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LONG-TERM SOLAR MODULATION OF RADIOCARBON PRODUCTION

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The variation of atmospheric radiocarbon concentration over the past 8,000 years is generally well explained in terms of the modulation of radiocarbon production by the Earth's magnetic field. The reconstruction of this variation as based upon the known fluctuation of the Earth's field, however, is slightly out of phase with and of a smaller amplitude than the empirically derived curve.

Correlations between solar magnetic activity and climatic trends are well established over a period of a few hundred years. Furthermore, it has been demonstrated that the solar magnetic field modulates the production of radiocarbon in the same manner as does that of the Earth. By assuming that the correlation between solar activity and climate stems from some fundamental process, climatological information can be used to derive the behavior of the solar field over an extended period of time. The solar field thus established, along with knowledge of the Earth's field, yields a curve of radiocarbon concentration which is in much better agreement with the empirical curve.

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Radiocarbon dating depends upon the knowledge (or presumption) of the concentration of radiocarbon in the environment at the time that the specimen was absorbing carbon. In the early stages of radiocarbon dating, this concentration was assumed to be constant through time and equal to recent (pre-industrial) values. Historical and dendrochronological calibration, however, soon demonstrated that this is not the case. The concentration of atmospheric radiocarbon has, in fact, oscillated by some 10 percent over the past 8,000 years. The fundamental form of this curve has been explained in terms of the modulation of radiocarbon production by the geomagnetic field (Elsasser, Ney, and Winkler, 1956; Bucha, 1967, 1969). The changing magnetic field modifies the intensity of incoming cosmic radiation and, thereby, the rate at which nitrogen atoms are converted into radiocarbon (carbon-14) through neutron bombardment.

Over the past decade, a standard model has been employed by numerous authors (Lingenfelter and Ramaty, 1970; Damon, 1970; Lal and Venkatavaradan, 1970) in their studies of radiocarbon variation.

There exist, however, two features of the observed calibration curve which the standard model fails to explain satisfactorily. Theory predicts that the maximum value in the concentration of radiocarbon should follow the minimum value in the strength of the geomagnetic field (and, therefore, the maximum in the rate of radiocarbon production) by about 1,000 years. However, the production curve derived from the known geomagnetic variation and the empirically derived calibration curve appear to have little or no phase difference. A second problem involves the amplitude of variation in radiocarbon concentration. The manner in which the production of radiocarbon varies with the strength of the geomagnetic field, as well as the variation of the geomagnetic field itself over the past 8,000 years, is well established. It will be shown below,

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however, that the variation in radiocarbon concentration predicted on this basis accounts for only 70 percent of the observed variation.

The rate at which the concentration of atmospheric radiocarbon varies is not simply its rate of production minus its rate of decay. Rather, it involves a complicated process in which carbon is constantly exchanged among several reservoirs.

The vast majority of free carbon on the planet is in the oceans. A small portion of this lies above the thermocline (the upper 100 meters) and is readily exchanged with atmospheric carbon, but most of it lies below the thermocline and is exchanged at a much slower rate.

Radiocarbon is constantly being produced in the upper atmosphere, rapidly mixing throughout the atmosphere, and being exchanged among the reservoirs in the same manner as is the much more prevalent isotope carbon-12. The vast majority of exchangeable carbon is in the form of carbon-dioxide. Less important features of the model include sedimentation of carbon compounds in the ocean, the absorption of carbon (both temporarily and permanently) by organisms, and the direct exchange of carbon-dioxide between the atmosphere and the deep ocean across the outcrop of frigid waters around Antarctica. Although these may be important features in a model describing very short-term fluctuations of radiocarbon concentration, the long-term variations are dealt with adequately by employing a simple two-box model in which carbon-dioxide is exchanged between the atmosphere and the ocean.

If the atmosphere has an inventory of radiocarbon A, and the ocean has a radiocarbon inventory B, then,

$$dA/dt = Q(t) - \lambda A - K_A A + K_B B \qquad (1)$$

where Q(t) = the rate of production of radiocarbon as a function of time

λ = the decay constant of radiocarbon

K_A = the exchange constant of atmospheric carbon-dioxide (this is simply the inverse of the average residence time)

K_B = the exchange constant of oceanic carbon-dioxide

The corresponding equation describing the variation of oceanic radiocarbon is

$$dB/dt = -\lambda B + K_A A - K_B B \qquad (2)$$

Note that if the system is in equilibrium, with neither A nor B increasing or decreasing, then dA/dt = O, $Q = \lambda(A+B)$, and $A/B = (\lambda + K_B)/K_A$.

