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On the presence of regular periodicities in the thermoluminescence profile of a recent sea sediment core

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We briefly discuss how the thermoluminescence (TL) profile of a young marine sediment provides phenomenological information on the changes in the environmental conditions in the past 18 centuries. The main periodicities present in the TL profile are studied and the similarities between the TL variations and the fluctuations in the contemporary tree-ring $\Delta^{14}C$ signal are considered. An interesting result is the presence, in the TL data, of a well-defined 11-year cycle which is stable and 'in phase' for the entire period analysed. We also discuss how four dominant periodicities present in the TL data may be rewritten as the sum of an 11.4-year and of an 82.6-year cycle (reminiscent respectively of the Schwabe and of the Gleissberg cycles of solar activity), which are both amplitude modulated by a 206-year wave. This last periodicity has already been shown to play a dominant role in the $\Delta^{14}C$ record. These results suggest that the TL profiles of recent marine sediments may be successfully used as a new line of evidence for solar variability in the past centuries.

1. INTRODUCTION

In previous studies (Cini Castagnoli *et al.* 1984*a*, *b*, 1988*a*, *b*; Cini Castagnoli & Bonino 1985, 1988) we analysed the variations of the thermoluminescence (TL) level accumulated in the fine polymineral material (grains less than 44 μm in size) of young marine sediments. In recent cores (about 2000 years before present (BP)), the predepositional exposure of the crystals is in general not completely altered by the irradiation produced *in situ* by the local radioactivity. Thus the analysis of the TL fluctuations in these cores indicate, it is hoped, how the environmental conditions, which determine the TL level accumulated by the crystalline minerals before deposition, change with time. In the above papers the principal periodicities present in the TL profiles have been determined and the affinity of the TL signal to the solar variability has been explored. In this paper we further discuss the TL periodicities and consider the possible correlations between the TL signal and tree-ring radiocarbon data. These results may thus provide new phenomenological information on the characteristic temporal variations of the solar–terrestrial system and on the mechanisms that drive the terrestrial rhythms.

Let us now briefly consider how TL time series are measured. When the material of a core is heated some of the charges that are trapped in the polymineral crystals of the sediment are released, generating a TL signal. If the sedimentation rate is measured by independent methods (such as measurement of the ^{210}Pb concentration) then the TL depth profile (i.e. the succession of the TL relative intensities measured in contiguous layers of the sediment) may be transformed in a TL time series. In past years we analysed the TL profiles of several cores from different coastal sites, each core having a different sedimentation rate and being sampled with a different sampling interval. Common features were detected in the TL profiles of the different cores, and consistent periodicities on both decennial and secular timescales have been determined.

In the case of the GT14 core, drilled in the Ionian Sea in 1979, it was possible to conduct a detailed analysis on a TL profile that spans approximately 18 centuries (Cini Castagnoli *et al.* 1988*a*, *b*). The GT14 core is 1.17 m long and has been drilled in the Gulf of Taranto near Gallipoli (Italy), at 39°45′55″ N, 17°53′30″ E. The drilling site is located on the continental shelf at 18 km from the coast, in a water depth of 166 m. The core has been sampled at equal intervals $\Delta d = 2.5$ mm and well-defined, regular oscillations with periods of 89 mm, 7.8 mm and 6.97 mm have been detected. The use of the ^{210}Pb method and a careful tephroanalysis of known volcanic events, together with the information deduced from the presence of a ^{137}Cs peak at the top of the sediment, allowed for the precise determination of the sedimentation rate. The sampling interval Δd has been found to correspond approximately to a time interval $\Delta t = 3.87$ years and the TL depth profile was consequently transformed in a TL time series. The temporal periods of the main regular oscillations detected in the TL profile have correspondingly been determined. The 11-year solar cycle in particular was detected with a high confidence level in the resulting TL signal (Cini Castagnoli *et al.* 1988*b*). Here we (1) discuss the principal features present in the TL profile of the GT14 core and (2) we analyse, using the method of cyclograms (Galli 1988), the stability of the phase of the 11-year cycle during the time interval spanned by the core.

