GEOMAGNETIC-HELIOMAGNETIC MODULATION OF ATMOSPHERIC RADIOCARBON PRODUCTION

PAUL E DAMON and TIMOTHY W LINICK

Laboratory of Isotope Geochemistry, Department of Geosciences
University of Arizona, Tucson, Arizona 85721

ABSTRACT. New Arizona high precision $\Delta^{14}C$ data back to 6500 BC plot close to an 11,300-yr period sinusoid extrapolated from the post 5300 BC data (offset = +32‰, half amplitude = 51‰ and phase lag = 2.29 radians). The trend curve is modulated by high latitude components of the non-dipole field with a fundamental period of 2400 yr. Based upon a model of Lund and Banerjee (1985), the non-dipole field rotates and every 1200 yr the high latitude maxima pass over the north magnetic pole and near the south magnetic pole in reversed polarity. This modulates cosmic ray production producing extended maxima ca AD 1700, 700 BC, 3100 BC, and 5500 BC. The 2400 period appears to be stationary. The magnetic field also modulates the amplitude of the solar activity induced cycles of periods 200, 80, and 11 yr as can be seen in the Zürich-Bern Camp Century ice core data as well as in the $\Delta^{14}C$ fluctuation data. Reinterpretation of the Camp Century ^{10}Be data indicates that it is in agreement with magnetic field as well as solar activity modulation of terrestrial radioisotope production.

INTRODUCTION

At the time of the Twelfth Nobel Symposium, 16 years ago, three major causes of atmospheric ^{14}C fluctuations were identified and discussed (Olsson, 1970). These were astrophysical effects, in particular, solar modulation of the ^{14}C production rate, geophysical effects, specifically changes in the earth's magnetic field, and climate effects involving changes in carbon reservoir parameters and exchange rates.

Recent reviews of archaeomagnetic and rock magnetic data suggest an increase of the virtual axial dipole moment (VADM) by ca 60% from ca 5500 to 2300 BP followed by a decrease to the present value of close to 8.0×10^{22} Am^2 (Barton, Merrill & Barbetti, 1979; Champion, 1980). Magnetic data prior to 5500 BP are scarce, mainly limited to Japan and Europe, and do not definitively support the alleged sinusoidal variation of the dipole field (Barton, Merrill & Barbetti, 1979). In addition to changes in the dipole field intensity, the magnetic data are affected by dipole wobble, changes in intensity of the nondipole field and the westward drift of the nondipole field. During the last century, the main nondipole centers have moved to the west by ca 0.18°/yr on the average according to Strangway (1970) and, more recently, 0.15°/yr according to Lund and Banerjee (1985).

Secular variations of atmospheric ^{14}C concentration with a time scale of decades to a few centuries and amplitudes up to 2% were first reported by de Vries (1958, 1959). These secular variations, called the "de Vries effect" by Damon and Long (1962), have been amply confirmed (see Damon, Lerman & Long, 1978, for documentation). Stuiver (1961, 1965) was the first to show a convincing relationship between the de Vries effect fluctuations and solar activity and subsequent work has served only to confirm his conclusions (Damon, Lerman & Long, 1978). Indeed, ^{14}C is produced by secondary neutrons resulting from cosmic ray induced spallation and it is well known that solar activity modulates the cosmic ray intensities reaching the earth (Lingenfelter & Ramaty, 1970) and so there can be no doubt that ^{14}C production varies with solar activity.

The influence of climate on the ^{14}C concentration has often been discussed, most recently and quantitatively by Siegenthaler, Heimann and Oeschger (1980). These authors demonstrate that purely physico-chemical effects such as changes in the volume and surface temperature of the oceans are not significant. This conclusion was previously reached by Damon (1970). Siegenthaler, Heimann and Oeschger (1980) point out that biologic effects, such as may have occurred during major climatic fluctuations like transition from glacial to interglacial climates, may have been more important. Biologic changes must be drastic and occur over a short period of time to produce measurable effects. For example, they demonstrate that a doubling of the biopshere from 50 to 100% of its present size would result in an increase in Δ^{14}C from 0.4% to 1% if the biosphere grew linearly during 500 yr but would increase to 2% if the change took place within 100 years. Drastic changes in the atmosphere-ocean CO_2 exchange flux or in ocean circulation would also measurably change the concentration of atmospheric ^{14}C. For example, they suggest that a 20% increase in the worldwide wind velocity over the ocean would increase the CO_2 transfer velocity by 50% implying a decrease of 2% in atmospheric ^{14}C concentration. A change in the global formation of deep ocean water represented by a decrease or increase of eddy diffusion by a factor of two would lead to an atmospheric ^{14}C change by +10.4% or −5.5%, respectively. Siegenthaler, Heimann and Oeschger (1980, p 190) conclude "it appears improbable that the observed ^{14}C wiggles (de Vries effect) could have been caused by fluctuating exchange rates."

