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LONG-TERM SOLAR VARIABILITY DEDUCED FROM CHANGES IN THE ATMOSPHERIC ^{14}C PRODUCTION RATE

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RESUMEN

Un análisis espectral de la producción de ^{14}C en la atmósfera (300-1900 d.C.) evidencia la existencia de oscilaciones superseculares en la actividad solar. Se somete a prueba la significación y estabilidad de estas oscilaciones mediante la reproducción del registro histórico. La extensión de este registro hacia el futuro muestra que una nueva oscilación del tipo Spörer, similar a la ocurrida durante el siglo XV, es muy probable que ocurra de nuevo alrededor del año 2300.

ABSTRACT

A power spectral analysis of the atmospheric ^{14}C production rate (300-1900 AD) has yielded evidence of the existence of supersecular oscillations in solar activity. The significance and stability of these oscillations is tested by reproducing the historical record. The results of a projection into a future period show that a new Spörer type oscillation, similar to that occurred in the 15th century, will probably occur again around the year A.D. 2300.

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INTRODUCTION

Several studies on solar variability have been based on the number of sunspots seen on the visible disk of the Sun (Gleissberg, 1944; Mitchell, 1965; Radoski *et al.,* 1975; Otaola and Zenteno, 1983). However, this record is limited to the last 284 years and the quality of the data is not homogeneous. Therefore, in order to extend backwards in time the study of solar variability and at the same time to have a more or less homogeneous record we have had to resort to indirect data by using the dendrochronological signature of the ^{14}C production rate in the Earth's atmosphere.

The use of ^{14}C content in the atmosphere as an indicator of past solar variability has been pointed out by many authors (Stuiver, 1961, 1965, 1980; Bray, 1967; Suess, 1965; Damon, 1970, 1977). ^{14}C is produced in the atmosphere by a variety of nuclear interactions, being the $^{14}N(n, p)^{14}C$ reaction the most effective. The neutrons responsible for the production of ^{14}C, result from spallation caused by the incoming galactic cosmic rays which, in turn, are modulated by the large scale elctromagnetic conditions of the interplanetary medium through which they travel towards the Earth. As these conditions are solar regulated, the cosmic-ray flux and hence the ^{14}C production rate show an inverse correlation with the level of solar activity (Forbush, 1954; Lingenfelter, 1963). Therefore, the history of solar activity in the past can be reconstructed if we have a long enough record of the ^{14}C production rate in the atmosphere and due account is taken of the long-term quasi-sinusoidal variation in the earth's dipole field which also modulates the incoming cosmic-ray flux, and thus the ^{14}C production rate.

Stuiver and Quay (1981) have provided us with such a record which covers the 300 to 1900 AD interval. The ^{14}C production rate is derived from tree-ring ^{14}C measurements using a carbon reservoir model that takes into account carbon exchange between the biosphere, atmosphere and oceans. With this record which correlates well with the level of solar activity, as measured by the historical registers of the number of sunspots (Stuiver, 1980; Stuiver and Quay, 1980) it is possible to study indirectly the possible existence of very long-term periodicities on solar activity.

It is the purpose of this paper to test the reality or not of these very long-term periodicities using the non-integer method (NIM) of power spectral analysis (Schickedanz and Bowen, 1977).

ANALYSIS AND DATA

The method of power spectral analysis used in the present paper, the NIM, is based on a modification of the usual Fourier equations so as to permit the computation of non-orthogonal coefficients (non-independent) using non-integer values. This provides substantially finer resolution than conventional methods and a very good approximation to a continuous spectrum is obtained so that further smoothing by a window which is independent of the data analyzed is not required. A further advantage of the NIM is that the significance of the spectral estimates is easy to assess (F-test) and as the method also gives the amplitudes and the phases of the oscillations involved, an appropriate estimate can be made of the original data series or some future extrapolation.

We have analyzed the whole record of decennial values of the ^{14}C production rate changes ΔQ_M, relative to the average production rate Q_M for the interval 1000-1860, given by Stuiver and Quay (1981) for the 300-1900 AD period. Figure 1 shows this 1600 year long record.

