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ATMOSPHERIC RADIOCARBON: IMPLICATIONS FOR THE GEOMAGNETIC DIPOLE MOMENT

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INTRODUCTION

The geomagnetic field is one of the major physical fields of the earth. Because its source is fluid motion in the outer core, it exhibits temporal changes, called secular variation, which are quite rapid compared to most geologic phenomena. The prehistoric secular variation is usually inferred from paleomagnetic data. We will discuss here how changes in the atmospheric ^{14}C content can be used to gain additional insight into the behavior of the dipole moment over the past 8500 years. By rewriting the differential equations representing the ^{14}C geochemical cycle in finite-difference form, we are able to convert the atmospheric ^{14}C activity record into an equivalent radiocarbon dipole moment.

DIPOLE MOMENT AND ^{14}C FLUCTUATIONS

The changing strength of the geomagnetic dipole moment is one of the fundamental modes of secular variation of the recent geomagnetic field. Spherical harmonic analyses of geomagnetic field strength measurements since 1835 reveal a 6% linear decrease of the dipole moment (McDonald and Gunst, 1967). Syntheses of paleomagnetic field strengths (paleointensities) covering the last few millennia (Barton, Merrill, and Barbetti, 1979) show a quasi-sinusoidal oscillation of the dipole moment, subsuming the more recent linear decrease. This oscillation has a period of 8000 to 10,000 years, a mean moment of ca 8×10^{22} Am^2 (equal to present-day value), and maximum moment of ca 12×10^{25} Am^2 occurring 2000 to 2500 years ago. More attention has recently been given to the possibility that dipole moment fluctuations occur with periods less than the long-term 8000 to 10,000-year oscillations. Rapid paleointensity fluctuations on the order of 1000 years or less have been found at several different localities (see Games, 1980). Spectral analysis of dipole moment data by Champion (1980) revealed small concentrations of power at periods of 575,

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750, 950, and 2060 years (besides the predominant periodicity at 8700 years). Burlatskaya et al (1970) found a statistically significant dipole moment periodicity of 1000 years, and possibly significant peaks at 350 and 500 years. Yukutake's (1971) analysis of the magnetic field for the 17th and 18th centuries suggested a dipole moment fluctuation with a characteristic time of ca 350 years.

The nature of the paleointensity experiment, other modes of secular variation, and the poor temporal and spatial distribution of the paleointensity data make it difficult to conclusively infer these shorter periodicities from the paleomagnetic data (Barton, Merrill, and Barbetti, 1979). Holocene paleointensities become increasingly sparse prior to 2500 years BP due to the scarcity of well-dated archaeologic materials and igneous rocks. The geographic distribution of the Holocene data is poor for the entire record. Most of the data are from Europe and Asia; 98% are from the northern hemisphere. The current magnetic field shows an asymmetry between the northern and southern hemispheres (McDonald and Gunst, 1967). It is clearly risky to infer global magnetic field behavior from the primarily northern hemisphere archaeomagnetic data base.

^{14}C is created in the atmosphere when neutrons generated by cosmic ray interactions combine with ^{14}N. The flux of the charged cosmic rays into the atmosphere and the consequent ^{14}C production rate is modulated by the changing strength of the dipole moment (Elsasser, Ney, and Winckler, 1956; Lingenfelter and Ramaty, 1970). Thus, ^{14}C production is a global integrator of the magnetic field. As the production rate changes, ^{14}C activity in the various geochemical reservoirs will exhibit corresponding changes. A detailed 7300-year record of atmospheric activity fluctuations was determined from ca 1200 ^{14}C measurements on dendrochronologically dated tree-ring samples (Klein et al, 1980). This record can be used as a proxy indicator of dipole moment changes. The predominant long-term trend in ^{14}C activity with a peak-to-peak amplitude of ca 90 $^{o}/oo$ and a period of 8000 to 10,000 years is accepted to be due to the dipole moment oscillation with the same characteristic periodicity. Smaller wiggles (Suess, 1970; de Jong, Mook, and Becker, 1979) are superimposed upon this trend. Houtermans (ms) showed amplitude spectra peaks in the ^{14}C data at periods of 1000, 400, and 200 years. The 200-year periodicity has been confirmed by Neftel, Oeschger, and Suess (1981). Although these higher frequency fluctuations are generally assumed due to heliomagnetic modulation of ^{14}C production, there remains the possibility of dipole moment oscillations of similar frequency. Damon, Lerman, and Long (1978) reviewed the general problem of temporal fluctuations of ^{14}C.