SECULAR VARIATIONS OF ATMOSPHERIC RADIOCARBON DURING THE LAST SEVEN MILLENNIA

Prior to the Tenth International Radiocarbon Conference held in August 1979, there were 1200 measurements on dendrochronologically dated tree-ring samples, principally *Pinus longaeva* and *Sequoia gigantea* (bristlecone pine and giant sequoia) from the southwestern United States (Klein *et al,* 1980). A data set comprised of these 1200 measurements was detrended by logarithmic compression and polynomial regression. After the data were detrended, the residuals of the data around the trend were analyzed by a Fourier regression technique in overlapping intervals of 500 yr. The data were then winsorized, welded, and recombined with the trend to form a ^{14}C fluctuation curve. The effectiveness of the Fourier regression to retrieve real signals from a noisy data set was then tested against artificial data as well as the two sets of high precision data then available in the literature (de Jong, Mook & Becker, 1979; Stuiver & Quay, 1980). The results verified the remarkable effectiveness of the method. Additional high precision results have been reported but are not yet available (Pearson & Baillie, 1983; Pearson, Pilcher & Baillie, 1983).

The signal retrieved from the 1200 analyses and reported by Klein *et al* (1980) is plotted in Figure 1. The parameters of the sinusoidal trend curve are offset = 32‰, half amplitude = 51‰, period = 11,300 yr and phase lag = 2.29 radians (131.1°). This period and amplitude are identical to that reported by Bruns *et al* (1983) based on La Jolla ^{14}C dating of dendrochron-
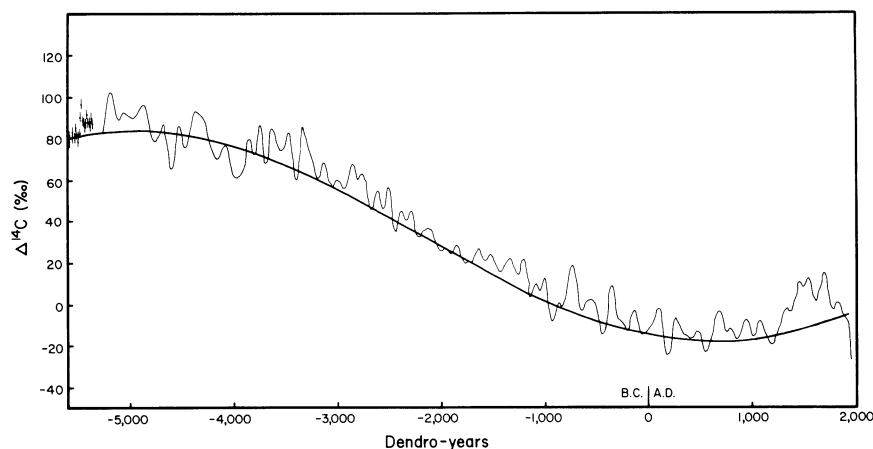
Fig 1. ^{14}C fluctuation curve based on 1200 measurements of dendrochronologically-dated tree rings from laboratories reported in Damon *et al* (1980); Klein *et al* (1980). The trend curve is an 11,300 yr sinusoid. Note the ca 200-yr period de Vries effect (Suess wiggles) resulting from solar modulation. A 2400-yr period is expressed by extended maxima following the minimum at AD 1100 to present, 800 BC to AD 100, and 3800 BC to 2800 BC.

ologically-dated bristlecone pine and a floating European oak series. The Maunder minimum (^{14}C maximum) can be seen at AD 1700, the Spörer minimum at AD 1500, and the Wolf minimum at AD 1300. These peaks are beautifully resolved in the high-precision data of Stuiver and Quay (1980). It is noteworthy that the Spörer minimum is further split by two peaks of lower amplitude 80 yr apart. The minima are each 200 yr apart. A 150–200–yr periodicity was first reported by Willis, Tauber and Münnich (1960) for variations over the past 1300 yr and Damon, Long and Grey (1966) suggested a periodicity of 200 yr. However, it was only through the persistent efforts of Hans Suess over several decades that this periodicity has been clearly demonstrated and extended over the last seven millennia (Suess, 1980). The persistence of this ca 200-yr periodicity has been shown to extend over the entire 8500-yr La Jolla record by Sonett (1984). We have used the Burg maximum entropy method (Burg, 1975) to search for higher frequencies in the MEM power spectra of the composite data set. Periodicities of 80 and 100 yr persist with a lag of 200 and prediction error filters (PEF) of 25, 75, and 100 as well as with a lag of 400 and PEF of 25, 50, and 100. The 80-yr periodicity is identical with the 80-yr solar cycle in auroral frequency numbers observed by Gleissberg (1965). The Fourier power spectrum of the oxygen isotope record from Camp Century ice shows dominant frequencies of 78 and 181 yr (Johnsen, Dansgaard & Clausen, 1970).

Houtermans (1971) developed a technique for calculating the Fourier power spectrum of unequally spaced data and employed the method on the La Jolla ^{14}C data covering the last seven millennia. He found significant periodicities at 2350 ± 100 yr, 1300 ± 35 yr, 420 ± 15 yr, and 210 ± 10 yr. Wallick, working in this laboratory, used the Blackman-Tukey method on

the same data set and obtained significant periodicities at 2320 yr, 1160 yr, 540 yr, 250 yr, and 200 yr. Less significant peaks were observed at 410 yr, 180 yr, and 100 yr. A very strong 2400-yr peak is also observed in the composite data set discussed earlier. Sonett (1984) has also shown that the 200-yr periodicity in the La Jolla data persists over the 8500-yr La Jolla record and appears to be associated with an intense longer period, 2080^{+680}_{-410}. Although Sonett makes little of it, the most intense short period peak ($>100 < 400$) in the MEM derived spectrum is 180 yr. Sonett also confirms the lack of stationarity in the medium to short period spectra (100–500–yr period; see also Damon, 1977, Table 5, p 439).