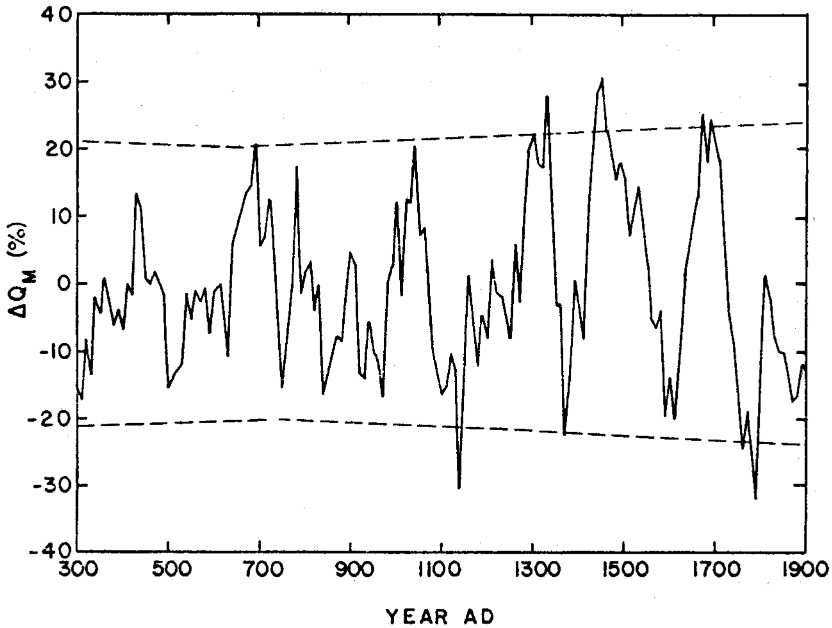

Fig. 1. ^{14}C production rate changes ΔQ_M, relative to the average 1000-1800 production level, for the 300-1900 interval. The dashed lines reflect the influence of geomagnetic field changes on the magnitude of the solar induced production rate changes (taken from Stuiver and Quay, 1981).

The dashed line reflects the influence of the long-term variation in the geomagnetic field intensity on the magnitude of the ^{14}C production rate changes.

As the NIM has proved to be a useful tool to detect long-term trends or cycles in short time series without the need of assuming prior to the analysis the order of the trend, the record was not preconditioned by the removal of any trend nor filtered in any way prior to the analysis.

The spectral estimates were determined for each 0.1 data point, which provided 1600 estimates of the spectrum with wavelengths resolvable to 1 year. The partial correlation coefficients between the sine and cosine waveforms for each spectral estimate were found to be insignificant, so that for practical purposes the estimates possess the property of orthogonality (independence).

RESULTS

Figure 2 shows the spectrum of the ^{14}C production rate changes for the period 300-1900. Besides the spectrum, confidence levels at the 1, 5 and 10%, according to the Fisher-Snedecor F-test, are plotted as dotted lines. It can be seen that there are significant peaks at wavelengths

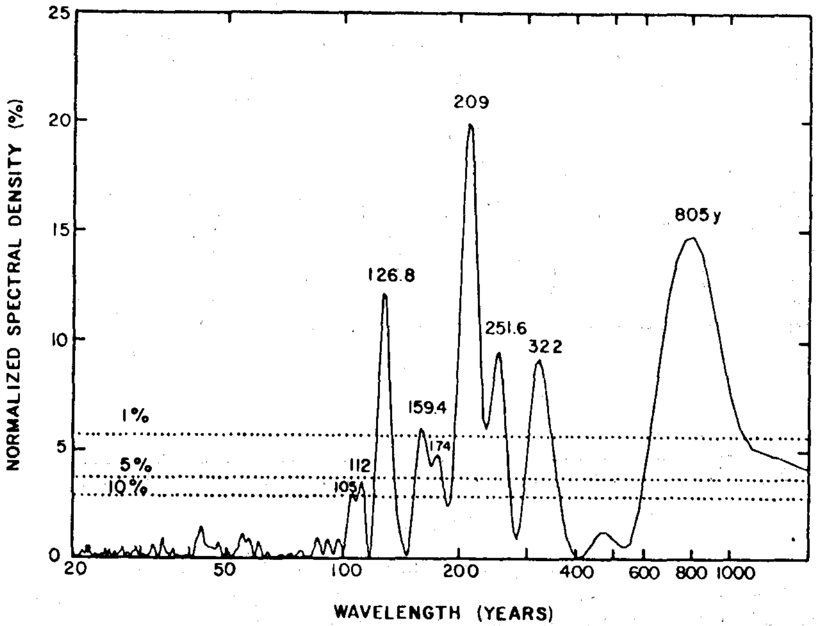

Fig. 2. Non-integer spectrum of the ^{14}C production rate changes ΔQ_M for the interval 300-1900.

of 105, 112, 126.8, 159.4, 174, 209, 251.6, 322 and 805 years and there is not any indication of the presence of persistence (red noise) in the spectrum. As the number of cycles in the sample increases towards shorter wavelengths, the confidence in the stability of the spectral peaks also increases. Thus, for wavelengths < 320 years, five or more cycles are present in the complete data set which ensures the stability of those peaks. Evidently, there are two dominant peaks that correspond to periods of 127 and 209 years. On the other hand, since all periodicities with wavelengths greater than 320 years are repeated less than five times in the data sample, the significance and stability of the 322 and 805 years peaks is not so evident. Nevertheless, the fact that the NIM also gives the amplitudes and the phases of the oscillations involved, enables us to reproduce the ΔQ_M curve by combining the dominant peaks. In this way we can test the reality of the spectral peaks in the actual record and at the same time to extend the waveforms into an independent future period.

