\frac{\pi r}{R_c}\right)}\left[\frac{\sin\left(\frac{\pi r}{R_c}\right)}{(\pi r/R_c)} - \cos\left(\frac{\pi r}{R_c}\right)\right] \sin\theta . \tag{57}$$

Integrating this over a semicircular area of the core through which current flows

$$I = \frac{\pi}{\mu_0} B_0 R_c \left(\frac{R_e}{R_c}\right)^3 \int_0^\pi \left(\frac{\sin x}{x} - \cos x\right) dx, \tag{58}$$

where $x = \frac{\pi r}{R_c}$. Determining the value of the integral in (58) to be 1.8519 and using $B_0 = 6.20 \times 10^{-5}$ tesla for the value of the polar field and $R_e = 6.371 \times 10^6$ meters for the earth radius, the current (I) in the earth's core is found to be 6.16×10^9 amperes.

Figure 1 shows the distribution of the current density with distance from the center in the magnetic equatorial plane. The maximum current density of 5.95×10^{-4} amp/m² occurs at approximately a distance of ⅔ of the core radius.

VI. Joule Heating in the Earth's Core

One may solve for the Joule heating in the earth's core by means of the integration

$$P = \iiint \frac{J^2}{\sigma} dV , \tag{59}$$

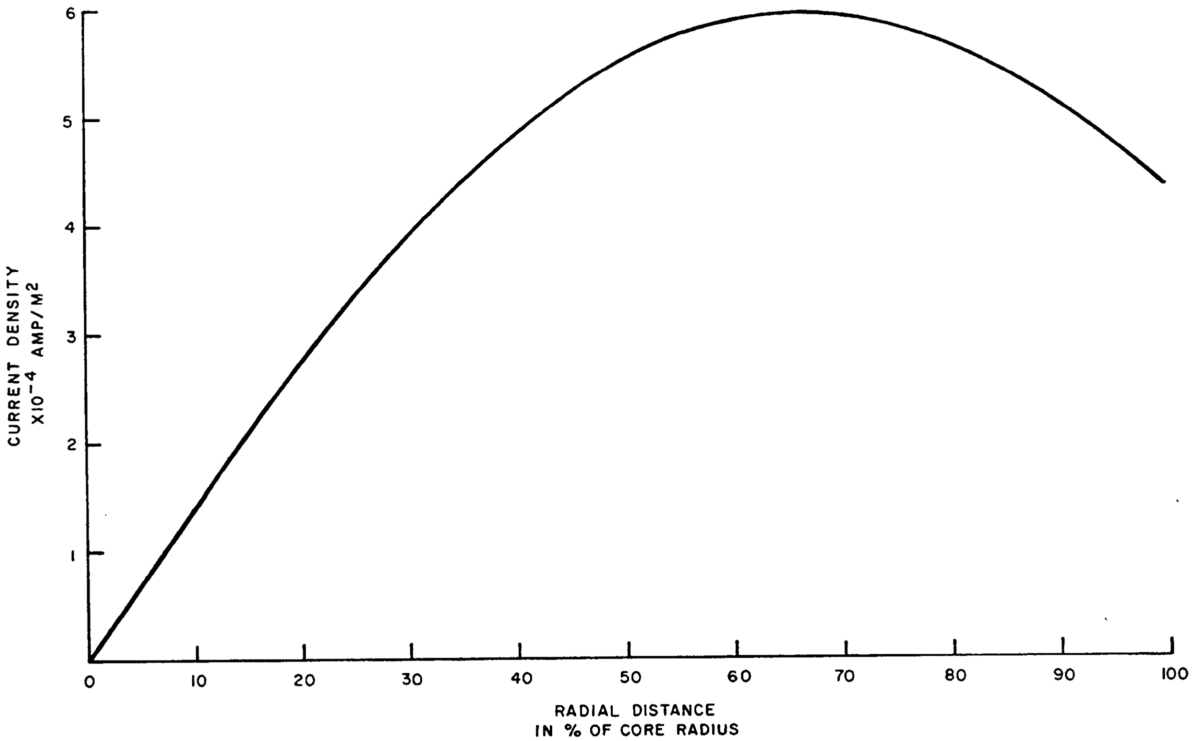

Figure 1. Current density in the magnetic equatorial plane as a function of radial distance.