Some of these periods have also been observed in other than ^{14}C data. For example, Cohen and Lintz (1974) find evidence for periodicities of 179, 89.6, 11.2, and 9.8 yr in the sunspot data from AD 1793–1971 with the 179-yr period being a beat phenomenon rather than primary excitation. In addition to the periodicities of 78 yr and 181 yr, previously mentioned, Dansgaard *et al* (1971) find evidence for a persistent period of ca 350 yr in the Greenland ice core oxygen record for the last ten millennia and a significant periodicity of ca 2000 yr back to 45,000 BP. Finally, Lund and Banerjee (1985) find evidence for a fundamental wave length of 2400 yr with harmonics at 1200, 800, and 600 yr for secular variation of the last Quaternary paleomagnetic field. According to Lund and Banerjee (1985, p 821), "the fundamental wavelength of 2,400 years is very noteworthy because that is the estimated time for the nondipole field to rotate 360° due to westward drift."

Our analysis (Fig 1) indicates large positive deviations of Δ^{14}C ca AD 1700, 700 BC, and 3300 BC. These positive fluctuations are also observable in the longer La Jolla data set including south German oak samples and also ca 5500 BC. It seems that it is no coincidence that these major past deviations from the trend curve occur every ca 2400 yr. Allowing for the appropriate lag time between magnetic minimum and ^{14}C maximum of 230 yr (Siegenthaler, Heimann & Oeschger, 1980; Damon, Sternberg & Radnell, 1983), the dipole and major nondipole would have been in anticoincidence at AD 1470, 930 BC, 3330 BC, and 5730 BC.

SIMULATION OF THE RADIOCARBON FLUCTUATION CURVE

In order to simulate the Δ^{14}C variations around the 11,300-yr sinusoidal trend curve and demonstrate the effect of modulation by the earth's magnetic field, we have chosen the nondipole paleomagnetic drift period of 2400 yr and harmonics. We have also chosen solar periods of 200 yr, 80 yr, and 11 yr, and assumed that their amplitudes are modulated by an 11,300-yr dipole magnetic field plus the westward drifting major nondipole field components (Lingenfelter & Ramaty, 1970; Damon, 1977). The resulting equation has the form:

$$\Delta^{14}C(\text{‰}) = A_{i=0} + \sum_{i} [A_i \sin (\omega_i t - \zeta_i)]$$

$$+ \sum_{j,k} [(A_j + A_k \sin (\omega_k t - \zeta_k)) \sin (\omega_j t - \zeta_j)] \quad (1)$$

where the A_i, ω_i, and ζ_i refer to the amplitudes, frequencies and phase lags of the magnetic components; the A_j, ω_j and ζ_j are the corresponding values for the solar periodicities whose amplitudes, A_j, are also modulated with an amplitude of A_k by the magnetic field variations. The data are shown in Table 1.

Figure 2 presents the results of the evaluation of Eq 1 from AD 1820 to 5300 BC. Large, extended, positive deviations of $\Delta^{14}C$ occur ca AD 1700, 700 BC, and 3300 BC, as expected, despite the strong attenuation by the high magnetic dipole field assumed to peak at 300 BC. However, the solar activity induced peaks (SAIP) are subdued on either side of the early BC maximum in both the smoothed data curve and in the simulated data as anticipated by the high intensity of the dipole field. The SAIP are not subdued on the early BC side of the 3100 BC maximum as a predicted result of the lower dipole magnetic field (in both figures). Also average values remain below the 11,300-yr trend curve from 3800–4800 BC in both figures, again in agreement with the drifting 2400-yr magnetic cycle. These features can also be seen very clearly in the spline-fitted data of Bruns *et al* (1983, Fig 1). The simulated data nicely reproduce the Medieval Warm Epoch minimum at AD 1100 and the $\Delta^{14}C$ maxima at the Wolf, Spörer and Maunder minima. Furthermore, the reality of the ca 200-yr periodicity in the smoothed data set is evidenced by the near coincidence of major ca 200 year period maxima and minima in the two figures with a few exceptions where significant phase shifts occur. Exceptions can be seen at 900 BC, 2700 BC, and 3700 BC.