Figure 3 shows the results of such reproduction and extension, up to the year 2500 AD, which were made by selecting the amplitudes and the phases of all those spectral peaks significant at the 10% level in the spectrum of the ΔQ_M series (Fig. 2). The correlation coefficient between the actual (solid curve) and estimated (dashed curve) series

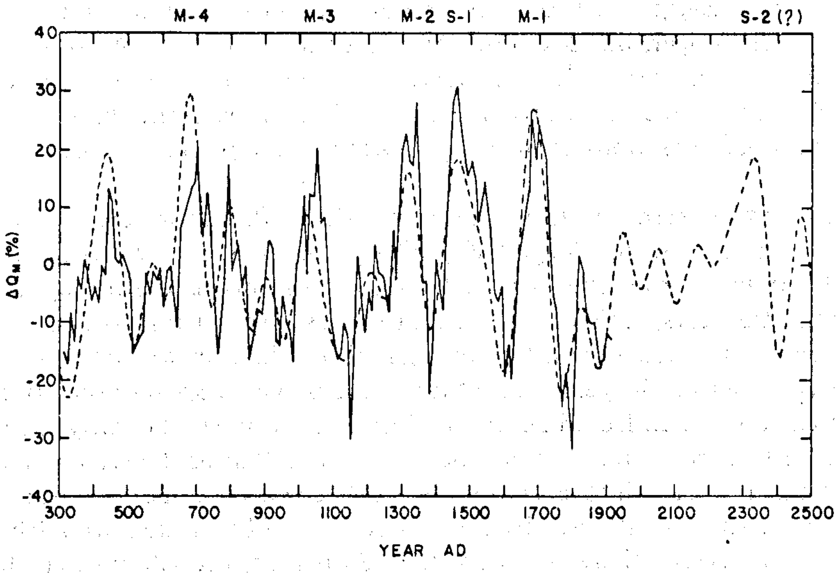

Fig. 3. The estimated (dashed curve) and actual (solid curve) ΔQ_M series for historical and predicted periods.

amounts to +0.83 involving a 95% confidence region of ±0.05. The significance of correlation exceeds 99.99% as proved by the t-test. The general agreement between the two series confirms the significance and stability of the main spectral peaks, including those at wavelengths greater than 320 years.

It is noteworthy that no periodicities at wavelengths less than 100 years are present in the spectrum. This may very well be the result of the 60 year carbon residence time in the biosphere which makes the atmosphere to act as a low-pass filter.

SUMMARY

Although it is difficult to assert which of the oscillations found in the spectrum of ^{14}C production have a solar origin, the superposition of the most significant oscillations can very well give account of the major changes in solar activity on the past. Maxima in ^{14}C production have been shown to be the signature of marked decreases in solar activity, and viceversa (Eddy, 1977; Stuiver, 1980).

The results shown in Figure 3 show quite clearly what Stuiver and Quay (1981) have identified as major Maunder type oscillations (M-1/M-4), each lasting 120-140 years, and one Spörer type oscillation (S-1), which lasts longer, but does not differ much in magnitude. All of these periods of maximum ^{14}C production rate coincide with periods on which sunspot records, auroral counts, naked-eye sunspot reports and corona-less descriptions of the eclipsed sun are rare or almost absent.

As for the extension up to the year A.D. 2500, we forecast the existence of a new isotope stage ($\Delta Q_M \geqslant 10$ percent) around the year A.D. 2300. Judging from the expected duration of this new isotope stage (about 200 years), this could be identified as a Spörer type oscillation. However, the switch from low to high ^{14}C production will take about 120 years, about 40 years more than in the previous Spörer oscillation, whereas the switch from high to low ^{14}C production will be fairly rapid, about 80 years. Here, it should be emphasized that as the record analyzed did not take into account the most recent data (20th century), which are strongly affected by the combustion of fossil fuels after 1890 (the Suess effect), there is a more than 85 percent probability that the ΔQ_M curve will reach a maximum around the year A.D. 2300, and therefore that a new minimum in solar activity will occur.

Although the relationship between solar variability and climate has not been yet very well established, due to the lack of a physical mechanism, Willet (1974), based entirely on a solar-climatic analogy with the past, has predicted a new "Little Ice Age", circa 2200-2500, somewhat more severe than that from 1500-1850, as a consequence also of a new prolonged minimum in solar activity around that time.

On the basis of the present study we can conclude that the major changes in solar activity during the past, like the Maunder and Spörer minima, are far from being periodic but are the result of the superposition of various significant and stable oscillations in the 100-1000 yr period range.

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