Since we are assuming that the entire inventory of radiocarbon is contained in the atmosphere and ocean, we can replace B in Equation (1) with (I-A), where I represents the entire inventory. This is done because I is easily defined as follows:

$$I(t) = I_o e^{-\lambda t} + \int_0^t Q(T)\, e^{-\lambda(t-T)}\, dT \qquad (3)$$

where I_o is the inventory of radiocarbon at t=O.

Proceeding to solve Equation (1):

$$dA/dt + A(\lambda + K_A + K_B) = Q(t) + K_B I(t) \qquad (4)$$

Introducing a factor $e^{(\lambda+K_A+K_B)t}$ and integrating, we have

$$A\, e^{(\lambda+K_A+K_B)t} = \int (Q(t) + K_B I(t))\, e^{(\lambda+K_A+K_B)t}\, dt \qquad (5)$$

Now all that remains is to define the production function Q(t), use it and an initial condition (I_o) to define I(t), and perform the integration in Equation (5) to obtain A(t). If the capacities of the atmosphere and ocean are assumed to be constant or slowly varying, the ratio A/B will always be identical to the ratio of atmospheric carbon-dioxide to oceanic carbon-dioxide. Therefore, the atmospheric radiocarbon concentration will be proportional to A.

Elsasser, et al. (1956) shows that the rate of production of radiocarbon is inversely proportional to the strength of the geomagnetic field to the power of .52. The form of the geomagnetic field itself has been shown to have undergone a sinusoidal variation over the past 8,500 years which can be described by the following equation:

$$M(t) = M_o - K \sin(2\pi t/8{,}000 + \phi) \qquad (6)$$

where M_o = the strength of the magnetic field at t=0

ϕ = a phase constant

and K = the amplitude of variation in field strength.

To simplify the calculations, ϕ is set equal to zero, and t=0 corresponds to the year 6500 B.C. M_o will be set at 1.0 and K at .35 (Bucha, 1969). Using Equation (6) and Elsasser's relationship for radiocarbon production as a function of field strength, we can derive the production function Q(t). Normalizing A(t) at 1.0 at t=0 and plotting the curve, we find that Q(t) can be nicely described by the following equation:

$$Q(t) = 1.0 + C \sin 2\pi t/8{,}000 \qquad (7)$$

where C = .25 for 0<t<4,000 years,

and C = .15 for 4,000<t<8,000 years. Damon (1970) uses a larger amplitude of magnetic field oscillation and concludes that the geomagnetic field fluctuation is sufficient to account for the magnitude of variation in radiocarbon concentration. However, the quantities he quotes as being taken from Kigoshi and Hasegawa (1966) are not those derived from their geomagnetic work which they cite (Nagata, 1963), but rather they are contrived figures stated as being necessary to explain the calibration curve. The quantities employed in this work are from Bucha (1969).

Using Equation (7), we can now perform the integration in Equation (3) and determine I(t):

$$I(t) = (I_o - 1.0/\lambda + C\omega/(\lambda^2+\omega^2))\, e^{-\lambda t} + 1.0/\lambda + (C/(\lambda^2+\omega^2))\,(\lambda \sin \omega t - \omega \cos \omega t) \qquad (8)$$

where w = $2\pi/8{,}000$ years.