TABLE 1

Parameters used in simulating the $\Delta^{14}C$ (‰) atmospheric fluctuation curve

Period (T_i) (yr)	Frequencies (degrees/yr)			Amplitude (‰)			Phase lags (degrees)		
	ω_i	ω_j	ω_k	A_i	A_j	A_k	ζ_i	ζ_j	ζ_k
Steady State				37.0					
11,300	0.03186			46.0	0.0	0.0	+131.1		
2,400	0.1500			7.0	0.0	0.0	− 52.5		
1,200	0.3000			3.6	0.0	0.0	− 15.0		
800	0.4500			1.8	0.0	0.0	+202.5		
600	0.6000			1.0	0.0	0.0	+240.0		
11		32.7273		0.0	1.0	0.0		+2528.0	
$(200)_j$ $(11,300)_k$		1.8000	0.03186	0.0	9.0	3.0		+ 360.0	+161.7
$(200)_j$ $(2,400)_k$		1.8000	0.1500	0.0	9.0	1.5		+ 360.0	− 18.6
$(200)_j$ $(1,200)_k$		1.8000	0.3000	0.0	9.0	0.5		+ 360.0	+ 7.8
$(80)_j$ $(11,300)_k$		4.5000	0.03186	0.0	5.0	1.5		+1035.0	+162.7
$(80)_j$ $(2,400)_k$		4.5000	0.1500	0.0	5.0	0.75		+1035.0	− 13.6

[Where not given, magnetic modulation terms are assumed to be neglible]
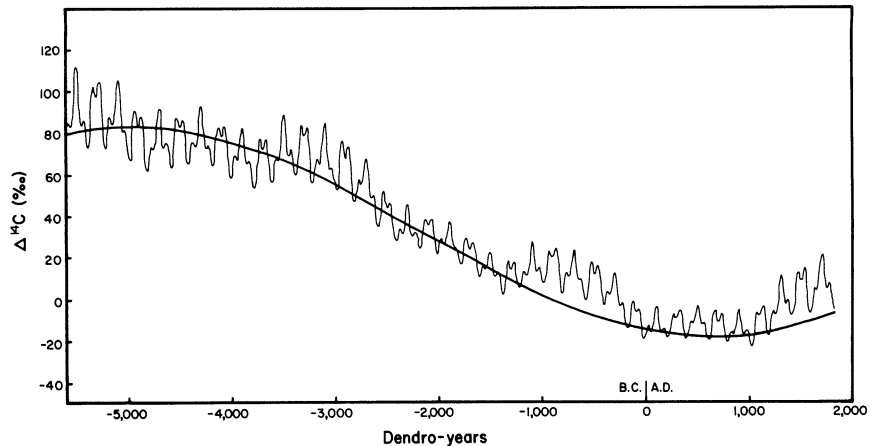
Fig 2. Simulation of the ^{14}C fluctuation curve by solar cycles of 200 and 80-yr periods and magnetic cycles of 11,300 yr for the earth's magnetic dipole moment and 2400 yr plus weak harmonics (1200, 800, and 600 yr) by the non-dipole field. The magnetic components also modulate the amplitude of the solar cycles to produce larger solar cycle fluctuations when the dipole and non-dipole field are less intense and a dampening effect when the magnetic components are more intense. The dampening effect can be seen on either side of the 2400-yr extended maximum of Δ^{14}C (1100–200 BC) where both the dipole and non-dipole field are more intense. The Medieval Warm Epoch minimum occurs at AD 1100 and the Wolf, Spörer and Maunder minima (Δ^{14}C maxima) occur at AD 1300, AD 1500, and AD 1700. The Spörer minimum peak is split by the 80-yr cycle (*cf* Fig 1).

Figure 3 extends the simulated data to 8000 BC to show the postulated maxima ca 5500 BC and 7900 BC, and Figure 4 detrends the data to show the 2400, 1200, 200 and 80-yr modulation of the trend. Detrended data sets show a similar, but not as symmetric, pattern (Klein *et al*, 1980, Fig 2; Suess, 1980, Fig 1). In addition to measurement error, the non-regularity could result from non-stationarity of the higher harmonics of the westward paleomagnetic drift. The 2400 fundamental period appears to be stationary.
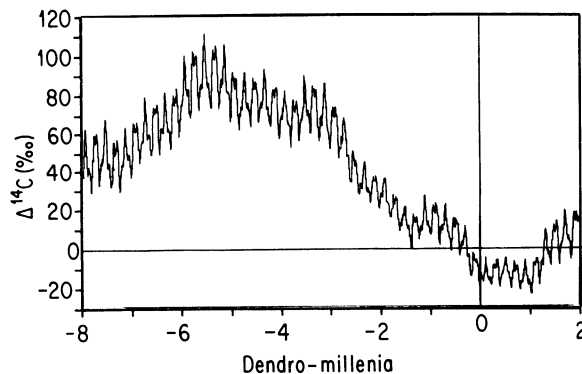
Fig 3. The simulated Δ^{14}C is extended to 8000 BC. The simulation predicts another extended maximum from 5800 BC–5100 BC if the 2400-yr non-dipole cycle is stationary.
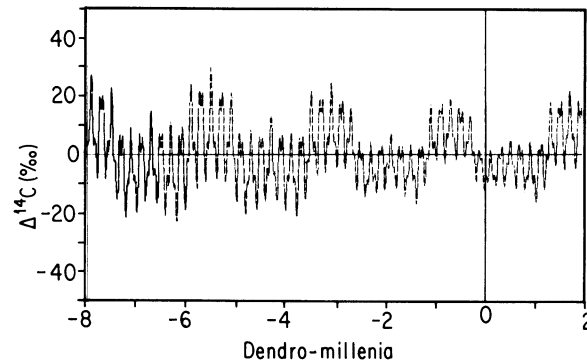
Fig 4. The simulated curve after the removal of the 11,300-yr period trend shown here probably overstates the symmetry because the 1200-yr non-dipole harmonic is made to maximize simultaneously with every maximum and minimum of the 2400-yr fundamental frequency. Fourier spectral analysis suggests that the harmonics are less stable than the fundamental 2400-yr period.

