Reflections on Geomagnetic Reversals

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Several investigators have noted that the Earth's magnetic dipole has been decreasing during the last century. Some have indicated that if the trend continues the dipole would be zero within a few thousand years, indicating that a reversal was occurring. Few if any take such suggestions seriously because of the weakness of the conditional if clause. An example of such a "prediction" is taken from the recent series of definitive models and reasons are given describing why such predictions of reversals are quite meaningless. It is known that the Earth's magnetic field, at the surface of the Earth is predominantly dipolar. From paleomagnetic studies it is also known that this predominantly dipolar field has reversed its direction many times. Some studies indicate that although, at the present time, the dipole of the Earth is decreasing quite rapidly, the total magnetic energy outside the core is remaining nearly constant. This idea is reexamined using the recent definitive models and found to be true. The main purpose of this paper is to investigate the characteristics of relatively simple core sources which can produce the observed predominantly dipolar field and then cause the field to reverse without much loss of the total energy outside the core. A simple source in the outer core cannot produce the outstanding dipolar pattern that is observed. The right combination of many simple sources, the strongest of which must be very deep in the outer core, can create the dipolar pattern as has been shown in several previous studies. A very simple source system deep in the outer core is contrived to illustrate one way in which the main characteristics of a reversal can be realized.

1. Introduction

It has been known for many years that the dipole of the geomagnetic field has been decreasing. This has led to the suggestion that the Earth's field may be headed for another reversal.

MCDONALD and GUNST (1968) indicate that since the time of Gauss "the Earth's dipole moment has decreased sensibly linearly, at the rate of approximately 5% per century". They conclude that "if this rate persists, the dipole moment will vanish in A.D. 3991." They also indicate that concurrent with the decrease in the dipole moment there has been a significant growth of the non-dipole field and the non-dipole non-quadrupole field indicating that the dipole field is being driven destructively to smaller values by fluid motions which

transform its magnetic energy into the near neighboring modes of higher degree. Other authors have noted similar trends and have made similar suggestions regarding a reversal if the trend continues (HARWOOD and MALIN, 1976).

In Section 2 examples are given of apparent linear trends in the geomagnetic dipole and in the energy outside the Earth of the geomagnetic dipole, using data from the recently determined Definitive Geomagnetic Reference Field models for 1965, 1970, and 1975 (DGRF 65, 70, 75) and the International Geomagnetic Reference Field model for 1980 (IGRF 80) (PEDDIE, 1982). It is suggested that the energy of the geomagnetic dipole outside the Earth may be as good an indicator of an impending reversal as the dipole itself, but that neither are really of any value for this purpose because of the very short time period of the observations as compared to the time period involved in a true reversal.

It is assumed here that the spherical harmonic reference radius is the radius of the Earth as is usually the case. Between reversals the zonal first degree spherical harmonic coefficient, SHC, g_1^0 is typically many times larger than any other coefficient. This is what gives the Earth's field a dipolar pattern, nearly aligned with the Earth's rotation axis, and has made it possible for paleomagnetism to yield valuable information on polar wandering and continental drift. At the present time the absolute value of g_1^0 is 5.3 times its nearest rival h_1^1 , and is 9.9 times g_2^1 which is the largest coefficient with degree greater than 1. During a reversal g_1^0 goes through zero which will likely cause substantial changes in the distribution of the energy in the system. No one, of course, has observed the energy pattern through a reversal, but recently the energy density spectrum at various levels throughout the Earth and the energy spectrum outside the Earth and in the mantle have been considered by several authors (MCDONALD and GUNST, 1968; VEROSUB and COX, 1971; BENTON *et al.*, 1982; and MEYER *et al.*, 1983).

In Sections 2 and 3 the dipole and the energy pattern are discussed using the data from the four DGRF and IGRF tenth-degree models mentioned above. The total magnetic energy outside the Earth's surface is found to be decreasing with time. This decrease is caused mainly by a decrease in the first degree term of the energy spectrum (energy of the magnetic dipole). From the short-term data base used in this study both the dipole moment and its energy outside the Earth's surface appear to be decreasing linearly, which, of course, is impossible because the dipole energy term is proportional to the square of the dipole moment.

It is found that although the total magnetic energy outside the Earth's surface is decreasing, the total energy outside the core is remaining nearly constant.