We now use Equations (7) and (8) in Equation (5) and perform the integration to determine A(t):

$$A(t) = \frac{(1.0 + K_B/\lambda)}{(\lambda+K_A+K_B)} + K' e^{-(\lambda+K_A+K_B)t} + \frac{K_B(I_o-(1.0/\lambda) + C\omega/(\lambda^2+\omega^2))}{(K_A+K_B)}\, e^{-\lambda t} + \frac{C(\lambda+K_A+K_B)(\lambda^2+\omega^2 + K_B\lambda) - \omega^2 K_B}{(\lambda^2+\omega^2)(\omega^2+(\lambda+K_A+K_B)^2)} \sin \omega t - \frac{C\omega((\lambda^2+\omega^2+K_B\lambda) + K_B(\lambda+K_A+K_B))}{(\lambda^2+\omega^2)(\omega^2 + (\lambda+K_A+K_B)^2)} \cos \omega t \qquad (9)$$

The unit of A is arbitrarily determined by our setting Q(O) equal to 1.0 units/year. We will, however, calibrate A(t) such that it will represent the concentration of radiocarbon through time as compared to the current concentration. For the evaluation of Equation (9), values for the constants are assigned as follows:

λ = Ln (.5)/5,730 years = 1.21 10^{-4}/year

K_A = 1/30 year

K_B = 1/900 year

K′ is a constant of integration and can also be set equal to zero because it decays with a half-life of only twenty years and, hence, cannot affect the value of A(t) significantly for more than a very short time.

The two halves of A(t) are now evaluated separately. A range of values for I_o is assigned to the equation representing the period 4,000<t<8,000, and the value which yields the best fit to the most recent portion of the curve is selected. This will not be the same value of I_o to be used in the earlier portion of the curve, as the production functions are different. However, that value can now be determined by using Equation (3). Now the earlier curve is evaluated and adjusted so the two halves meet at t = 4,000. The whole curve is now calibrated such that its lowest point (at t = 7,000) has the value of .992, which is empirically determined. The final equation expressing A(t) is:

$$A(t) = 1.030 - .019\, e^{-\lambda t} + .029 \sin \omega t - .034 \cos \omega t$$

for 0<t<4,000 years and (10)

$$A(t) = .989 + .068\, e^{-\lambda t} + .017 \sin \omega t - .021 \cos \omega t$$

for 4,000<t<8,000 years.

A(t) is plotted in Figure 1 along with the observed calibration curve. The problems of phase and amplitude mentioned above are both readily apparent.

Most of the constants involved in the model are well determined or have an insignificant effect upon the solution. The two exceptions to this are K_A and K_B. These constants are not determined with adequate accuracy, and, in that they may have a significant effect upon the phase of the predicted curve with regard to the observed curve, they warrant further investigation. The two constants have been assigned values covering a broad range, and the corresponding lag times between the peaks of the predicted and observed curves have been calculated. The results are displayed in Figure 2. The area enclosed by the double line covers the range of likely values of K_A and K_B. It appears that no reasonable manipulation of the two independent variables can bring the predicted curve in phase with the observed curve: a lag time of anywhere from 500 to 1,200 years is always indicated. The lag time is most strongly affected by these two parameters and is not significantly influenced by the inclusion of more reservoirs. Damon (1970) investigated the effects of ocean temperature upon the problem, but concluded that there are two opposing effects which tend to cancel one another. Although climate may influence the problem by modifying the relative capacities of the reservoirs or affecting the average residence time, it does not appear to be sufficient in itself to account for the problems of amplitude and phase. The problem apparently requires inspection on a more detailed level to determine additional components which may be of use in predicting the large scale fluctuations in radiocarbon inventory.