ARIZONA HIGH-PRECISION DATA BEYOND 5350 BC

Figure 5 shows our high-precision data for early BC time. The data lie symmetrically around the extension of the 11,300-yr sinusoid as previously indicated by Bruns *et al* (1983) for the south German oak data. An extended maximum occurs at 5500 BC as predicted from the 2400-yr westward paleomagnetic drift. This extended maximum can also be seen in the south German oak data of Bruns *et al* (1983, Fig 1). An extended minimum can be seen from 6900–6400 BC in the south German oak data of Bruns *et al,* which corresponds to the predicted minimum of the 2400-yr cycle.

Between 6175 and 6550 BC the major minima are ca 200 yr apart, but
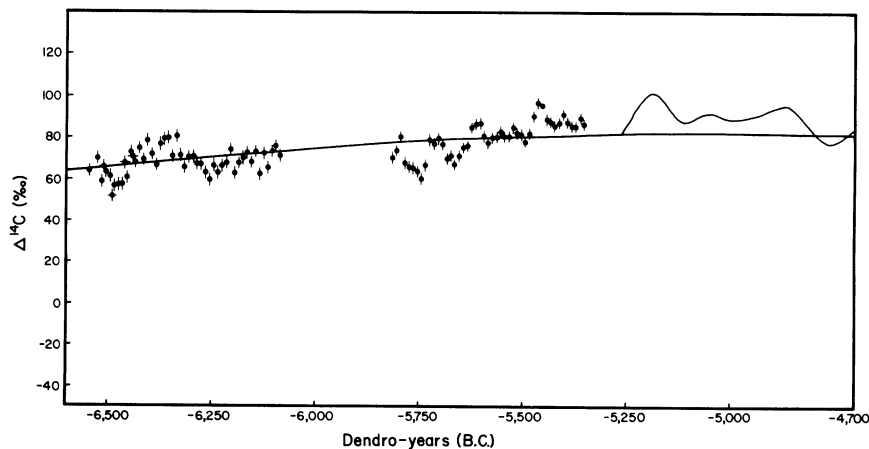
Fig 5. The 11,300-yr period trend curve based on younger data is extended to 6600 BC. Note that the new Arizona high precision data falls around the extended trend curve. The minima at 6450 and 6250 BC are 100 yr apart but maxima and minima are closer to 125 yr apart between 5800 and 5350 BC. The 200-yr solar cycle appears to be non-stationary during the 6th millennium BC.

maxima and minima average closer to 125 yr apart between 5350 and 5825 BC suggesting non-stationarity in this time period.

RADIOCARBON DIPOLE AND NON-DIPOLE MODULATION OF ^{14}C PRODUCTION

There seems to be excellent agreement concerning the reality of solar activity modulation of the concentration of atmospheric ^{14}C both from the tree ring ^{14}C data and ice core ^{10}Be data (Beer *et al*, 1984). However, Beer *et al* reach the conclusion that

> the absence of a clear long term trend in the ^{10}Be concentrations measured in the Camp Century ice core indicates that there has not been a change in the geomagnetic dipole moment large enough to significantly affect atmospheric radioisotope production rates during the last 4,000 years.

We disagree and will now reinterpret the ^{10}Be ice core data to show that the magnetic field has changed as predicted from the secular variation of ^{14}C.

First, the relationship between ^{14}C production as a function of time, Q(t) is non-linearly related to the geomagnetic dipole moment, M(t) (Elsasser, 1956).

$$Q(t) \propto M(t)^{-\alpha} \qquad (2)$$

where $\alpha = 0.52$. Sternberg and Damon (1979, Fig 12) show that, as a consequence of this non-linear relationship, a decrease in the intensity of the dipole moment has a much greater effect on Q(t) than a corresponding increase. The variation of M(t) required to produce the Δ^{14}C trend curve (Fig 1) is shown in Figure 6C. A 21% increase is required in M(t) between 2500 and 300 BC to produce the required 12% decrease in production rate, Q(t). This production rate change has been transferred also to Figure 6B, which is modified from Figure 3 of Beer *et al* (1984). They chose as an initial condition "a steady state ^{14}C production rate defined by the mean value during the first 1000 yr of the ^{10}Be record." Thus, their simulated curve would only show the effect of the magnetic field following the termination of the steady state at 2500 BC and would not require the long time lag which would be a consequence of a higher dipole moment in the past. They assume an attentuation factor of 4 in Δ^{14}C which we accept. Thus, we would expect a decrease in Δ^{14}C of 30‰ compared to 25‰ from Figure 6B.