In Section 4, the SHC of current loops in the core are investigated to see if varying simple core sources can be found which approximate what is seen in the magnetic record regarding reversals. That is, what kind of varying core sources can give very large first degree coefficients compared to the other SHC, will permit the magnetic energy outside the Earth's surface to decrease as a reversal is approached and at the same time keep the total energy outside the core relatively constant. Simple time varying core sources satisfying the above requirements are found.

2. Trends Sometimes Taken as Indicators of an Impending Reversal

It should be stated at the outset that a decreasing magnetic dipole or a decreasing magnetic energy pattern do not necessarily presage a reversal. Either of these factors can certainly go up and down many times before a real reversal occurs. Nevertheless, reversals are of sufficient interest that some speculation is admissible.

A factor of rather fundamental importance to this study is

$$F_n = \sum_{m=0}^n [(g_n^m)^2 + (h_n^m)^2], \quad (1)$$

where the g 's and h 's are the usual quasi-normalized SHC in tesla (T). The energy spectrum outside a sphere of radius b is given in Joules by

$$E_n = \frac{2\pi a^3}{\mu_0} \frac{(n+1)}{(2n+1)} \left(\frac{a}{b}\right)^{2n+1} F_n, \quad (2)$$

where a is the radius of the Earth and μ_0 is the magnetic permeability of free space (McDONALD and GUNST, 1968; VEROSUB and COX, 1971; BENTON *et al.*, 1982). The total energy outside a sphere of radius b is

$$E = \sum_{n=1}^{\infty} E_n \quad (3)$$

which is usually truncated at some reasonable value of $n = N_{\max}$. For later reference, the mean energy density spectrum on a sphere of radius b as given by MEYER *et al.* (1983) is

$$U_n = \frac{(n+1)}{2\mu_0} \left(\frac{a}{b}\right)^{2(n+2)} F_n. \quad (4)$$

The amplitude of the magnetic dipole moment is given by

$$M = cF_1^{1/2}, \quad (5)$$

where $c = 4\pi a^3/\mu_0$ if S.I. units are used.

Magnetic energy spectrum values for the energy outside the Earth for the four models already described are listed in column four of Table 1 and are plotted as a function of time for the four models in Fig. 1. A few of them are shown using an enlarged scale in Fig. 2. It is seen that the first degree spectral term dominates the spectrum accounting for approximately 97% of the total energy outside the surface of the Earth as described by the first ten terms of the analysis. The second largest spectral component is the second degree term which accounts for only 1.7% of the total energy. Figures 1 and 2 are closely

related to the curves of the amplitude of the n th-degree main field harmonics shown by OSTROWSKI (1982).

The well-known decrease in the energy of the dipole term is shown clearly in Fig. 2. The total energy is also decreasing, but not quite as rapidly as the dipole term. Part of this difference is made up by the increase with time in the quadrupole term, $n=2$, as shown in Fig. 2. The third degree term which has an energy nearly one-half that of the quadrupole term is also steadily increas-

Fig. 1 Some energy spectral terms outside the Earth vs time. n is the spherical harmonic degree. Total denotes sum of first 10 degrees.

ing. Some higher degree terms are increasing and some are decreasing, but their amplitudes are low enough to have little effect on the total energy at the present time. The energy in the $n=4$ harmonic is only about one-quarter that in the $n=3$ harmonic.

The energy curves for $n=6$ to 10 show a clear upward concavity. This may be an indication that the core motion is progressively feeding more energy into small scale turbulent cells as the dipole term decreases. Turbulence theory assumes that the flow of energy in momentum space is from larger to smaller eddies

Fig. 2 Selection of some of the curves in Fig. 1, drawn here with an expanded scale.

except under certain conditions in rotating media (ELASSER, 1956).

Both the first degree spectral term and the total energy are seen to be decreasing at what appears to be a linear rate. The first degree spectral terms fits the linear regression curve

$$E_1 \text{ (Joules)} = 8.259 \times 10^{17} - 1.349 \times 10^{15} \text{ (year-1965)} \quad (6)$$

with a root mean square residual (rms) of 1.11×10^{14} Joules, which is only 0.013 percent of the energy in the first degree term, which is indeed a very good fit. If this continues, we see from (6) that E_1 will equal zero in 612 years from 1965 or in A.D. 2577.

Alternatively, if in (5) we set $c=1$ and leave the SHC in nT, we get a linear regression for the normalized dipole moment of

$$M \text{ (nT)} = 30,952 - 25.47 \text{ (year-1965)} \quad (7)$$

with an rms value of 2.32 nT which fits the data a little better than (6). If (7) continues, M will equal zero in 1215 years from 1965 or in A.D. 3180.

