A PROBABLE ~ 2400 YEAR SOLAR QUASI-CYCLE IN ATMOSPHERIC $\Delta^{14}C$

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ABSTRACT

A 2200-2600 year quasi-periodicity is present in atmospheric $\Delta^{14}C$ records after removal of long-term trends due to the geomagnetic dipole amplitude variation. This periodicity consists of both a long-term variation of the mean and a superposed, approximately recurring pattern of century-scale variations. The strongest of these latter variations occur near maxima of the ~ 2400 year $\Delta^{14}C$ cycles. The residual record can be modeled to first order as an amplitude modulation of a century-scale periodic forcing function by a ~ 2400 year periodic forcing function. During the last millennium, the largest century-scale variations (occurring near the most recent 2400 year $\Delta^{14}C$ maximum) are known to be mainly a consequence of the pronounced Maunder, Spörer, and Wolf solar activity minima, as verified by independent proxy solar activity records. Therefore, during this period, amplitude modulation has been occurring primarily in the sun and not in the terrestrial radiocarbon system. It is therefore inferred that the ~ 2400 year forcing function is mainly solar although some secondary terrestrial feedback into the $\Delta^{14}C$ record is likely. This conclusion has implications for the predictability of future pronounced solar activity minima and for the interpretation of certain minor Holocene climatic variations.

INTRODUCTION

Deviations of atmospheric ^{14}C versus time ($\Delta^{14}C$) are produced in part by solar-induced changes in galactic cosmic ray flux which in turn modulate the radiocarbon production rate [Stuiver, 1961; Stuiver and Quay, 1980; Sonett, 1984; Damon, 1988; and references therein]. Directly dated tree ring $\Delta^{14}C$ records covering the last ~ 8000 years therefore represent one of the best available proxy measures of solar magnetic variability. However, an important problem in the interpretation of such records is the separation of solar variability contributions from other potential terrestrial sources of radiocarbon variability. In this paper, empirical methods are used to investigate whether millennium-scale variations in the radiocarbon record are primarily solar or terrestrial in origin.

ANALYSIS

Figure 1 shows a high-precision $\Delta^{14}C$ record resulting from the 12th International Radiocarbon Conference [Stuiver and Kra, 1986]. A long-term trend is present that has been shown to be largely consistent with a modeled response to the ~ 11,000 year geomagnetic dipole moment amplitude variation as derived from archeomagnetic records [Sternberg and Damon, 1983; Damon, 1988]. Figure 2 shows the same record after detrending by removal of a least-squares-fitted cubic polynomial representing long-term changes in geomagnetic dipole moment intensity. Note that the residual radiocarbon variations are now plotted with an inverse scale so that decreases in $\Delta^{14}C$ are upward and correspond to increases in