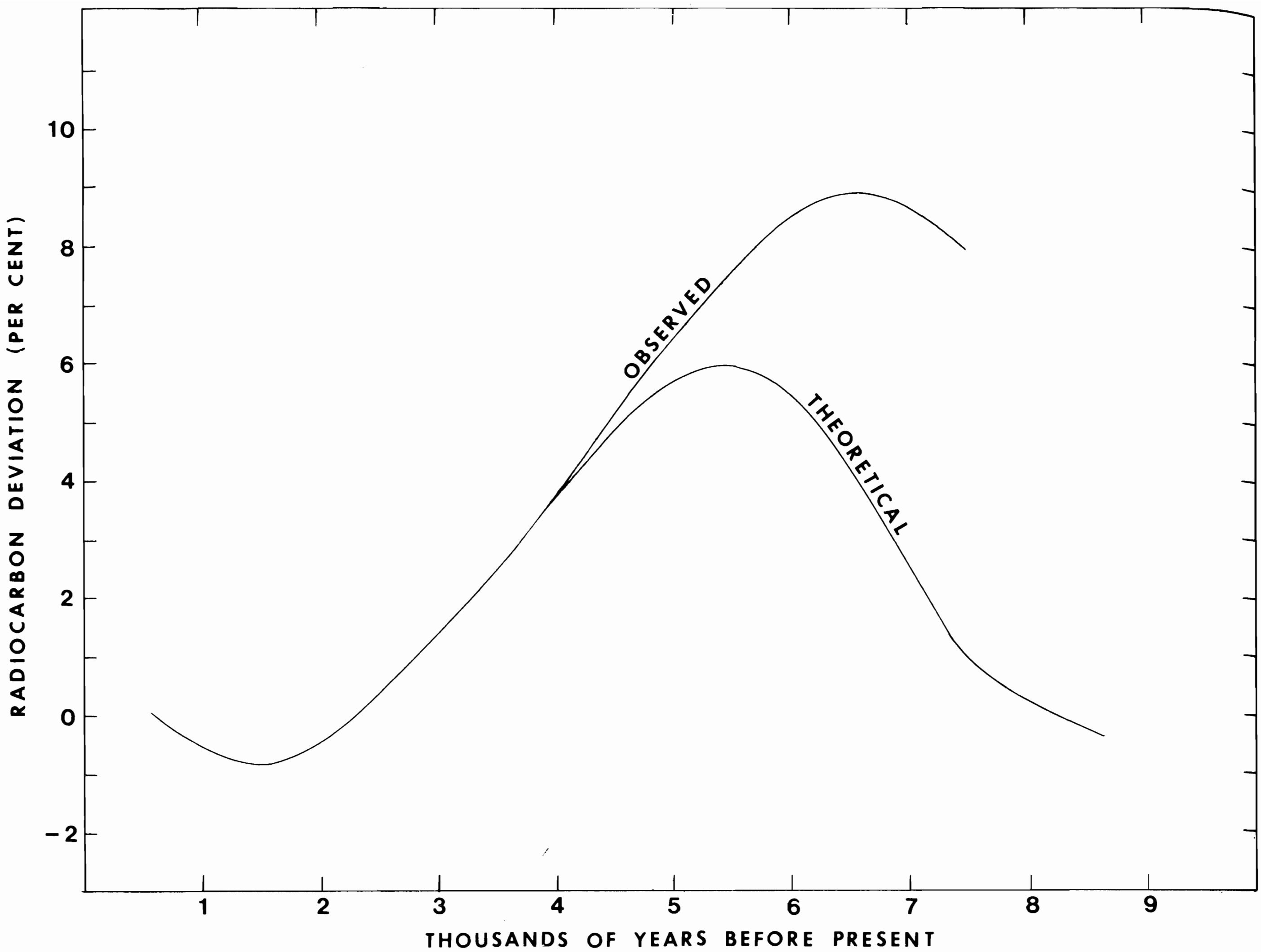

Figure 1. The theoretical and observed variation in radiocarbon concentration over the past 8,000 years. The curve predicted by a model employing geomagnetic modulation is too small in amplitude and reaches its climax about 1,000 years after that of the observed curve.

Significant correlations have been demonstrated between solar magnetic activity and climate as well as solar activity and small scale fluctuations in radiocarbon concentration. Eddy (1976) has found that accounts of sunspots, aurora, and other phenomena indicative of solar magnetic activity are correlated with climatic conditions, especially in the case of the Maunder minimum (a period of some sixty years during which very few sunspots were observed) and the most severe portion of the Little Ice Age, when winters across Europe were particularly cold. The sunspot-climate correlations have been thoroughly reviewed by Lamb (1972) and shown to be statistically significant. A number of authors (notably Stuiver, 1961) have established a relation between sunspot numbers and the rate at which radiocarbon is produced. It is apparent that the solar magnetic field modulates radiocarbon production in the same manner as does that of the Earth.

Although the relation between solar activity and climate has been demonstrated convincingly, the process behind this relation is by no means obvious. Proposed explanations include: the effect of the solar field upon electrical phenomena in the Earth's atmosphere with a resultant effect on weather patterns (Markson, 1978), changes in the spectral distribution of solar radiation with magnetic activity, and actual variations in solar energy output. Although solar magnetic phenomena are very complicated and poorly understood, there are indications that the character of convection in the sun's atmosphere is strongly dependent upon solar energy output (Dearborn and Newman, 1978), and it is established as well that magnetic activity is in turn a result of atmospheric motions (Bumba and Kleczec, 1975).