The estimation of the time of a reversal is a very precarious operation, but from the data used here one of the above estimates is as good as the other even though they differ by nearly a factor of two. The difficulty is, of course, that the Taylor's series approximation of any function can be quite good over a short interval, but it may be very poor over an extended interval. We know that

$$E_1 \propto M^2, \quad (8)$$

so that if one is linear in time the other cannot be linear over an extended period of time.

The fallacy in the "predictions" made above is immediately apparent by noting that Equation (6) indicates an energy of the dipole term outside the Earth of twice the present value 612 years before 1965, and (7) indicates a dipole moment of twice the present value 1215 years before 1965. Historically it is known from archeomagnetic studies that neither of these are true (MERRILL and MCELHINNY, 1983). Furthermore, if quadratics or cubics are fitted to the "observed" values of g_1^0 , g_1^1 , and h_1^1 from the four models being used and E_1 and M are constructed from these values as quadratics or cubics in time, and solutions are found for E_1 and M equal to zero, two or three solutions will be found some of which may be imaginary. Solutions thus found are very unrealistic.

The conclusion that the simple predictions of a reversal as described above cannot be of much value is based solely on the historical consequences, known to be untrue, when linear, quadratic, or cubic approximations are made using available observations. The conclusion has nothing to do with the total energy of the system. The present trend in the dipole moment and its energy outside the Earth are, of course, consistent with an approaching reversal but do not

necessarily predict one. It will be shown later that a reversal can occur with very little loss in the total magnetic energy outside the core of the Earth.

3. Energy and Energy Density as a Function of Radius and Time

Using Eqs. (2) and (4), the energy spectrum of the total energy outside a given radius b and the mean energy density spectrum at that radius were computed. These values are shown in Table 1 for $b=0.5a$ (a little inside the core-mantle boundary) and for $b=a$ (Earth's surface). Column four of Table 1 has already been referred to. Some of the energy spectral terms of the energy outside $b=0.5a$ are plotted vs time in Fig. 3 for comparison with Figs. 1 and 2.

The factor $(a/b)^{2n+1}$ in (2) becomes very important in boosting the high degree terms when b is less than a . As can be seen in Table 1, the energy spectrum for the energy outside $b=0.5a$ drops just a little more than one order of magnitude in going from degree 1 to degree 10, whereas, the energy spectrum for energy outside the Earth's surface drops nearly seven orders of magnitude. The energy spectrum of the energy outside $b=0.5a$ is quite flat except for the $n=1$ term which is roughly an order of magnitude higher than the other values. These general features were pointed out by MEYER *et al.* (1983).

We found earlier that the first degree term accounted for 97% of the total energy outside the Earth. Table 1 shows that the first degree term accounts for only 60% of the total energy outside $b=0.5a$. This feature may make it easier to account for the energy in the magnetic field when a reversal occurs. Note in Fig. 3 that the dipole term ($n=1$) is steadily dropping, but the total energy is concave upward and in 1980 is nearly as large as it was in 1965.

Examination of Eqs. (2) and (4) shows that the average energy density spectrum at a given radius, less than a , increases with n more rapidly than does the energy spectrum of the energy outside that radius. Figures 4 and 5 show the average energy density spectrum vs time for $b=0.5a$ and for the surface of the Earth, respectively. Note, in Fig. 4, how the first degree term is decreasing at a nearly linear rate, but the total curve is flat between 1970 and 1975 with a definite upturn from 1975 to 1980. The loss in the first degree term is compensated for by the increases in higher degree terms. Figure 5 shows that on the Earth's surface the average energy density for $n=1$ and the total average energy density are both decreasing as a function of time.

4. Source Model to Produce Observed Features

It is known that a very complicated set of dipole sources (ALLDREDGE and STEARNS, 1969) or current loops (PEDDIE, 1979) can produce the main features of the dipolar geomagnetic field that are observed. It is presumed that these sources could evolve in such a way as to create a reversed dipolar field. To try to follow any such changes through a reversal would be very complicated so that the essential features of the change from one polarity to the other would

Table 1. Magnetic energy spectrum and the mean energy density spectrum for various regions.