Next, we consider the effect of the non-dipole magnetic field which appears to have been nearly stationary (*ie*, constant period and no phase shift) during the past eight millennia from its effect on the Δ^{14}C fluctuation data. From the Δ^{14}C date, the non-dipole field should have been a minimum at ca AD 1700 which corresponds to a large 200-yr period Maunder minimum solar peak in both Figures 1 and 6B. The SAIP is surrounded by an extended maximum in both figures. Figure 6A is deduced from Figure 4-4 of Strangway (1970) which shows the vertical component of the non-dipole field for 1945. Most important for modulation of cosmogenic isotope production are the high latitude components of opposite sign centered around 340° in both hemispheres that now oppose the dipole moment. Other components are globally distributed at low to mid-latitude in such a way as to have a smaller effect on cosmogenic isotope production. We have assumed that the 2400-yr period non-dipole field has repeated
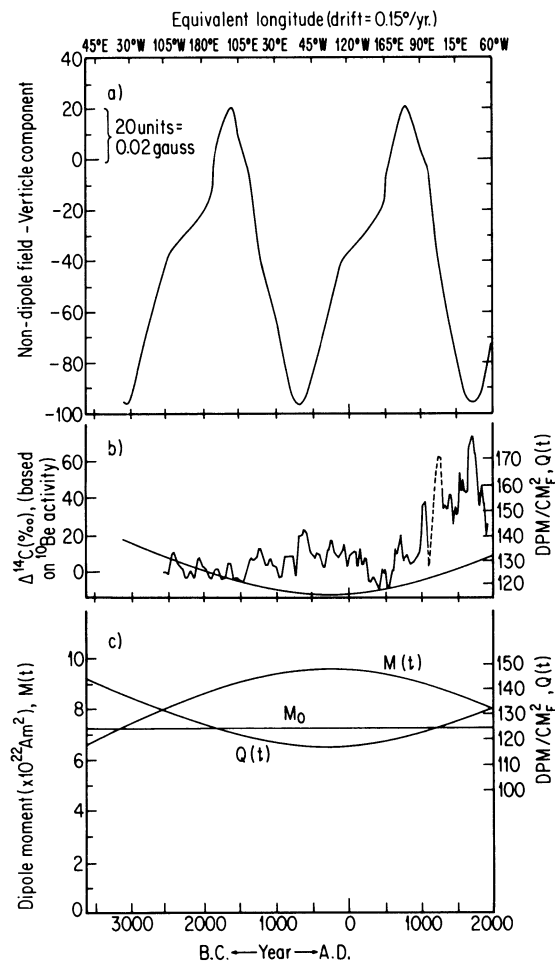
Fig 6. Reinterpretation of the [10]Be data from the Camp Century ice core (Beer *et al*, 1984) showing that [10]Be production is strongly modulated by the earth's magnetic field.

A. The vertical component of the high northern latitude non-dipole field which is now centered over eastern Greenland with opposite polarity to the magnetic pole. When assumed to precess around the North Pole at the same latitude and at the rate of 0.15°/yr westward drift (period of 2400 yr), it opposes and supports the north magnetic pole every 1200 yr. It would be in maximum opposition at Camp Century near the north magnetic pole at ca 700 BC and AD 1700 causing the extended maxima of [10]Be production between 1400 BC–AD 300 and AD 1200–present.

B. The postulated Δ^{14}C (‰) variation of Beer *et al* (1984) based on the [10]Be concentration in Camp Century ice. We have obtained the production rate (right ordinate) from the ^{14}C production based on the sinusoidal magnetic dipole moment required to generate the 11,300 yr ^{14}C cycle and the present dipole moment intensity. The production rate is strictly applicable only to the dipole field, but, fortuitously 170 dpm/cm²$_E$ is about the production rate required by Stuiver and Quay (1980) at zero sunspot number. The dipole component is of secondary importance to the non-dipole and solar components from 2500 BC–present. Beer *et al* (1984) assumed no pre-2500 BC magnetic field variation and a steady-state magnetic field during the first 1000 yr of the [10]Be record to generate the Δ^{14}C curve, and, consequently, their simulated Δ^{14}C curve based on [10]Be variations would not show the long delay (ca 1200 yr) observed in the directly determined Δ^{14}C data. For this reason, we do not include a time lag in modeling Δ^{14}C.

itself by rotating westward at the rate of 0.15° per year around the pole according to this model of Lund and Banerjee (1985). The minimum of the vertical component of the non-dipole field occurs at 770 BC and it is negative opposing the dipole field from 1400 BC to AD 600, producing the Δ^{14}C and ^{10}Be increase during that time. The non-dipole field opposes the dipole field again from AD 1100 to the present, suggesting a causal relationship to the extended maximum around the Wolf through Maunder minima. The minimum of the non-dipole field is reached at AD 1730, suggesting that it will continue to decrease into post modern time contributing to the Suess (1955) effect and requiring caution in evaluating the fossil CO_2 contribution to the Suess effect. We conclude that both the solar modulation and magnetic field effects are present in both the Δ^{14}C data from tree rings and the ^{10}Be data from the Camp Century ice core.

CONCLUSIONS

We have simulated the ^{14}C fluctuation assuming solar modulation with a period of 200 yr and two high frequency components. The results are in accord with the conclusion of Suess (1980) concerning the existence of this solar modulation period and it seems to be nearly stationary during the last seven millennia BP but may be non-stationary in the eighth millennia BP. We have also confirmed the conclusion of Bruns *et al* (1983) that the 11,300-yr period trend line continues to 6500 BC. We have assumed that this trend is the result of a nearly sinusoidal change in the earth's magnetic dipole moment during the Holocene and is modulated by a strong, stationary fundamental non-dipole component of the 2400-yr period with less significant harmonics at periods of 1200, 800, and 600 years. The magnetic components, in turn, modulate the amplitude of the solar components which probably account for the failure of the Fourier power spectra to verify the 200-yr period between 3300 and 1000 BC. The following observations tend to support the reality of magnetic modulation:

1) Although some changes in the reservoir parameters, such as changes in ocean circulation, can produce an effect of equivalent magnitude, it is difficult to conceive of a sinusoidal effect other than that produced by a uniform process such as the oscillating magnetic dipole field.