Regardless of the actual process involved, it is interesting

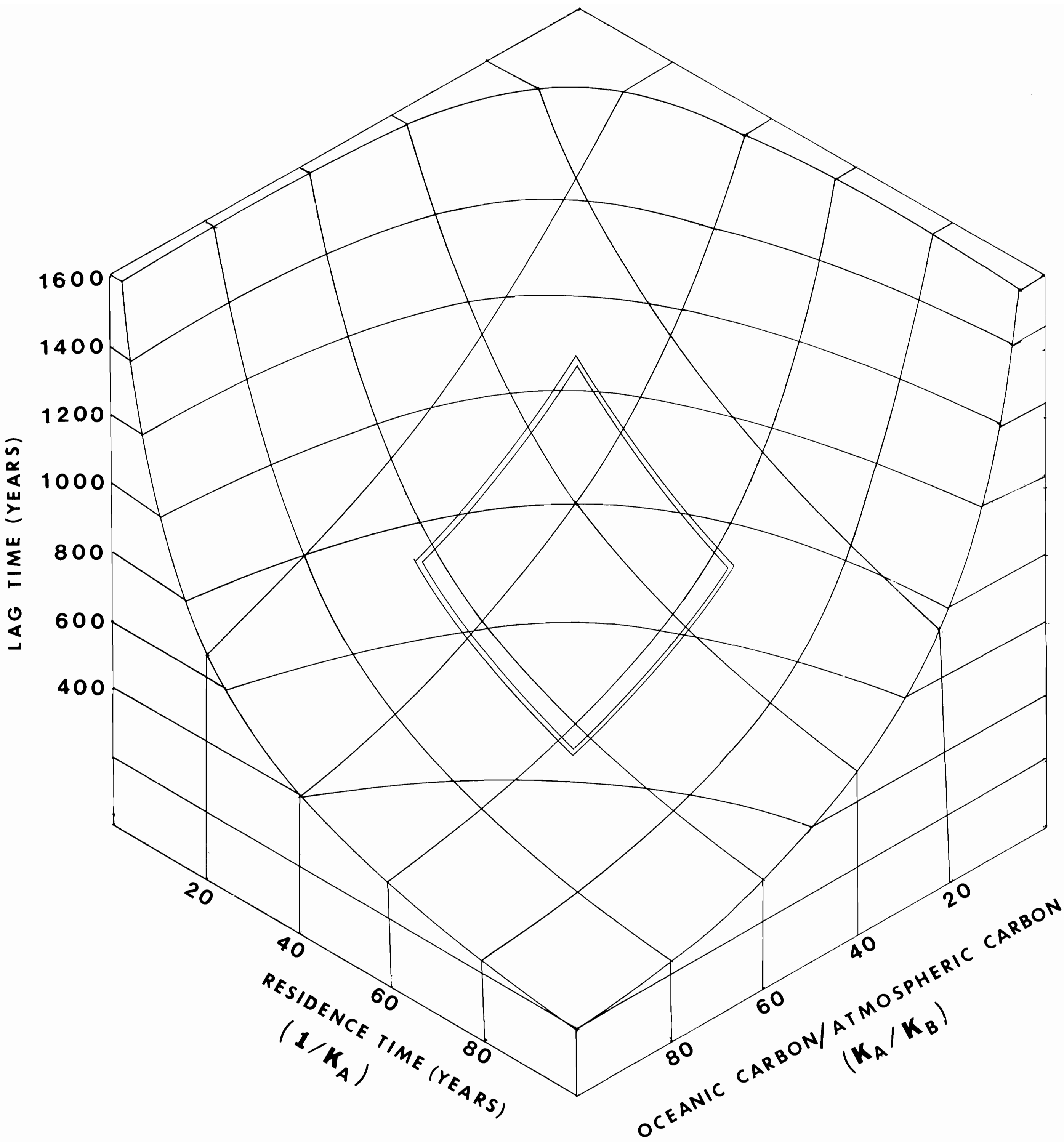

Figure 2. The lag time between the maxima of the observed and theoretical curves as a function of the atmospheric residence time for carbon and the ratio of oceanic to atmospheric carbon. The double line encloses the area corresponding to the most likely values of the independent variables.

to hypothesize that the relation between solar activity and climate is of a fundamental origin and can be assumed to exist over an extended period of time. Using this hypothesis, the long-term trend of solar magnetic activity can be established on the basis of known climatic trends of the past, and the manner in which radiocarbon production has been influenced by the solar field can be estimated.