Epoch	n	Earth spectrum (Joules)			Mean energy density spectrum (Joules/m ³)		
		Outside radius = $0.5a$		Outside earth's surface	at radius = $0.5a$	At surface of earth	
1965	1	6.6069	E18	0.8259 E18	0.04879	0.7624	E-3
	2	0.4559	"	0.1425 E17	0.00561	0.2192	E-4
	3	0.8026	"	0.6270 E16	0.01383	0.1351	E-4
	4	0.7997	"	0.1562 E16	0.01772	0.4325	E-5
	5	0.4603	"	0.2248 E15	0.01247	0.7608	E-6
	6	0.4906	"	0.5989 E14	0.01570	0.2396	E-6
	7	0.3566	"	0.1088 E14	0.01317	0.5023	E-7
	8	0.1820	"	0.1388 E13	0.00762	0.7262	E-8
	9	0.5299	"	0.1011 E13	0.02478	0.5909	E-8
	10	0.2784	"	0.1328 E12	0.01439	0.8578	E-9
Total		10.9629	"	0.8482 E18	0.17407	0.8032	E-3
1970	1	6.5548	E18	0.8193 E18	0.04841	0.7563	E-3
	2	0.4707	"	0.1471 E17	0.00579	0.2263	E-4
	3	0.8134	"	0.6354 E16	0.01402	0.1369	E-4
	4	0.7896	"	0.1542 E16	0.01749	0.4271	E-5
	5	0.4755	"	0.2322 E15	0.01288	0.7858	E-6
	6	0.4586	"	0.5599 E14	0.01468	0.2239	E-6
	7	0.3656	"	0.1116 E14	0.01350	0.5150	E-7
	8	0.1738	"	0.1326 E13	0.00727	0.6936	E-8
	9	0.5081	"	0.9691 E12	0.02376	0.5666	E-8
	10	0.2571	"	0.1226 E12	0.01329	0.7922	E-9
Total		10.8672	"	0.8423 E18	0.17109	0.7980	E-3
1975	1	6.4984	E18	0.8123 E18	0.04799	0.7498	E-3
	2	0.4871	"	0.1522 E17	0.00599	0.2342	E-4
	3	0.8258	"	0.6451 E16	0.01423	0.1390	E-4
	4	0.7777	"	0.1519 E16	0.01723	0.4206	E-5
	5	0.4850	"	0.2368 E15	0.01313	0.8015	E-6
	6	0.4343	"	0.5302 E14	0.01390	0.2121	E-6
	7	0.3771	"	0.1151 E14	0.01392	0.5311	E-7
	8	0.1773	"	0.1353 E13	0.00742	0.7076	E-8
	9	0.5131	"	0.9787 E12	0.02400	0.5722	E-8
	10	0.2599	"	0.1240 E12	0.01344	0.8009	E-9
Total		10.8356	"	0.8358 E18	0.17125	0.7924	E-3
1980	1	6.4451	"	0.8056 E18	0.04760	0.7437	E-3
	2	0.5088	"	0.1590 E17	0.00626	0.2446	E-4
	3	0.8418	"	0.6577 E16	0.01451	0.1417	E-4
	4	0.7611	"	0.1486 E16	0.01686	0.4116	E-5
	5	0.4896	"	0.2391 E15	0.01326	0.8091	E-6
	6	0.4175	"	0.5096 E14	0.01336	0.2038	E-6
	7	0.4065	"	0.1240 E14	0.01501	0.5725	E-7
	8	0.2063	"	0.1574 E13	0.00863	0.8233	E-8
	9	0.5509	"	0.1051 E13	0.02577	0.6143	E-8
	10	0.2997	"	0.1429 E12	0.01549	0.9235	E-9
Total		10.9272	"	0.8299 E18	0.17674	0.7875	E-3

Fig. 3 Selected energy spectral terms outside $b=0.5a$ vs time. n is the spherical harmonic degree. Total denotes sum of first 10 degrees.

Fig. 4 Selected average energy density spectral terms at $b=0.5a$. n is the spherical harmonic degree. Total denotes sum of first 10 degrees.

likely be obscured. In an attempt to emphasize the essential characteristics of sources which can cause a reversal, very simple sources were investigated. A single centered dipole was, of course, ruled out as not being physically possible. It was assumed that the sources had to be in the outer core.

Off hand it would seem like a very easy thing to find a simple source which could explain a reversal. Such a source should be capable of producing a value of $F_1^{1/2}$ (see Eq. 1) which is more than seven times as large as $F_2^{1/2}$, and which

Fig. 5 Selected average energy density spectral terms at $b=a$ (Earth's surface). n is the spherical harmonic degree. Total denotes sum of first 10 degrees.

can change in a way that will reduce $F_1^{1/2}$ to a very small value without reducing the total energy of the system appreciably.

