COSMOGENIC RADIOCARBON AND CYCLICAL NATURAL PROCESSES

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ABSTRACT: We investigated relations among solar activity, climate and cosmogenic radiocarbon in a time series of various astrophysical, geophysical, archaeological and historical data. We studied records of tree-ring thickness, aurora borealis, the catalog of visible sunspots, sedimentary deposits from lakes and oceans, global glacial advance and retreat chronology, polar ice cores and human migrations. In these data, we searched for evidence of medium- and long-term solar cycles. Application of different spectral techniques to the atmospheric 14C concentration time series indicates the existence of spectral lines at a few dominant periodicities ranging from 11 yr to ca. 2 ka. Different laboratories have confirmed the presence of the ca. 210- and 2000-yr spectral features in long 14C series in tree rings. The ca. 210-yr 14C cycle is probably caused by heliomagnetic modulation of the cosmic-ray flux. The extrema of both the ca. 210-yr 14C period and solar activity correlate with the cold and warm epochs of global climate, at least for the past millennium, and this correlation has the correct sign. The periods of low solar activity are well correlated with the Little Ice Ages. The cause of the ca. 2 ka 14C period is, as yet, uncertain, but evidence from the analyses of various natural records shows that it could have a solar origin. In this study, we obtained powerful manifestations of solar activity and climate warming epochs at ca. 1500, 3800, 6100, 8200, 10,500 and 12,600 BP. A similar feature occurs in epochs of minimum amplitude in the 14C content in tree rings. Thus, solar activity may affect both the 14C content in the Earth’s atmosphere and climate.

INTRODUCTION

Detailed studies of radiocarbon content in tree rings provide a unique data set for precise 14C age calibration of materials formed in isotopic equilibrium with atmospheric CO2. We focus here on the Holocene, i.e., the last 10 ka. The beginning of this interval corresponds to an uncertain calendar age, because the observed atmospheric calibration curve flattens near 10 ka. De Vries (1958) was the first to demonstrate evidence for secular variations of natural 14C content in the Earth’s atmosphere. Willis, Tauber and Münnich (1960) showed that atmospheric 14C activity appears to be cyclical, with a period of ca. 200 yr over the past 1300 yr. Suess (1965) showed that tree rings contain quantitatively short-term wiggles and secular variations in the content of cosmogenically produced 14C in the atmosphere. However, it has long been assumed that the measured short-term fluctuations, with amplitudes of <1% in the natural 14C concentration, represent random variations. The precise measurements needed to define the short-term fluctuations induced by solar activity will require high precision as well as sensitivity (Damon et al. 1978). Accuracies of the 14C measurements were insufficient to demonstrate the irrefutable existence of the wiggles. These earlier measurements of 14C concentration were subject to large laboratory uncertainties and statistical fluctuations. After numerous interlaboratory checks on measurements of 14C content in identical samples in different countries, methodological flaws were largely identified and eliminated. One must be cautious in separating and interpreting short-term cyclical fluctuations from the 14C content, because spectral analysis of series of data with high noise components raises the question of extracting the true harmonics from the spurious spectral lines. However, reliable experimental material now accumulated in the 14C content in samples of known age suggests the possibility of selectively separating, from the 14C data, information generated by a complex of interfering astrophysical and geophysical processes.
High-precision measurements of the $^{14}$C content in tree rings of known age to study causes of changes in atmospheric $^{14}$C concentrations in the past began ca. 20 yr ago in different world laboratories. Many measurements have been made, both of continuous annual series of tree-ring samples, covering time scales from decades to hundreds of years, and of continuous samples of decadal or bidecadal rings, spanning several millennia (see, e.g., Stuiver and Kra 1986; Stuiver and Becker 1986; Pearson et al. 1986). $^{14}$C measurements show not only three types of fluctuations: short-term (years to several decades); medium-term (decades to several hundreds of years); and long-term (thousands of years), but also their details. These fluctuations are characterized by a different amplitude of change in the $^{14}$C concentration: fractions of a percentage, 1–2% and as much as 11%, respectively, for short-, medium- and long-term fluctuations (see Fig. 1, Stuiver and Kra 1986).