2) Both the simulated Δ^{14}C curve and smoothed Δ^{14}C data confirm the modulation effect on solar cycles caused by the oscillating magnetic dipole. The amplitude of the de Vries effect (Suess wiggles) from 2600 to 1200 BC is relatively subdued, indicating modulation by the strong dipole magnetic field; but the effect is obscured in the first millennia BC by the non-dipole field being superimposed on the magnetic pole but 180° out of phase.

3) The 2400-yr non-dipole component of the magnetic field strongly modulates the Δ^{14}C trend curve and, from its effect on ^{14}C production, appears to be stationary.

4) The 2400-yr non-dipole component also strongly modulates the production of ^{10}Be as evidenced by a clear signal in the Camp Century ice core.

5) The predicted effect of the earth's magnetic dipole on ^{10}Be produc-

tion from 2500 BC to the present is small and compatible with the trend of the ^{10}Be data from the Camp Century ice core.

The magnitude of the effect on isotope production of the 2400-yr period high latitude components of the non-dipole field seems, at first sight, to be surprisingly large, but we observe that every 1200 yr they coincide with the magnetic pole and modulate the field at the north pole by $+.02$ and -0.10 gauss and at high southern hemisphere latitudes by -0.1 and $+0.17$ gauss. The field at the north pole would be ca 0.68 gauss if the non-dipole component was zero. Thus, the effect is -15% and $+3\%$ of the dipole field intensity and sufficient to produce the observed effect.

Einstein is reported to have said that "God does not lie and is not a practical joker." We conclude that, if the postulated dipole and non-dipole modulation are not real, the practical joke is on us.

Note added in proof:

During the conference in Trondheim Beer *et al* (1986) extended the comparison of the ^{10}Be in ice cores with ^{14}C in tree rings back to the early Holocene. The extended ^{10}Be data appeared to be compatible with the ^{14}C data back to 7000 BC and with the shielding effect of the earth's magnetic field.

Kromer *et al* (1986) presented data indicating an increase in Δ^{14}C prior to 7000 BC which does not follow the previous 11,300 yr sinusoid. Such a deviation from the sinusoidal relationship is not surprising considering the drastically different climate that prevailed in pre-Holocene time. On the contrary, it would be surprising if there were no Pleistocene climate effect on Δ^{14}C.

ACKNOWLEDGMENTS

REFERENCES

Barton, C E, Merrill, R T and Barbetti, M, 1979, Intensity of the Earth's magnetic field over the last 10,000 years: Physics Earth & Planetary Interiors, v 20, p 96–110.
Beer, J, Andrée, M, Oeschger, H, Siegenthaler, U, Bonani, G, Hofmann, H, Morenzoni, E, Nessi, M, Suter, M, Wölfli, W, Finkel, R and Langway, C, Jr, 1984, The Camp Century ^{10}Be record: implications for long-term variations of the geomagnetic dipole moment: Nuclear Instruments & Methods Phys Research Sec B, v 233, no. 2, p 380–384.
Beer, J, Oeschger, H, Siegenthaler, U, Finkel, R C, Bonani, G, Hofmann, H J, Morenzoni, E, Nessi, M, Suter, M, Wölfli, W and Langway, C C, Jr, 1986, The history of solar modulation of radioisotope production in the atmosphere: a comparison of ^{10}Be and ^{14}C records, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 12th, Proc: Radiocarbon, this issue.
Bruns, M, Rhein, M, Linick, T W and Suess, H E, 1983, The atmospheric ^{14}C level in the 7th millennium BC, *in* Mook, W G and Waterbolk, H T, eds, ^{14}C and archaeology: PACT, Strasbourg, v 8, p 511–516.

Burg, J P (ms), 1975, Maximum entropy spectral analysis: PhD dissert, Stanford Univ, Stanford, California.

Champion, D E (ms), 1980, Holocene geomagnetic secular variation in the western United States: PhD dissert, California Inst Technol.

Cohen, T J and Lintz, P R, 1974, Long term periodicities in the sunspot cycle: Nature, v 250, p 398–400.

Damon, P E, 1970, Climatic versus magnetic perturbation of the atmospheric C 14 reservoir, *in* Olsson, I U, ed, Radiocarbon variations and absolute chronology: Nobel symposium, 12th, Proc: New York, John Wiley & Sons, p 571–593.

———— 1977, Variations in energetic particle flux at earth due to solar activity, *in* White, O R, ed, The solar output and its variations: Boulder, Colorado Assoc Univ Press, p 429–448.

Damon, P E, Lerman, J C and Long, A, 1978, Temporal fluctuations of atmospheric ^{14}C: causal factors and implications: Ann Rev Earth Planetary Sci, v 6, p 457–494.