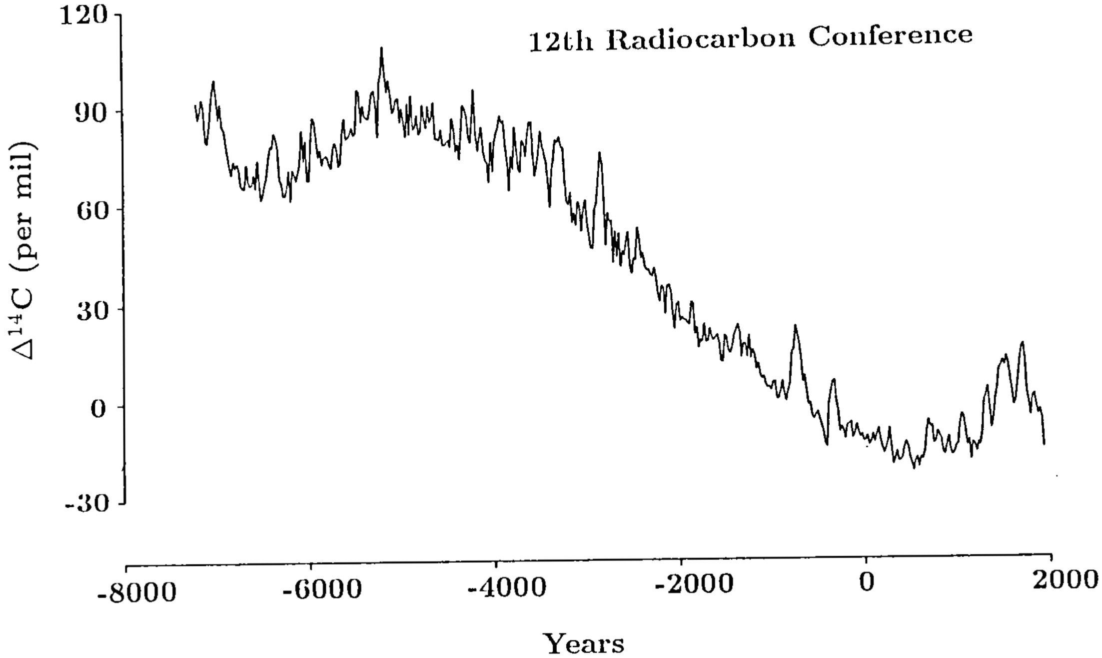


Figure 1. 12th International Radiocarbon Conference calibration record produced by combining high-precision records from a series of laboratories [Stuiver and Kra, 1986]. (Data courtesy of M. Stuiver and R. Kra)

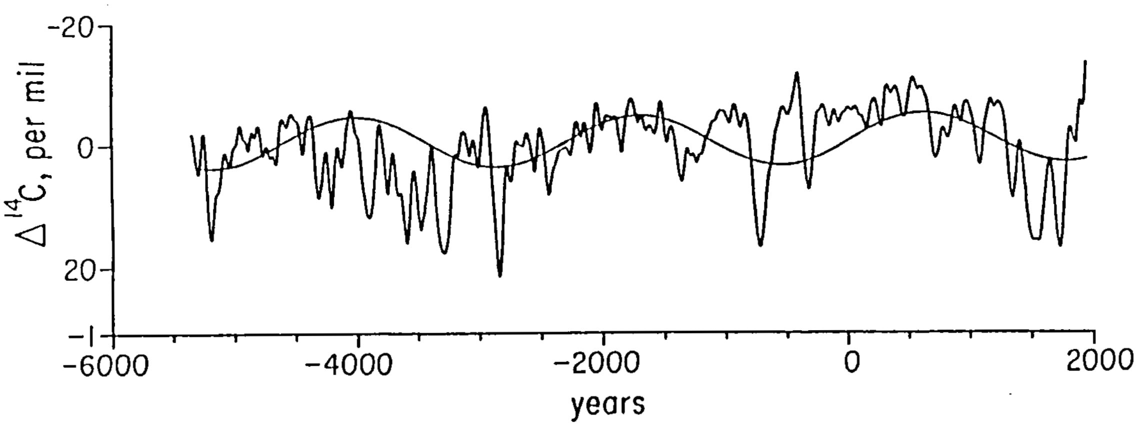


Figure 2. Residual Conference Δ^{14}C record after detrending to remove the long-term geomagnetic variation and smoothing to minimize variations with periods less than approximately 100 years. Note that the vertical scale has been inverted so that Δ^{14}C maxima map solar activity minima. A least-squares-fitted sinusoid is superposed to indicate the approximate locations of maxima and minima of the $\sim$ 2400 year quasi-cycle.

solar activity.

The residual variations of Figure 2 exhibit a 2200-2600 year quasi-periodicity that has been recognized in power spectral analyses and visual examinations of various radiocarbon records [Houtermans, 1971; Denton and Karlén, 1973; Suess, 1980; Sonett and Finney, 1989]. To indicate the approximate locations of maxima and minima of this quasi-cycle, a sinusoid with a $\sim$ 2400 year period was least-squares-fitted to the residual record (fitted parameters: period = 2310 years; amplitude 4.08 per mil) and is superposed on the record in Figure 2. A geomagnetic origin for this quasi-periodicity in $\Delta^{14}C$ has been considered unlikely since there is no dipole moment amplitude variation near a period of 2400 years [Damon and Sonett, 1990]. However, there is a well-known climatic period near 2500 years [Mitchell, 1976; Pestiaux et al., 1987]. Several earlier investigators have reported that this $\sim$ 2500 year climate variation has been nearly in phase with the inverted $\Delta^{14}C$ record during the last 8000 years [Bray, 1968; 1970; Denton and Karlén, 1973]. Figure 3 compares the residual $\Delta^{14}C$ record of Figure 2 to well-dated proxy northern hemispheric climate indicators including $\delta^{18}O$ from the Camp Century Greenland ice core [Dansgaard et al., 1984] and the Devon Island Canada ice core [Fisher, 1982] as well as to the temperature-sensitive Campito Mountain bristlecone pine tree ring width record of LaMarche [1974]. A tendency for climatic minima to be associated with $\Delta^{14}C$ maxima is evident. The last of these climatic minima was the Little Ice Age [Eddy, 1977].