We examine here the medium-term variations of a period of ca. 210 yr and long-term variations of a period ca. 2 ka in terrestrial $^{14}$C concentration, and the relation between the $^{14}$C record and some cyclical natural processes.

**MANIFESTATION OF MEDIUM- AND LONG-TERM $^{14}$C FLUCTUATIONS**

By examining $^{14}$C content, one is able to draw important conclusions about the $^{14}$C activity level in wood samples of known age. First, it is important to note Suess’ (1978) experimental data that extended to ca. 7 ka BP from which he plotted his calibration curve. A characteristic feature of these data is the almost identical uncertainty in all the measurements (ca. 0.4%). Admittedly, considerable gaps exist in his series at different intervals. At the University of Arizona, Damon et al. (1980) compiled >1200 determinations of $^{14}$C activity in blocks of rings of bristlecone pine and giant sequoias extending beyond 7 ka BP, in a compendium of results from various laboratories (Klein et al. 1980).

High-precision $^{14}$C measurements of dendrochronologically dated wood samples, each covering 10 yr, are now available for AD 1950–6000 BC (Stuiver and Becker 1993). The U.S. bristlecone pine and the German oak chronologies covering the last 9150 cal yr (Stuiver, Pearson and Braziunas 1986) have recently been extended to ca. 11,400 BP (Kromer and Becker 1993).

One can observe the physical manifestation of the ca. 210-yr cycle in the relative deviations of the measured $^{14}$C activities upon removal of the long-term trend. Figure 1 shows these ca. 210-yr $^{14}$C concentration oscillations during the last two millennia derived from several results summarized in Stuiver and Kra (1986). Note that the magnitude of these $^{14}$C content oscillations are sensitive to geomagnetic field intensity changes. Most data on the behavior of the intensity of the archæomagnetic field indicate that values of the dipole moment peaked 2000–2500 yr ago (e.g., see Merrill and McElhinny 1983).

The mathematical manifestation of this 210-yr period can be obtained by applying statistical techniques of time series analysis. The classical method analysis, Fourier harmonic and Blackman-Tukey spectral analysis, have been applied first to the cosmogenic $^{14}$C data. Using Fourier analysis of the $^{14}$C content variations, Houtermans (1971) reported the ca. 200- and 2000-yr periodicities. The Fourier spectrum of $^{14}$C variations during the period 5300 BC–AD 150 in bristlecone pine samples measured in La Jolla showed a conspicuous spectral line at ca. 200 yr (Suess 1980). Neftel, Oeschger and Suess (1981), and even more conclusively, Sonett and Suess (1984) confirmed this period in the La Jolla spectrum.

Figure 2 shows changes in the $^{14}$C content based on tree-ring data, ranging back to ca. 11,400 BP. Note that the major anomalies occur every ca. 2 ka and represent the strongest feature in the $^{14}$C record on a long-term scale. This feature becomes more pronounced when filtering the raw data,
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according to Dergachev (1992). The maximum amplitude of the large-scale oscillations occurs at ca. 450, 2700, 4950, 7200 and 9450 BP, and minimum amplitude of these oscillations occurs at ca. 550, 3800, 6100 and 8300 BP. Four larger medium-term fluctuations (Hallstattzeit maxima) occur every 2100–2400 yr in the $^{14}$C concentration for the past seven millennia, based on compendia of results from various laboratories (Damon, Cheng and Linick 1989; Damon and Sonett 1992). These maxima occur at 250–450, 2700, 4870 and 7150 BP. The strongest feature in the $^{14}$C record with the long period of ca. 2 ka was extracted from La Jolla data (Suess 1978) after removing the long-term sinu-

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Fig. 1. Changes in $^{14}$C concentration relative to an average value (Stuiver and Kra 1986). The intervals indicate a repetitive pattern of medium $^{14}$C oscillation.

Fig. 2. Bidecadal values of $^{14}$C content changes to ca. 11,400 BP (Stuiver and Reimer 1993). Arrows show anomalously high values of $^{14}$C content.
soidal trend curve with a period of ca. 10 ka (Dergachev and Akhmetkereev 1990). The long-term trend can be determined in various ways (e.g., sine equations, moving averages, splines).