Damon, P E, Lerman, J C, Long, A, Bannister, B, Klein, J and Linick, T, 1980, Report on the Workshop on the Calibration of the Radiocarbon Dating Time Scale, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 3, p 947–949.

Damon, P E and Long, A, 1962, Arizona radiocarbon dates III: Radiocarbon, v 4, p 239–249.

Damon, P E, Long, A and Grey, D C, 1966, Fluctuation of atmospheric C^{14} during the last six millennia: Jour Geophys Research, v 71, p 1055–1063.

Damon, P E, Sternberg, R S and Radnell, C J, 1983, Modeling of atmospheric radiocarbon fluctuations for the past three centuries, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 11th, Proc: Radiocarbon, v 25, no. 2, p 249–258.

Dansgaard, W, Johnsen, S J, Clausen, H B and Langway, C C, Jr, 1971, Climatic record revealed by the Camp Century ice core, *in* Turekian, K K, ed, The late Cenozoic glacial ages: New Haven and London, Yale Univ Press, p 37–56.

de Jong, A F M, Mook, W G and Becker, B, 1979, Confirmation of Suess wiggles: 3200–3700 BC: Nature, v 280, p 48–49.

de Vries, HL, 1958, Variation in concentration of radiocarbon with time and location on Earth: Koninkl Nederlandse Akad Wetensch Proc, ser B 61, p 94–102.

———— 1959, Measurement and use of natural radiocarbon, *in* Abelson, P H, ed, Researches in geochemistry: New York, John Wiley & Sons, p 169–189.

Elsasser, W, 1956, Cosmic-ray intensity and geomagnetism: Nature, v 178, p 1226–1227.

Gleissberg, W, 1965, The eighty-year solar cycle in auroral frequency numbers: Jour Br Astron Assoc, v 75, no. 4, p 227–231.

Houtermans, J C (ms), 1971, Geophysical interpretations of bristlecone pine radiocarbon measurements using a method of Fourier analysis for unequally-spaced data: PhD dissert, Univ Bern, Switzerland.

Johnsen, S J, Dansgaard, W and Clausen, H B, 1970, Climatic oscillations 1200–2000 AD: Nature, v 227, no. 5257, p 482–483.

Klein, J, Lerman, J C, Damon, P E and Linick, T, 1980, Radiocarbon concentration in the atmosphere: 8000-year record of variations in tree rings: first results of a USA workshop, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 3, p 950–961.

Kromer, B, Rhein, M, Bruns, M, Schoch-Fischer, H, Münnich, K O, 1986, Radiocarbon calibration data for the 6th to 8th millennium BC, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 12th, Proc: Radiocarbon, v 28, no. 2B.

Lingenfelter, R E and Ramaty, R, 1970, Astrophysical and geophysical variations in C14 production, *in* Olsson, I U, ed, Radiocarbon variations and absolute chronology: Nobel symposium, 10th, Proc: New York, John Wiley & Sons, p 513–537.

Lund, S P and Banerjee, S K, 1985, Late Quaternary paleomagnetic field secular variation from two Minnesota lakes: Jour Geophys Research, v 90, no. B1, p 803–825.

Olsson, I U, 1970, ed, Radiocarbon variations and absolute chronology: Nobel symposium, 12th, Proc: New York, John Wiley & Sons, 652 p.

Pearson, G W and Baillie, M G L, 1983, High precision measurement of Irish oaks to show the natural atmospheric ^{14}C variations of the AD time, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 11th, Proc: Radiocarbon, v 25, no. 2, p 187–196.

Pearson, G W, Pilcher, J R and Baillie, M G L, 1983, High precision measurement of Irish oaks to show the natural variations from 200 BC to 4000 BC, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 11th, Proc: Radiocarbon, v 25, no. 2, p 179–186.

Siegenthaler, U, Heimann, M and Oeschger, H, 1980, ^{14}C variations caused by changes in the global carbon cycle, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 2, p 177–191.

Sonett, C P, 1984, Very long solar periods and the radiocarbon record: Rev Geophysics Space Physics, v 22, no 3, p 239–254.

Sternberg, R S and Damon, P E, 1979, Sensitivity of radiocarbon fluctuations and inventory to geomagnetic parameters, *in* Berger, R and Suess, H E, eds, Radiocarbon dating, Internatl ^{14}C conf, 9th, Proc: Berkeley, Univ California Press, p 691–720.

Strangway, D W, 1970, History of the earth's magnetic field: New York, McGraw-Hill, 168 p.

Stuiver, M, 1961, Variations in radiocarbon concentration and sunspot activity: Jour Geophys Research, v 66, p 273–276.

———— 1965, Carbon-14 content of 18th and 19th century wood, variations correlated with sunspot activity: Science, v 149, p 533–535.

Stuiver, M and Quay, P D, 1980, Changes in atmospheric ^{14}C attributed to a variable sun: Science, v 9, p 1–20.

Suess, H E, 1955, Radiocarbon concentration in modern wood: Science, v 122, p 415–417.

———— 1980, The radiocarbon record in tree rings of the last 8000 years, *in* Stuiver, M and Kra, R S, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 2, p 200–209.

Willis, E H, Tauber, H and Münnich, K O, 1960, Variations in the atmospheric radiocarbon concentration over the past 1300 years: Radiocarbon, v 3, p 1–4.