There are two "end-member" candidate sources of the $\sim$ 2400 year quasi-periodicity in atmospheric $\Delta^{14}C$. First, the $\Delta^{14}C$ could be responding entirely to a terrestrial climate cycle of uncertain origin through a redistribution of ^{14}C between the atmospheric and oceanic reservoirs. Second, the $\Delta^{14}C$ could be responding entirely to a solar quasi-cycle of the same period and the $\sim$ 2500 year climate period could be independently driven by solar variability. In order to distinguish between these possibilities, it is helpful to consider the detailed characteristics of the radiocarbon record of Figure 1 together with independent proxy solar activity records covering the last 1000 years.

Century-scale variations in the $\Delta^{14}C$ record are believed to be dominantly of solar origin as evidenced by their correlation with the independently verified Maunder and Spörer solar activity minima of the last millennium [Eddy, 1976; 1977; Stuiver and Quay, 1980; Stuiver and Braziunas, 1989]. As can be seen in Figure 2, the strongest century-scale variations tend to occur near successive maxima of the $\sim$ 2400 year $\Delta^{14}C$ cycles. In addition, it has been shown that century-scale variations in the most recent $\sim$ 2400 year cycle in $\Delta^{14}C$ are positively correlated with similar short-term variations in each of the two previous cycles [Hood and Jirikowic, 1990]. Thus, the quasi-periodicity consists of both a long-term variation of the mean and a superposed, approximately recurring pattern of century-scale variations.

The behavior of the residual $\Delta^{14}C$ record can be interpreted in terms of amplitude modulation of a century-scale solar forcing function by a longer-term forcing function [Sonett, 1984]. Figure 4 shows a simplified example of amplitude modulation in which a 200-year sinusoid is modulated by a 2400-year sinusoid. Pronounced short-term maxima (note the inverted scale) occur in the resulting time series (Figure 4c) at intervals of the longer period. **If the 2400-year forcing function (represented in Figure 4b) were dominantly terrestrial in origin, then we would expect to be able to observe**