Much fruitful research has been done in recent years in applying statistical techniques to 14C data. High-precision 14C data from tree rings have a well-defined spectrum, consisting of numerous periods of detrended data ranging from 11 yr to ca. 2400 yr. After Houtermans (1971), who reported a periodicity of ca. 2 ka, this large-scale variation of terrestrial 14C was established by analyzing the spectral characteristics of the high-precision data with different techniques of time series analysis (e.g., Damon, Cheng and Linick 1989; Sonett and Finney 1990). At present, most experimental workers are not skeptical about the existence of periodicities in the natural 14C content, and meaningful spectral lines at several periods in the 14C sequences are not widely accepted. These periodic occurrences constitute an important source of scientific information.

A LINK BETWEEN CYCLICITY OF 14C AND FLUCTUATIONS OF SOLAR-TERRESTRIAL PHENOMENA

The 210-Year Period

Let us observe the appearance of the ca. 210-yr period in various natural processes. The Maunder, Wolf and Spörer minima of solar activity are well-documented periods, separated by the ca. 200-yr intervals. Schouve (1955) was among the first to observe the 210-yr cycle with the naked eye. He showed that the aurorae are more numerous in the even centuries than in the odd centuries. Chistyakov (1985) observed less solar activity during the odd 17th century than in the even 16th century. Xu (1990) found clear evidence of the 210-yr cycle in the historical solar record of ancient China.

The 200-yr trend is being documented on a global scale. Alexeev (1987) determined the variations for periods of 10.5 ± 0.5 yr, 85 ± 10 yr and 220 ± 20 yr in meteorite falls (although causally related correlations with solar variability are not evident). In his analysis of the rate of change of the angle of geomagnetic field direction, using contemporary and historical archaeomagnetic data, Tarling (1988) showed the periodicity to be ca. 200 yr. Goncharov (1993) showed that the invasions of great nomadic tribes from the Central Asian Steppe into agricultural regions of Europe, China and South Asia from the 4th to the 16th centuries were connected with the 210-yr cycle. These invasions occurred in middle latitudes after a dip in solar activity. Castagnoli et al. (1991) reported that the spectral analysis of three carbonate profiles from the Ionian Sea showed periodicities similar to those detected in the 14C spectra. An important group is a triplet at 206 yr, amplitude-modulated of 2000 yr. High-precision 14C data are now well established for most of the Holocene, where medium-term 14C variation is attributed to changes in the 14C production rate.

Ribes et al. (1990) proposed a simple model describing the convective processes at the time of low sunspot activity, and estimated the change of solar luminosity through the 11-yr and longer cycles, such as the Maunder minimum. With this model, the mean variation of the solar constant over several decades could cause changes of 0.5%. The model, then, is a plausible physical mechanism linking the Maunder minimum to the Little Ice Age and to changes in solar activity.

Most of the observed variability of atmospheric 14C concentration of at least the last ca. 11,000 cal yr can be attributed to helio- and geomagnetic modulation of the 14C production rate induced by the cosmic-ray flux. The influence of glacial-interglacial climate change on atmospheric 14C concentration had a secondary effect (Akhmetkereev and Dergachev 1981). Stuiver and Buzina (1993) also showed that the differences among glacial, deglacial and interglacial conditions had only secondary effects, as follows from two facts: 1) the model-derived 14C production history agrees with the 14C rate derived from documented changes in the geomagnetic field over the past 30 ka; and 2) the global-scale 14C reservoirs respond relatively quickly to changes in ocean mixing processes, such
that the new atmospheric \(^{14}\text{C}\) level will have recovered after ca. 2 ka (ocean turnover time). But relatively quick changes in ocean exchange between the mixed layer and deep sea could cause rather large changes in \(^{14}\text{C}\) concentration.\(^1\) Major changes in the rate of deep-ocean ventilation occurred prior to 12,500 BP.