RADIOCARBON DIPOLE MOMENT

The relationship between dipole moment changes and ^{14}C activity has been examined by several investigators (see references in Sternberg and Damon, 1979). The general approach has been to model the ^{14}C geochemical cycle as a system of connected reservoirs. There is input to the system through ^{14}C production, loss from the system through radioactive decay, and first-order exchange of ^{14}C between the different reservoirs, or elements, of the system. The model can then be represented by a set of linear differential equations. Model parameters are selected. A sinusoidal dipole moment model consistent with the paleomagnetic data is chosen, and a corresponding production function calculated. Predicted ^{14}C fluctuations are then compared to the activity record.

Libby (1967) explicitly suggested that "the agreement of radiocarbon dates with historical records up to 3500 to 4000 years ago within 1 or 2% places a serious restriction on the types of variation which the earth's effective dipole moment could have undergone." Kigoshi and Hasegawa (1966), Ramaty (1967), and Sternberg and Damon (1979) explored the sensitivity of the predicted ^{14}C activity to different magnetic field models. Nonetheless, the forward modeling problem has only been used (and is most convenient) with dipole moments having the single, characteristic long-term periodicity.

Barton, Merrill, and Barbetti (1979) perceived that the tree-ring record of ^{14}C activity was more complete than the paleointensity data. They assumed that all ^{14}C fluctuations are due to geomagnetic modulation, "and that the production and decay of ^{14}C instantaneously balanced so that the atmospheric concentration varies linearly with production." The shape of their computed radiocarbon dipole moment (RCDM) showed a broad maximum between 1500 and 3000 BP, agreeing with the modeling of Sternberg and Damon (1979) and the compiled paleomagnetic data of Champion (1980). However, both the average RCDM ($\sim 7.5 \times 10^{22}$ Am^2) and the amplitude of the RCDM oscillation ($\sim 0.7 \times 10^{12}$ Am^2) were too low to be consistent with the paleomagnetic data.

We have improved upon the efforts of Barton, Merrill, and Barbetti (1979) by explicitly accounting for the effects of the carbon reservoir system (Sternberg and Damon, 1981). We used a two-box model with sedimentary sink (see Sternberg and Damon, 1979, Fig 2). One box represents the rapidly exchanging ambient reservoirs -- the atmosphere, biosphere, and mixed layer of the ocean. The other box represents the deep-sea. The system is represented by a pair of first-order linear differential equations:

$$\frac{dn_a(t)}{dt} = -(k_{as} + \lambda)\, n_a(t) + k_{sa} n_s(t) + Q(t) \tag{1}$$

$$\frac{dn_s(t)}{dt} = k_{as}\, n_a(t) - (k_{sa} + k_{ds} + \lambda)\, n_s(t), \tag{2}$$

where n_a and n_s are the ^{14}C contents of the ambient and deep-sea reservoirs; Q is the production rate; λ is the radioactive decay constant; and k_{as}, k_{sa}, k_{ds} the first-order exchange rates between the ambient reservoirs and deep-sea, deep-sea and ambient reservoir, and from the deep-sea to the sedimentary sink, respectively.

The forward modeling problem is done by inputting Q(t) and calculating the response, $n_a(t)$ and $n_s(t)$. However, we wish to do the converse. We followed the approach of Stuiver and Quay (1980b), who applied a finite-difference approximation to their linear differential equations to back-calculate the heliomagnetic production rate for 860 years of ^{14}C data. Using first-order backward differences, equations 1 and 2 become

$$\frac{n_a(t) - n_a(t - \Delta t)}{\Delta t} = -(k_{as} + \lambda)n_a(t) + k_{sa} n_s(t) + Q(t) \tag{3}$$

$$\frac{n_s(t) - n_s(t - \Delta t)}{\Delta t} = k_{as}\, n_a(t) - (k_{sa} + k_{ds} + \lambda)\, n_s(t) \tag{4}$$

These equations can be manipulated to obtain

$$n_s(t + \Delta t) = \frac{n_s(t) + k_{as}\, n_a(t + \Delta t)\, \Delta t}{1 + \Delta t\, (k_{sa} + k_{ds} + \lambda)} \tag{5}$$

$$Q(t + \Delta t) = (k_{as} + \lambda + 1/\Delta t)\, n_a(t + \Delta t) - \frac{n_a(t)}{\Delta t} - k_{sa}\, n_s(t + \Delta t). \tag{6}$$

The ^{14}C contents n_a and n_s then can easily be converted to activities.

Klein et al (1980) applied a multistage linear regression technique to derive annual per mil atmospheric activities from the 7300-year tree-ring record. This can be converted to the series $n_a(t)$. Once k_{as} has been selected, equation 5 will generate the time series $n_s(t)$ if $n_s(t=0)$ is known. This initial condition was calculated from equation

2 by assuming steady state. Once the time series $n_s(t)$ was generated, it was used along with $n_a(t)$ in equation 6 to generate the series $Q(t)$. To convert the production into an equivalent dipole moment, M, a relation of the following form was used:

$$Q = CM^{-\alpha} \tag{7}$$

where C is a constant of proportionality and $\alpha \approx 0.5$ (Elsasser, Ney, and Winckler, 1956; Ramaty, 1967). The constant C was calculated to set the dipole moment at AD 1950 to 8.065×10^{22} Am^2, the value given by McDonald and Gunst (1967).