Table 2 shows spherical harmonic coefficients normalized so that the first degree coefficients are equal to one for zonal dipoles and current loops using equations given by ALLDREDGE (1980). The examples given are for nearly extreme values of r/a within the outer core. It is seen that no single source such as these can produce by itself as large a ratio of F_1/F_2 as is observed.

Many combinations of dipole sources at a radius of 0.4 Earth's radius were tried but none were found which greatly favored the first degree terms as required by observations. The results were in all cases very much like column two in Table 2.

In trying to produce an outstanding $n=1$ term in the energy spectrum using only a small number of simple sources it was found necessary to use a combination of current loops near the inner-outer core boundary. This idea is consistent with the fact that ALLDREDGE and STEARNS (1969) found it necessary to place their dipoles at about $r=0.2$ Earth's radius to get the best fit to the observed field and the fact that PEDDIE (1979) found that unconstrained current loops with the largest magnetic moments were also very deep, often below the inner-outer core boundary.

Table 2. Normalized spherical harmonic coefficients for single zonal dipoles and current loops.

Dipoles			Current loops for $\theta_1 = 63.435^\circ$ (See Fig. 6)	
Degree				
n	$r/a = 0.5$	$r/a = 0.2$	$r/a = 0.5$	$r/a = 0.2$
1	1.0000	1.0000	1.0000	1.0000
2	1.0000	0.4000	0.4472	0.1789
3	0.7500	0.1200	0.0000	0.0000
4	0.5000	0.0320	-0.0894	-0.0057
5	0.3125	0.0080	-0.0375	-0.0010
6	0.1875	0.0019	0.0034	0.0000

r/a =radius to dipole or current element/Earth's radius.

θ_1 =angle for polar coordinate axis to current element (see Fig. 6).

A particularly simple source system was finally contrived to demonstrate at least one scenario by which a reversal with the "observed characteristics" might be effected. Consider two equal zonal current loops deep in the outer core with their current elements at a radius r from the center of the Earth, one with a central half angle θ_1 , and the other with $\theta_2=180-\theta_1$, (see Fig. 6). The two currents are both in the same direction originally. We can write for the combined normalized SHC of the two loops

$$g_n^0 = \frac{-2}{(n+1) \sin \theta_1} \left(\frac{r}{a} \right)^{n-1} \left[\left(\frac{dp_n^0(\cos \theta_1)}{d\theta_1} \right) + \left(\frac{dp_n^0(\cos \theta_2)}{d\theta_2} \right) \right] \quad (9)$$

{ALLDREDGE, (1980)}.

It can be shown that (9) is zero for all even values of n . This means that only the odd harmonics might prevent the dipole term from being very dominant. However, for odd n , P_n^0 is antisymmetrical about $\theta = 90^\circ$. Therefore, the two derivatives in (9) will have equal amplitudes and will have the same sign so that (9) will not, in general, be zero. However, it is easy to show that for $n=3$ both of the derivatives in (9) are zero if $\theta_1 = 63.435^\circ$ and $\theta_2 = 116.565^\circ$. For $n=1$ (9) gives $g_1^0 = 2.0$ which indicates that the dipole coefficients simply add. The coefficients for other odd values of n greater than $n=3$ will not be zero, but if r/a is small these coefficients will be very small compared to g_1^0 . They will equal twice the values shown in the fourth and fifth columns of Table 2 for the r/a values used there. All the even harmonics will be zero. It is seen that if $r/a = 0.2$ (deep in the outer core), the dipole term will dominate without question.

It is quite obvious, from the foregoing discussion, that if the current in the lower loop is reduced to zero, and $r/a = 0.2$, then the SHC will be those shown in the fifth column of Table 2, showing that the first degree term is reduced to one-half of its former value and the even harmonics have increased greatly. If the current in the lower loop is now allowed to grow to its former amplitude, but in the opposite sense, the dipole term will be reduced to zero

Fig. 6 Geometry of two zonal current loops deep in the outer core with supplementary polar angles.

(the midpoint of a reversal), all of the other odd harmonic terms which were small to begin with will go to zero, and the even harmonic terms will grow to twice those shown in the fifth column in Table 2. The second half of the reversal would be accomplished by having the current reverse in the upper current loop.

The first half of the above scenario is followed in Fig. 7 by tracing some of the energy spectral terms for the energy outside a distance of 0.5 Earth's radii, given by Eq. (2), and the total energy outside this radius, given by Eq. (3), as the normalized magnetic moment of the lower loop goes from 1 to -1 .