**The 2000-Year Period**

It is difficult to analyze numerous time series of natural data containing information on the 2 ka cycle. Bray (1968) detected the 2 ka wave in glacial advances of the 14th–18th and 4th–7th centuries BC. He associated them with depressions of solar activity. The appearance of giant peaks in 1375 and 1328 BC as well as in AD 1185 and 1239 (from the historical records of solar eclipses) indicates the extraordinary power of phenomena on the Sun (Chistyakov 1991). This example is direct evidence of the existence of the 2 ka cycle in the solar processes.

Apart from the transitions from glacial to interglacial, the 2 ka period is fixed in numerous terrestrial examples of climate change. By studying Barbados corals, Bard et al. (1990) established two rises of ocean level at ca. 12,300 and 10,000 BP. These results agree with epochs of \(^{14}\text{C}\) concentration minima. From studies of the ocean sediments off the coast of Portugal, Bard et al. (1989) determined a significant rise in ocean level from 14,500–13,500 BP. Two warm periods in Scotland, England and Ireland ca. 13 and 10 ka BP were documented by Atkinson, Briffa and Coope (1987). Chappellar et al. (1990) found distinct oscillations of methane in air bubbles of ice cores from the Vostok station at 13 and 10 ka BP. The methane concentration minimum occurred from 12–11 ka BP, corresponding to the cold period in the Younger Dryas.

Both thermoluminescence determinations on fine-grained sediment and \(^{14}\text{C}\) determinations on various organic fractions of paleosols from the profile of the Loess Plateau in central China (Zhou et al. 1992) indicate a weakened summer monsoon during the last glacial maximum followed by strengthening of the summer monsoon, beginning ca. 13 ka BP. The next increase of Asian summer monsoon circulation began from ca. 10,200 BP. Hertelendi, Sümegi and Szőör (1992) reconstructed the climate of the Great Hungarian Plain based on mollusk fauna and isotope geochemical data from 7–32 ka BP. The warmest climates with high July temperatures occurred ca. 8500, 12,500 and 17,000 BP. Comparing these paleotemperatures with temperatures of existing climate curves shows the same climate periods.

The maxima and minima of extreme changes of mean annual ocean temperatures in the Atlantic during the past 16 ka can be estimated from Arabadzhi’s (1988) results. Maxima appear at 15,600, 13,300, 11,100 and 6200, 4100, 1050 BP. Minima are at 14,600, 12,800, 10,500 and 5100, 2800, 400 BP. From 11,100–6200 BP (for maxima) and 10,500–5100 BP (for minima), the temperature curve reaches an extremely high peak; it seems that these intervals cover two fluctuations within a ca. 2 ka period. The mean interval between temperature extrema is 2400 ± 230 (12 events).

Using pollen data from France (Guiot et al. 1989) for the past 140 ka, Dergachev and Chistyakov (1992a) compiled a series of temperature maxima (estimated from a theoretical series of temperatures of ca. 2 ka). The temperature maxima of this series coincides well with the ocean temperature maxima in the Atlantic and with the low minima of the \(^{14}\text{C}\) content. Pestiaux, Berger and Duplessy (1987) also found these quasiperiodicities in the \(^{18}\text{O}\) record in ice cores and foraminifera from ocean cores. Secular climatic variations affect all living things. Archaeology offers important evidence of

\(^1\) Purely oceanic forcing is difficult to explain, involving exchange processes and complex ocean chemistry. Consideration of this problem is beyond the scope of this paper.
climate change and durations of both favorable and unfavorable intervals for human settlements. Dergachev and Chistyakov (1993) found that the most northern Paleolithic and Neolithic settlements, between which the typical period of abandonment averaged ca. 2 ka, correlate well with the warming periods.

**ON THE STRUCTURE OF THE 2000-YEAR CYCLE**

We established that the interval of the ca. 2 ka cycle includes alternating warm and cold periods (little climatic optima and little ice ages). We observed these alternations before, during and after glacial periods (Dergachev and Chistyakov 1992b). Increased solar activity is accompanied by climate warming and *vice versa*. Weak and strong peaks (several decades’ duration) are superimposed on the 2 ka trend in the variations of $\delta^{18}O$ concentration (Johnsen, Dansgaard and Clausen 1970). Oscillations in $\delta^{18}O$ and $\Delta^{14}C$ correlate well during the interval from AD 1300–1900 (Schöne 1981). Eddy (1976) noted that two episodes of strongly decreasing solar activity (the Maunder and Spörer minima) were preceded by the medieval maximum of solar activity. These episodes correspond to the last Little Ice Age and the Little Climatic Optimum.