RESULTS AND DISCUSSION

Three independent model parameters must be set. In equations 3 and 4, these are k_{as}, k_{sa}, and k_{ds}. For our initial parameter set, we used the following: $k_{as} = 1/50$ yr^{-1}, $k_{sa} = 1/1250$ yr^{-1}, $k_{ds} = 5 \times 10^{-6}$ yr^{-1}, $\alpha = 0.45$, and $\Delta t = 10$ yr. These values are in accord with others suggested in the literature for the two-box model (eg, Houtermans, Suess, and Oeschger, 1973). They also were successful in predicting a good fit to the ^{14}C data using a sinusoidal dipole moment in the forward problem (Sternberg and Damon, 1979).

The resulting raw RCDM is shown in Figure 1. The anticipated long-term quasi-sinusoidal variation is evident. However, the superimposed high-frequency variations are too large and rapid to represent real geomagnetic behavior. These fluctuations are an artifact of the modeling procedure. The ^{14}C system represented by equations 1 and 2 acts as a low-pass filter, causing this effect.

The amplitude response spectrum for fluctuations of ^{14}C in the atmosphere for the two-box model is show in Figure 2. It is compared with similar spectra for the three-box model, the five-box model, and the box diffusion model (see Damon, Sternberg, and Radnell, 1983). These plots show

$$\frac{n_a(\omega)}{Q(\omega)} \div \frac{n_a(0)}{Q(0)} ,$$

the normalized response (or attenuation) of atmospheric ^{14}C to a harmonic production rate. Changes in the activity of the reservoirs are attenuated relative to changes in the production rate. Because the system is a low-pass filter, high frequencies in the activity data will be amplified in the calculation of the RCDM.

Normalization of the amplitude spectra is by the DC gain (Lazear, Damon, and Sternberg, 1980), which is essentially a scaling factor relating $Q(0)$ to $n_a(0)$. The DC gains for the 3B, 5B, and BD have been adjusted downwards to values of

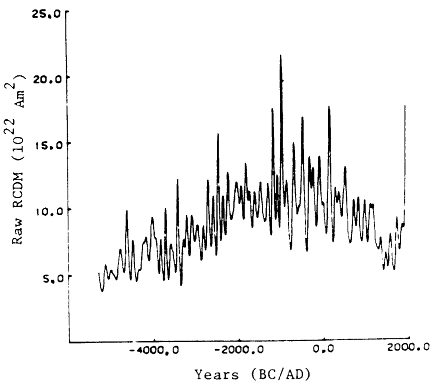

Fig 1. The raw radiocarbon dipole moment vs time. Calculated from the tree-ring activity record using a finite-difference representation of the two-box model.

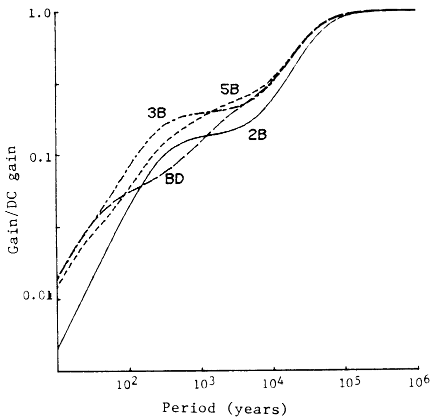

Fig 2. Amplitude spectra of reservoir models for atmospheric ^{14}C fluctuations. 2B, two-box model used in this study; 3B, three-box model; 5B, five-box model; BD, box diffusion model.

111 yr by the addition of sedimentary sinks (Damon, Sternberg, and Radnell, 1983). The DC gain for the two-box model is 352 yr. This is because the two-box model incorporates the mixed layer and biosphere into the ambient reservoir (Houtermans, Suess, and Oeschger, 1973) while the more complex models retain a separate mixed layer.

Much of the higher frequency content of the RCDM either represents noise in the activity data or heliomagnetic modulation. Sunspots are one manifestation of solar activity. Spectral analysis of post-AD 1750 sunspot numbers (Cohen and Lintz, 1974) shows that power is concentrated at a periodicity of 10.9 years corresponding to the well-known sunspot cycle. A smaller spectral peak exists at 110 years, and the longest periodicity of 179 years is due to a beating effect. Longer periodicities cannot be inferred from the extant sunspot record. Considering that the shorter periodicities noted for the dipole moment are $\geq$ 350 years, it may be possible to separate geomagnetic from heliomagnetic (and other high-frequency) effects.