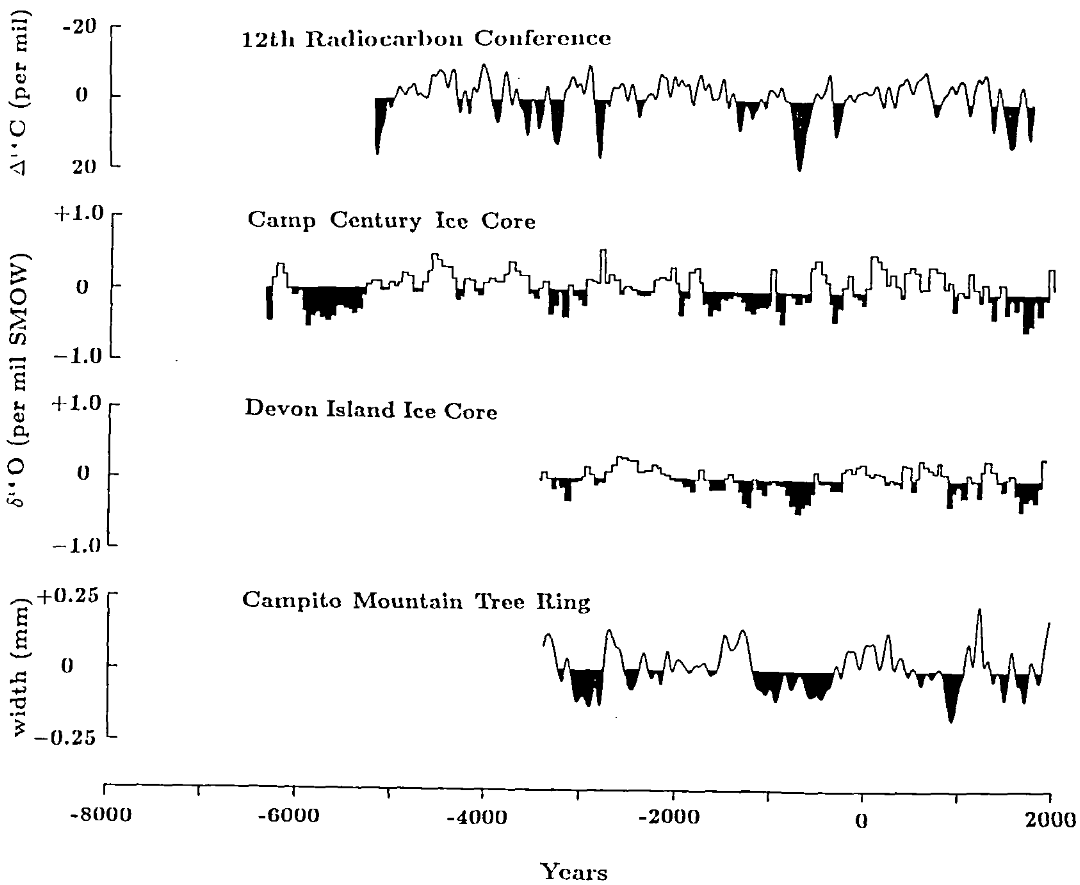
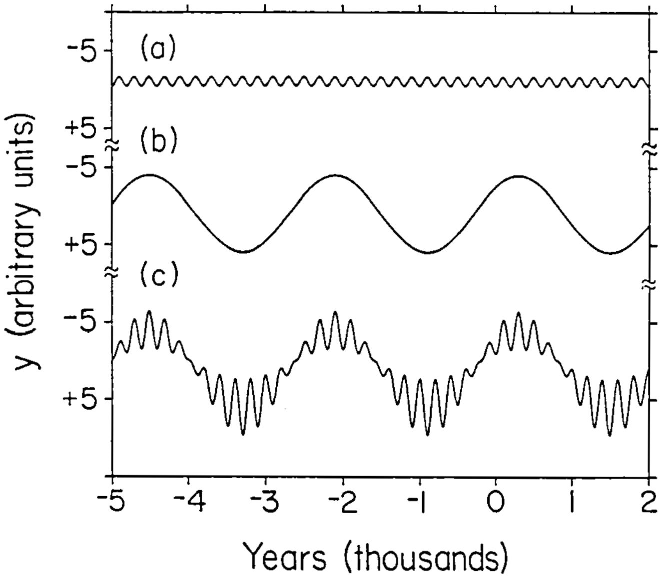


Figure 3. Comparison between the residual Conference $\Delta^{14}C$ record and several well-dated proxy northern hemispheric climatic indicators for the last 8000 years (see the text).



$$y = (1 + A\cos\omega_1 t)(1 + B\cos\omega_2 t)$$

where $A = 5$, $B = 0.6$, $\omega_1 = 2\pi/2400\ \mathrm{yr}^{-1}$, $\omega_2 = 2\pi/200\ \mathrm{yr}^{-1}$, and t is the time in years.

Figure 4. Simple model of amplitude modulation of a 200 year sinusoid (a) by a 2400 year sinusoid (b). The product is shown in (c) and has characteristics that are qualitatively similar to those of the residual $\Delta^{14}C$ record.