From the mean temperature change curve of the Atlantic Ocean (as discussed above), one can estimate the mean interval between two extrema, which is $T = 2400 \pm 200$ yr. Minima appear (900 ± 300 yr) ($\Delta T$) after maxima. We propose that the durations of the warm and cold phases equal $\Delta T$ and the duration of the quiet phase is $\delta T = 800–1300$ yr.

It is well known that climate warming is accompanied by transgressions of the World Ocean and regressions of lakes and seas with closed basins. From the data of Kalinin, Breslav and Klige (1975) on level fluctuations of the World Ocean and Caspian Sea, Dergachev and Chistyakov (1993) estimated the mean intervals of the 2 ka cycle structure: $T = 2500 \pm 300$, $\Delta T = 700 \pm 200$, $\delta T = 1100 \pm 500$ (Fig. 3). The analysis of detailed data on the sharp switch-over of warm and cold climate periods and the influences of these changes on human life for the last millennia enable us to represent the structure of the 2 ka solar and climatic cycle. Figure 3 shows these three phases: 1) the active (+) phase with a high level of solar activity and the little climatic optimum; 2) the depression (−) phase with a decrease in solar activity like the Maunder and Spörer minima and the Little Ice Age. This phase follows the active phase with the time shift of $\Delta T$; 3) the quiet phase $\delta T$. Chistyakov (1993) estimated the duration of this phase as $\delta T \approx 800$ yr. Reliable $^{14}C$ data enable us to trace both the separate elements in and the whole structure of the 2 ka cycle.

**CONCLUSION**

The last dip of solar activity (the Maunder minimum) ended at the start of the 18th century. In subsequent centuries, solar activity increased and the climate warmed. The strongest solar cycle was the 19th cycle with the sunspot maxima in 1957. In subsequent cycles, activity decreased. The last minimum of the 210-yr period in solar activity occurred at the end of the 19th century. The maximum
of this cycle should occur in the early 21st century. Climate warming accompanies increasing solar activity. Multicentury increases of solar activity are no longer possible. The present levels of solar activity and climate correspond to the quiet phase, $8T$, which will continue for several centuries. We found the possible fluctuations of the Sun’s luminosity during the maximum of its activity to be small (Dergachev and Chistyakov 1992a). Thus, we conclude that the Sun is a stable system. Much effort has been made to find solar cyclicity in the geophysical records. Evidence for a statistically significant 11(22)-, ca. 210- and ca. 2000-yr periodicity in various terrestrial indices is increasing.

REFERENCES


Bard, E., Fairbanks, R., Arnold, M., Maurice, P., Moyes, J. and Duplessy, J.-C. 1989 Sea level estimates during the last deglaciation based on $^{18}$O accelerator mass spectrometry $^{14}$C ages measured in Globigerina bulloides. Quaternary Research 31(3): 381–391.


mental Factors, Pushchino, Russia, 27 September–1 October.

Guio, J., Pons, A., de Beaulieu, J. L. and Reille, M. 1989
A 140,000-year continental climate reconstruction from

Hertelendi, E., Szemigi, P. and Szoor, F. 1992 Geochrono-
logic and paleoclimatic characterization of Quaternary
sediments in the Great Hungarian Plain. In Long, A.
and Kra, R. S., eds., Proceedings of the 14th Interna-

Houtermans, J. C. (ms.) 1971 Geophysical Interpretation
of Bristlecone Pine Radiocarbon Measurements Using
A Method of Fourier Analysis of Unequally Spaced

Johnsen, S. J., Dansgaard, W. and Clausen, H. B. 1970
Climatic oscillations 1200–2000 AD. Nature 227:
482–483.

questions of the contemporary ocean level. In Kalinin,
G. P. and Klige, R. K., eds., World Ocean Level Fluc-
tuations and Geomorphology Problems. Moscow,