Unfortunately, the area we now enter is more qualitative than quantitative. Although a correlation between climate and solar activity is apparent, no rigid relationship can be established. Furthermore, the effect of the solar magnetic field upon radiocarbon production is, also, only a statistically established phenomenon. It is possible only to assign magnitudes of radiocarbon production effects which are commensurate with those established by the study of recent fluctuations of climate, solar activity, and radiocarbon production.

Long-term variations in worldwide climate have been shown to depend to a large extent upon the orbital disposition of the Earth (Milanković, 1941; Hays, Imbrie, and Shackleton, 1976). Climatic conditions show a high degree of sensitivity to the amount of solar radiation received at high northern latitudes during times of the year which are important in terms of the growth and decay of glaciers. The insolation received at any particular point on Earth during a particular time of the year depends upon the eccentricity, obliquity, and longitude of perihelion of the Earth's orbit. These elements in turn vary as a result of perturbations from other planets and attraction of the sun and moon on the oblate shape of the Earth.

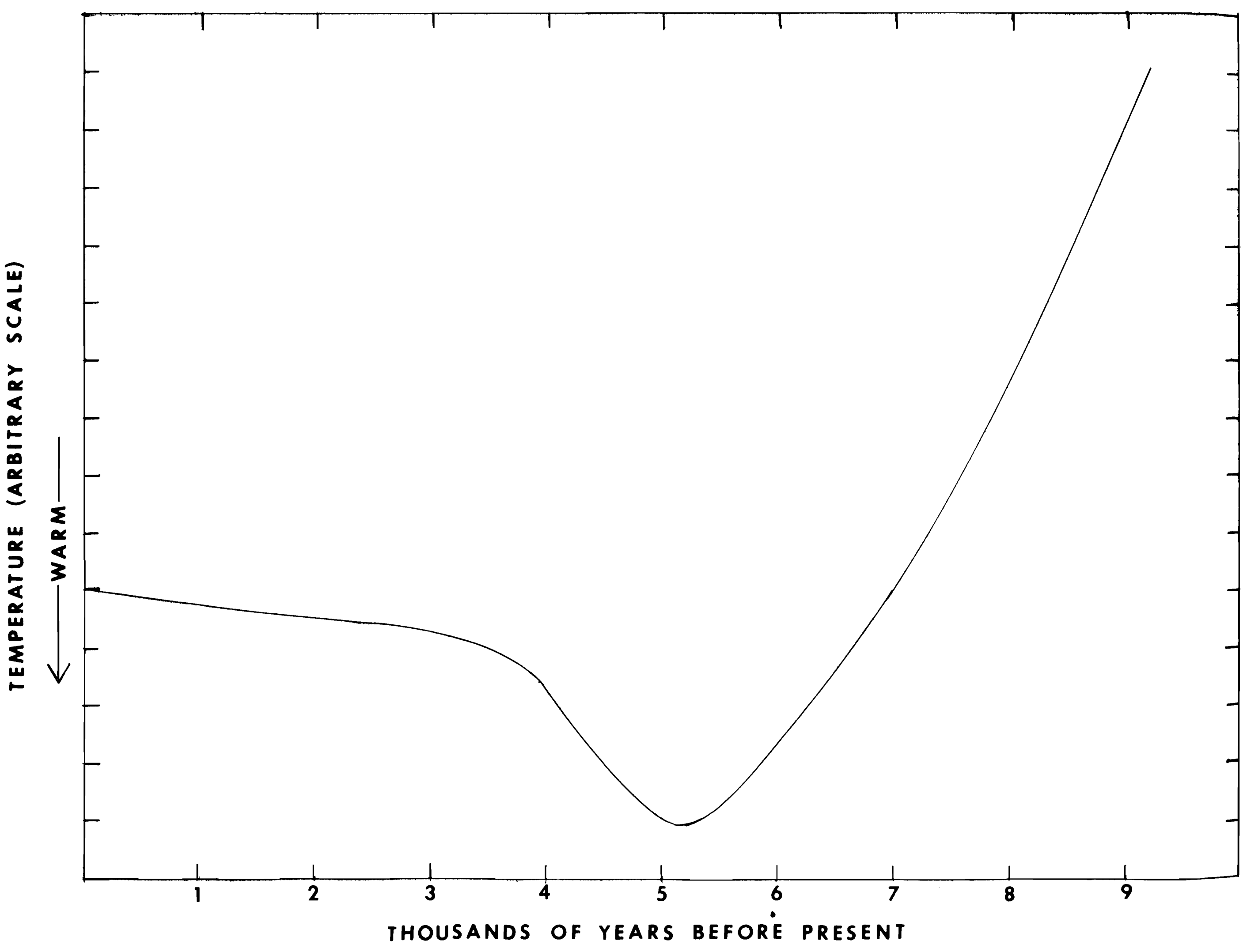

Figure 3. The global temperature trend over the past 9,000 years. This curve is derived by a number of investigators using a variety of techniques (Emiliani, 1966; Lamb, et al., 1966; and Wollin, et al., 1971). In that the actual temperature variations depend upon latitude, local weather patterns, and the medium studied, the scale is arbitrary.

Although most authors in the past have assumed that the most important time of year for the growth and decay of glaciers is the summer, Kukla (1975) has recently demonstrated that the autumn months are more important in this regard. The climate appears to respond very rapidly to changes in autumnal insolation at high northern latitudes, with a maximum in such insolation 6,000 years before present corresponding to the climatic "optimum" which then occurred, and an insolation minimum at 17,000 B.P. corresponding to the deepest portion of the last Ice Age.

If orbital variation is considered the only cause of long-term climatic change, then the temperature of the Earth should fall off symmetrically on either side of the insolation maximum at 6000 B.P. However, it can be seen in Figure 3 that this is not the case. Even though the rise in temperature approaching the climatic optimum is in agreement with theory in both form and magnitude, the decline in temperature since then is not as great as would be expected. It will be assumed that the difference between the predicted and observed climate trends is the result of fundamental solar influence of the same nature as that which has been demonstrated in recent times. The sun will be assumed to have been in a mode identical to that during the Maunder minimum up to some 7,500 years ago; at that point it began a steady change of state until it reached its present mode some 4,500 years ago. Such behavior on the part of the sun, with commensurate climatic change, would explain the observed climate trend.