where the current density from equation (57 is to be used. Choosing the volume element $2\pi r^2 \sin\theta \, d\theta \, dr$ reduces (59) to a double integral. After integrating with respect to θ from 0 to π and making the substitution $x = \frac{\pi r}{R_c}$,

$$P = \frac{2\pi^4 R_c}{3\sigma \mu_0^2} \left(\frac{R_e}{R_c}\right)^6 B_0^2 \int_0^\pi \left(\frac{\sin^2 x}{x^2} - \frac{2 \sin x \cos x}{x} + \cos^2 x\right) dx, \quad (60)$$

which yields

$$P = \frac{\pi^5 R_c}{3\sigma \mu_0^2} \left(\frac{R_e}{R_c}\right)^6 B_0^2 . \quad (61)$$

Using the previously determined value of conductivity and the present value of B_0,

$$P = 8.13 \times 10^8 \text{ watts}$$

or

$$P = 1.94 \times 10^8 \text{ calories/second}$$

for the Joule heating in the earth's core.

Conclusions

Application of Maxwell's equations to currents in the conducting core of the earth has yielded solutions for both the internal and external magnetic fields of the earth as functions of time.

The constants in these equations have been evaluated from the known data accumulated over a period of 130 years. The solutions show an aperiodic decay with a time constant of 1970 years (1400 year half-life) which has important geochronological implications.

This paper also demonstrates the usefulness of these solutions in studying properties of the core of the earth, by evaluating the conductivity, current distribution, total current, and joule heating in the earth's core.

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THE CHALLENGE OF HISTORICAL GEOLOGY

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Introduction

Over the past decades, no doctrine has so challenged the creationist interpretation of the physical universe, as that viewpoint based on the uniformitarian outlook. This method involves interpretation of past events solely in terms of present day occurrences.

Philosophically, uniformitarianists assume that "Nature" can be satisfactorily explained exclusively in terms of natural causes. Indeed, in an extreme form the teaching states, "there is no vestige of a beginning nor prospect of an end." Thus when consistently applied the doctrine entails the assumption that the Natural Universe is an autonomous (independent and self-existent) system, which exists without a creator God.

The vital truth of a created universe, sustained by the word of God's power, is of pivotal importance today—if man is not to end up as a mere chance collection of atoms. A clear stand for creation is necessary to prevent men rationalizing and accepting this sorry plight of a meaningless universe.

The Danger and the Challenge

If God is relegated to the position of the Unknown and Unknowable, or a "God of the gaps," not only is this false to the Scriptural teaching and the fact that "the Heavens declare the glory of God," but man is then designated as merely a bio-chemical machine. He grows for a while, declines, and at death returns to the dust. Or put in other words, man would be integrated into the void of nothingness, doomed to chaos and Old Night.

For this reason, creationists must take issue with historical geologists, who are ever seeking to justify their naturalistic interpretation of the Universe, by recourse to the doctrine, "the present is the key to the past." It is in this context especially that the challenge of historical geology should be seen, a challenge involving not only the origin of the Universe and its end, but also of the acme of creation—man himself.

As the facts and the interpretation of those facts cannot be separated, we can agree with Professor Hartshorne that scientific description includes ". . . both what is known and what can be inferred, both of the phenomena and of the process relations and associations of phenomena."[1] This leaves an amazing span of complex information in the hands of the historical geologist to interpret;

> . . . since the historical geologist is the only scientist who is presented with material for studying the history of the world in remote times, he finds that he must include historical botany, zoology, and human anatomy, and even to some extent historical social anthropology.[2]

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