Klein, J., Lerman, J. C., Damon, P. E. and Linick, T. Ra-
diocarbon concentration in the atmosphere: 8000-year
record of variations in tree rings. In Stuiver, M. and
Kra, R. S., Proceedings of the 10th International 14C

Kromer, B. and Becker, B. 1993 German oak and pine
14C calibration, 7200–9439 BC. In Stuiver, M., Long,

Merrill, R. T. and McElhinny, M. W. 1983 The Earth’s
Magnetic Field: Its History, Origin and Planetary

Neffel, A., Oeschger, H. and Susse, H. E. 1981 Secular
non-random variations of cosmogenic carbon-14 in the
terrestrial atmosphere. Earth and Planetary Sci-

Pearson, G. W., Plichter, J. R., Baillie, M. G. L., Corbett,
D. M. and Qua, F. 1986 High-precision 14C measurement
of Irish oaks to show the natural 14C variations from
AD 1840 to 5210 BC. In Stuiver, M. and Kra, R. S.,
ed., Proceedings of the 12th International 14C

Pestiaux, A., Berger, A., Duplessy, J. C. 1987 Paleocli-
matic variability at frequencies ranging from 1 cycle
per 10000 years to 1 cycle per 1000 years: Evidence
for nonlinear behaviour of the climate systems. Clima-

Ribes, E., Merlin, Ph., Ribes, J.-C. and Bartholat, R. 1990
Absolute periodicities in the solar diameter derived
from historical and modern data. Annales Geophys-


1981 Sunspot Cycles. Dowen, Hutchinson and
Ross, Inc.: 397 p.

Sonett, C. P. and Finney, S. A. 1990 The spectrum of ra-
diocarbon. Philosophical Transactions of the Royal

Sonett, C. P. and Suess, H. E. 1984 Correlation of bristle-
cone pine ring widths with atmospheric 14C variations:

Stuiver, M. and Becker, B. 1986 High-precision decadal
calibration of the radiocarbon time scale, AD 1950–
2500 BC. In Stuiver, M. and Kra, R. S., eds., Proceed-
ing of the 12th International 14C Conference. Radiocarbon

1993 High-precision decadal calibration of the ra-
diocarbon time scale, AD 1950–6000 BC. In Stuiver, M.
and Kra, R. S., eds., Calibration 1993. Radiocarbon

Stuiver, M. and Brazianas, T. F. 1993 Modeling atmos-
pheric 14C influences and 14C ages of marine samples
to 10,000 bc. In Stuiver, M. and Kra, R. S., eds., Calib-

Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th In-
ternational 14C Conference. Radiocarbon 28(2B): 805–
1030.

Stuiver, M., Pearson G.W. and Brazianas T. F. 1986 Ra-
diocarbon age calibration of marine samples back
to 9000 cal yr BP. In Stuiver, M. and Kra, R. S., eds., Proceed-
ing of the 12th International 14C Conference. Radiocarbon

Susse, H. E. 1965 Secular variations of cosmic ray pro-
duced carbon-14 in the atmosphere and their interpreta-

1978 The radiocarbon record in tree rings of the last
8000 years. In Stuiver, M. and Kra, R. S., eds., Proceed-
ing of the 10th International 14C Conference. Radiocarbon

Tarling, D. H. 1988 Secular variations of the geomag-
netic field — archaeomagnetic record. In Stephenson,
F. R. and Wolfendale, A. W., eds., Secular Solar and
Geomagnetic Variations in the last 10,000 Years. Dor-

Willis, E. H., Tauber, H. and Münich, K. O. 1960 Vari-
ations in the atmospheric radiocarbon concentration
over the past 1300 years. American Journal of Science

Xu, Z. 1990 Solar observations in ancient China and so-
lar variability. Philosophical Transactions of the Royal

Zhou, W., An, Z., Lin, B., Xiao, J., Zhang, J., Xie, J.,
Zhou, M., Porter, S. C., Head, M. J. and Donahue, D.
J. 1992 Chronology of the Baxie loess profile and the
history of monsoon climates in China between 17,000
and 6000 years BP. In Long, A. and Kra, R. S., eds., Proceed-
ing of the 14th International 14C Conference. Radiocarbon