All that remains is to translate our assumed pattern of

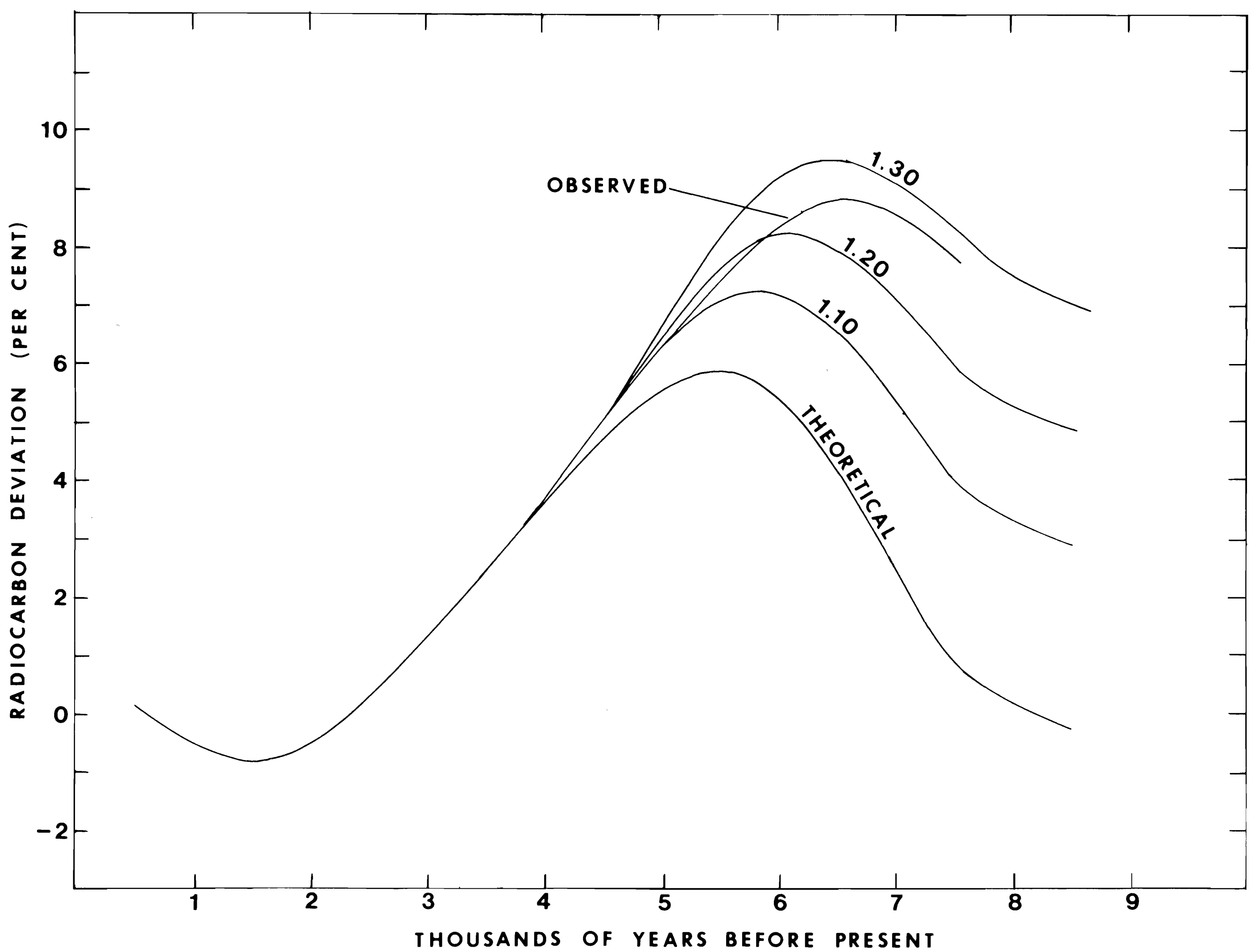

Figure 4. Three new theoretical curves which are based upon solar as well as geomagnetic modulation of radiocarbon production. The observed and predicted curves shown in Figure 1 are also reproduced. The number associated with each curve is the ratio of the radiocarbon production rate 7,500 years ago to the current production rate as due to changes in the solar magnetic field.

solar behavior into variations in radiocarbon production rate. Then, by combining solar modulation with the effect of the geomagnetic field, a new production function can be derived which can be used in Equations (3) and (5) to generate a new theoretical calibration curve. The increase in radiocarbon concentration during the Maunder minimum implies an increase in the rate of production of about 20 percent over a period of 60 years. This offers some idea of the magnitude of the solar influence to be expected.

In that the solar field is effective throughout a very large volume, it will modulate the intensity of cosmic rays in the Earth's vicinity. From this point, the Earth's field is of overwhelming importance. It is, therefore, easy to include the effects of solar modulation by simply multiplying its values of production modulation by those determined by the Earth's field. The production function obtained, however, is a rather complicated expression, and the integrations involved were, therefore, performed numerically.

A selection of theoretical curves which result is shown in Figure 4, along with the observed curve and the theoretical curve, which results from geomagnetic modulation alone.

The above model is, to be sure, over-simplified. Other variables affecting climate, such as albebo and cloud cover, have not been considered, and the form of the solar modulation curve is very simple, as the data do not justify a more detailed curve. We do conclude, however, that the inclusion of solar modulation as derived from a simple extension of of-served phenomena affects the theoretical calibration curve in a manner which brings it into closer agreement with the observed calibration curve.

It is possible that a detailed study of the radiocarbon curve over the last millenia, along with accurate climate and sunspot data, could lead to a more quantitative model; however, there are more important steps to be taken in other areas. The fundamental nature of solar magnetic phenomena is not well understood, and the exact nature of the solar-climate link has as yet to be explained. The resolution of these problems is fundamental to a coherent understanding of climate change and the radiocarbon calibration curve.

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