In Fig. 7, E_3 is not quite equal to zero for the normalized magnetic moment of the lower loop equal to one because θ_1 was taken as 63.4° instead of 63.435° and θ_2 was taken as 116.6 instead of 116.565 . Figure 8 is like Fig. 7 except it shows the energy outside the surface of the Earth.

Figures 7 and 8 show that for this simple system E_1 predominates before and after a reversal and that the total energy outside $b=0.5$ drops only one order of magnitude before it rebuilds. The top curve in Fig. 7 shows that outside $b=0.25a$ the total energy decreased very little as the current in the lower loop reversed. At the end, the total energy was nearly 55 percent of the starting energy.

Fig. 7 Energy of normalized spectral terms outside 0.5 Earth's radii for two current loops at a radius of 0.2 Earth's radius with polar angles of $\theta_1 = 63.4^\circ$ and $\theta_2 = 116.6^\circ$ (see Fig. 6). The normalized magnetic moment of the two loops start out equal, but the normalized magnetic moment of the lower loop varies from 1 to -1 . $E_{\text{total}}(b=0.5)$ (first 10 harmonics) is also shown. The top curve, $E_{\text{total}}(b=0.25)$, gives the total energy outside $b=0.25$ Earth's radius (first 30 harmonics were included).

Fig. 8 Energy of normalized spectral terms outside the Earth's surface for conditions described in legend for Fig. 7.

The even harmonics keep the energy from dropping very far. Figure 8 compared to Fig. 7 shows that the energy outside the surface of the Earth suffers more, percentage-wise, than the energy outside spheres within the core.

Some of the models discussed by HOFFMAN and FULLER (1978) and DODSON *et al.* (1978) suggest reversal sources somewhat like that discussed here.

5. Discussion and Conclusions

This paper has discussed various criteria that might be used in looking for reversals. The data base used here is too short to make any real predictions. If, however, the apparent linear decrease in the magnetic moment continues it would be zero in about 1200 years. If the apparent linear decrease in the first degree spectral term of the energy outside the Earth continues it will be zero in about 600 years.

The fallacy in these "predictions" is that they both indicate values twice their present values at times in the past equal to the predicted times for zeroes in the future and historically it is known that this was not true.

It is not a simple matter to construct core sources that collectively will result in a dominating dipole field as now exists without using sources very deep in the outer core. It is interesting to note that early work on dipole sources required to match the observed field required sources at about $0.2a$ (ALLDREDGE and STEARNS, 1969). This great depth to the sources is not all attributable to the fact that dipoles were used rather than current loops. PEDDIE (1979) found that unconstrained current loops with the largest magnetic moments were also very

deep, often below the inner and outer core boundary.

In the study reported here it was found that current loops near the inner and outer core boundary were required to produce a dipolar type field on the surface of the Earth. A single current loop with its current elements at $0.2a$ (near the inner and outer core boundary) has too much energy at harmonic numbers above one to match the observed energy spectrum of the energy outside the Earth's surface. To obtain the needed outstanding dipolar pattern, without interfering with higher degree terms, it was necessary to contrive a very special arrangement of two current loops deep in the outer core. A systematic reversal of the currents in these loops was found capable of creating a reversal without any big change in the energy external to the core.

It is not implied, of course, that the energy spectrum given by any vertical slice taken through Fig. 8 should approach the actual energy spectrum even after adding a constant to adjust the general level. For example, other sources farther from the center would be needed to raise E_3 with respect to E_5 so as to approach the observed energy spectrum. Other sources would also be needed to cause the even degree terms which are an essential part of the observed energy spectrum. This should be possible without destroying the outstanding dipolar character of the field far from a transition point so long as the deep current loops which produce Figs. 7 and 8 are allowed to dominate.

The above contrived system is consistent with recent convincing evidence from studies of several reversal transitions which indicate that the field is highly non-dipolar during a transition. Numerous paleomagnetic papers have been published recently on this topic. WILLIAMS and FULLER (1981) developed an axisymmetrical model in which, during a reversal, the dipolar energy was transmitted to higher degree zonal fields. THEYER *et al.* (1985) have concluded that although the Williams-Fuller model may be very helpful more complicated models will be necessary to account for the details of reversals. MERRILL and McELHINNY (1983, p. 164) summarize many of the papers on this topic. A recent new book by JACOBS (1984) should be consulted for further ideas about reversals from paleomagnetic studies and dynamo research.

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