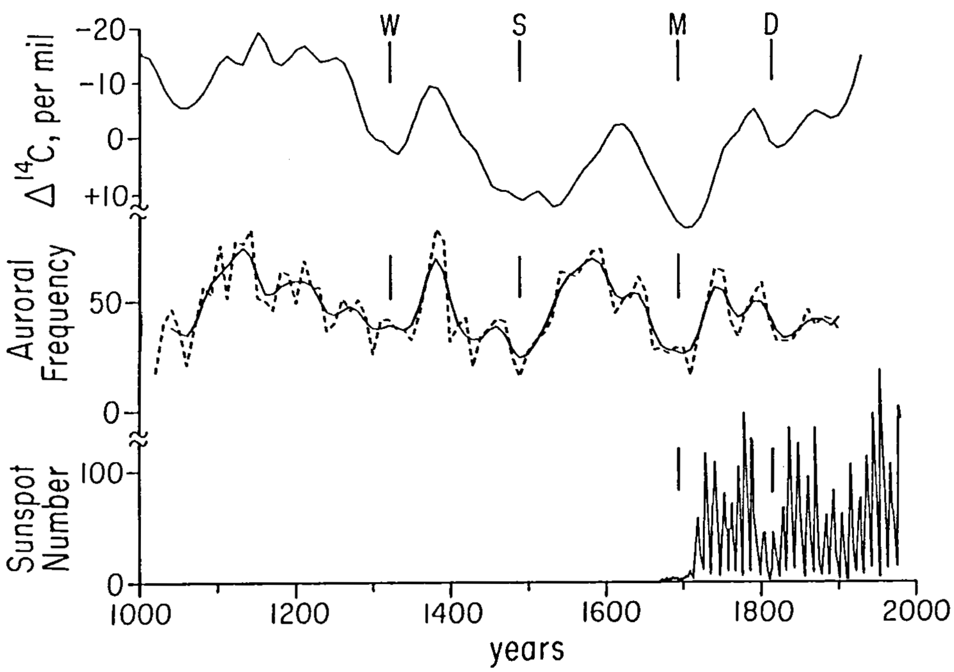


Figure 5. A comparison between the last 1000 years of the residual Conference $\Delta^{14}C$ series and two independent proxy solar activity indicators (see the text).

the unmodulated solar signal (represented in Figure 4a) in independent proxy solar records covering the last 1000 years. However, the latter records show the occurrence of pronounced minima in the form of the Wolf, Spörer, and Maunder solar activity minima.

Figure 5 compares the residual $\Delta^{14}C$ record for the current millennium with the auroral frequency record compiled by Schove [1987] and with mean annual sunspot number since 1670 [Waldmeier, 1961; Eddy, 1976]. Within the recent interval covered by the sunspot record, both the Dalton and Maunder sunspot minima are approximately reflected in the residual inverted $\Delta^{14}C$ record. At earlier times, the auroral record remains positively correlated with the inverted $\Delta^{14}C$ time series ($R = 0.55$ at 20 years lag versus the smoothed auroral record for the entire series) and exhibits minima that can be identified with the Maunder, Spörer, and Wolf minima in the $\Delta^{14}C$ time series. A broad maximum centered on A.D. 1150, known as the medieval maximum, is also evident in both records. **From the existence of pronounced minima in these independent proxy solar records near the last $\Delta^{14}C$ maximum, it is clear that amplitude modulation of century-scale solar variations has been occurring <u>in the sun</u> during the last 1000 years and not just in the terrestrial radiocarbon system.** By inference, the earlier strong variations occurring at $\sim$ 2400 year intervals are most probably produced mainly by solar changes although some secondary climatic feedback effects on $\Delta^{14}C$ can not be excluded. On this basis, the $\sim$ 2400 year forcing function that is modulating the atmospheric $\Delta^{14}C$ record is suggested to be primarily solar.

IMPLICATIONS

Clearly, the construction of more complete quantitative models for $\Delta^{14}C$ production and exchange appropriate for millennium scale variations would be valuable and may elucidate further the relative roles of terrestrial and solar forcing mechanisms. However, the empirical evidence discussed here for a dominantly solar origin of both the century-scale and longer-term ($\sim$ 2400 year) residual variations in the Conference $\Delta^{14}C$ record does allow several provisional implications to be stated. The first of these relates to the predictability of future long-term activity changes. Although the Babcock-Leighton models for the Hale magnetic cycle (involving distortion of an initially poloidal field by differential rotation in the convection zone) have been developed, these models along with dynamo theories for the origin of the magnetic field itself are not yet sufficiently advanced to allow extensions to longer time scales [e.g., Gough, 1977]. From a purely empirical standpoint, however, it is reasonable to expect that the inferred quasi-cyclicity will persist in the future. In particular, it can be projected that large Maunder- and Spörer-type minima are not likely to occur again until ca. A.D. 4000 and that these will be preceded by a lengthy period of relatively high solar activity. In addition, the above analysis (indicating that the $\sim$ 2400 year $\Delta^{14}C$ periodicity is dominantly of solar origin) supports a possible solar origin for the Holocene climatic cycle of the same approximate period (Figure 3).

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