To effect this separation, the raw RCDM was smoothed by convolution with a Gaussian smoothing function. Weights of this filter and the amplitude response have the shape of a normal distribution. The filter weights can be determined by specifying the response at a particular frequency. Furthermore, no phase-shifting is introduced. The filter used was designed to have a response of 10% for a period of 200 years since this periodicity seems to represent a breakpoint between geomagnetic and heliomagnetic effects. Some higher frequency information is inevitably admitted and some

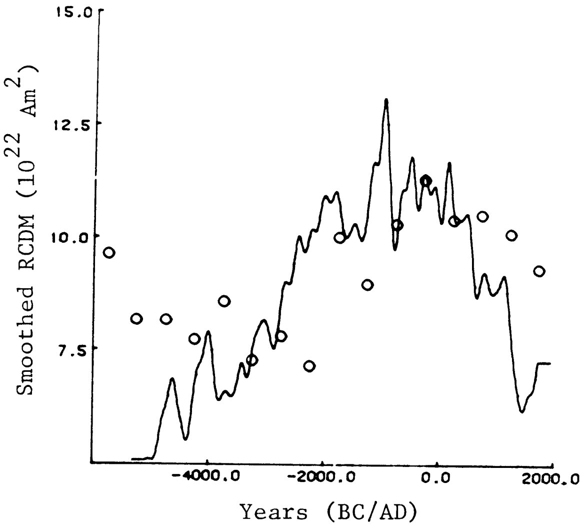

Fig 3. The smoothed ^{14}C dipole moment vs time. The circles are 500-yr averages for the dipole moment from paleomagnetic data (Champion, 1980).

lower frequency information is filtered. The response at periods of 10, 500, 1000 and 10,000 years is 0.01%, 69%, 91% and 99.9%, respectively.

The resulting smoothed RCDM is shown in Figure 3. The long period quasi-sinusoid is still evident, with an average moment of ca 9 x 10^{22} Am^2, an amplitude of 3 x 10^{22} Am^2, and a broad maximum lasting from ca AD 200 to 1100 BC. This is different than the earlier paleomagnetic syntheses which placed the dipole maximum early in AD times. However, Sternberg and Damon (1979) concluded from forward modeling that a sinusoidal dipole moment model should peak closer to 500 BC. This conclusion is also consistent with the recent paleomagnetic summary of Champion (1980). His 500-year interval average dipole moments are plotted as circles in Figure 3. These data show the peak dipole moment occurring at 300 BC.

The smoothed RCDM agrees quite well with the paleomagnetic data between 3000 BC and AD 1 with the exception of two points. However, the paleomagnetic results are consistently higher during the intervals 6000 to 4000 BC and AD 500 to 1900. There are three possible reasons for these discrepancies. First, the paleomagnetic results may not properly reflect the dipole moment due to their poor geographic distribution and their sparseness prior to 500 BC. The strength of the magnetic field is currently stronger in the northern hemisphere than at corresponding latitudes in the southern hemisphere (McDonald and Gunst, 1967). Since most archaeomagnetic data are from the northern hemisphere, this is in the right sense to account for the discrepancies.

A second possible problem is with the modeling. This could result from using an oversimplified model or from incorrect parameterization of the model. Figure 2 shows that there are differences in the amplitude spectra for the periodicities of interest, 10^2 to 10^4 years. Thus, these models as parameterized are not completely compatible with one another. Also, the two-box model parameters were assumed to be constant. However, reservoir sizes and exchange rates could vary over time in response to climatic change. These effects have probably been minor since the transition to the Holocene (Damon, 1970; Siegenthaler, Heimann, and Oeschger, 1980; Stuiver and Quay, 1980a), but might be significant for the calculations ca 7500 BP.

A third possible cause for the discrepancies between the RCDM and the paleomagnetic data is the choice of a proper filter. The final frequency content of the smoothed RCDM depends on the response functions of both the model and the filter. While the filter used was designed in accord with the general spectra of geomagnetic and heliomagnetic fluctuations, the final choice of response function and filter weights was somewhat arbitrary. Also, longer records of heliomagnetic activity might reveal lower frequencies that would overlap with geomagnetic frequencies.

In conclusion, the radiocarbon dipole moment successfully reflects the general pattern of recent variation of the dipole moment. The RCDM complements the paleomagnetic data, and may allow inferences to be made on north-south asymmetry of the magnetic field or variations of the reservoir parameters over time. Our future work will concentrate on refinement of the modeling (different parameter sets and more complex models) and further investigation of the nature of the discrepancies between the RCDM and the paleomagnetic data. We will also extend the RCDM back to 8550 BP, based on new ^{14}C measurements of older bristlecone pine samples.

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