2. TL FEATURES DURING THE SOLAR EVENTS OF MAUNDER, SPÖRER AND WOLF

To compare the TL signal with other proxy data for solar activity in figure 1 we show the radiocarbon tree-ring time series (*a*) and the TL time series from the GT14 core (*b*) for the period 1100–1900 A.D. The Δ^{14}C data are in the decadal form given by Stuiver & Braziunas (1988) and are plotted on an inverted scale. We can see that the TL data show the expected Maunder Minimum during the period 1645–1715 A.D. In this period the Δ^{14}C signal has a

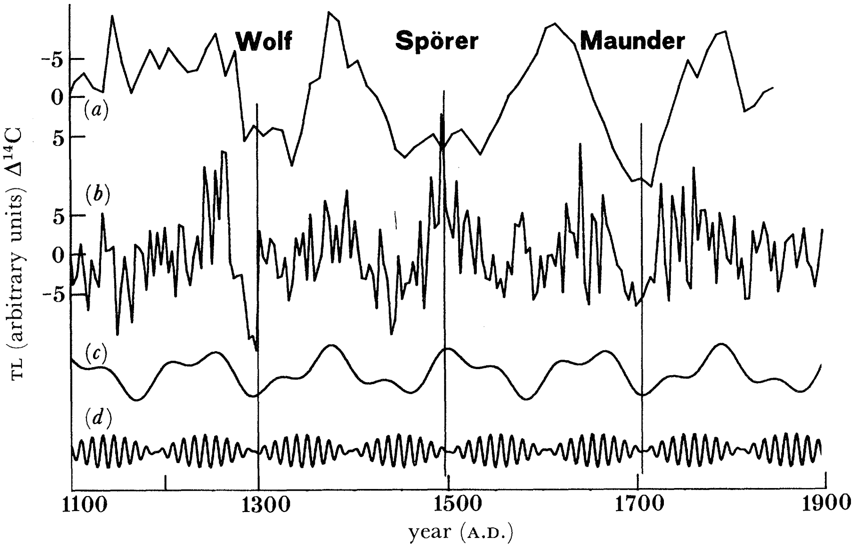

FIGURE 1. (*a*) The decadal Δ^{14}C record as given by Stuiver & Brazuinas (1988). (*b*) The detrended TL signal from the GT14 core. (*c*) The sum of the two TL waves with periods of 137.7 and 59 years. (*d*) The sum of the two TL waves with periods of 12.06 and 10.8 years.

well-known maximum. From the TL signal one also sees that the Spörer Minimum starts at the end of the fourteenth century, in agreement with the $\Delta^{14}C$ data. In the TL data, however, this event seems to have recovered around 1500 A.D., showing a double feature not present in $\Delta^{14}C$ signal. The end of the Spörer event is vice versa at about the same time for both series (around 1600 A.D.). The Wolf Minimum is finally observed in the TL series at the expected time (around 1300 A.D.), in agreement with the $\Delta^{14}C$ data.

3. THE TL PERIODICITIES

The power spectral density of the TL data (Cini Castagloni *et al.* 1988*b*) was computed by standard Fourier techniques from the detrended 427 points time series and is shown in figure 2. The spectrum shows sharp significant peaks among which the well-known 11-year cycle appears. The 95% significativity implies a significant interval $\frac{1}{2}P(f) \leqslant \pi(f) \leqslant 4\,P(f)$ where $\pi(f)$ is the 'true' spectrum and $P(f)$ is our spectral estimate. This because we have four independent glow curves for each layer and therefore four replicas of the 427 points time series. In figure 2 a second, low-level dashed curve is also reported. This curve is the spectrum computed for a fifth series, obtained from 'bleached' samples. One sample for each layer was in fact exposed to the action of a standard sunlamp for 420 min before measuring the glow curves. The bleached spectrum does not show any evident periodicity and provides a background noise level for the original TL spectra. In this respect we stress the fact that the secular and the decennial peaks of 137.7, 59, 12.06 and 10.8 years are all significant at the 95% significance level.

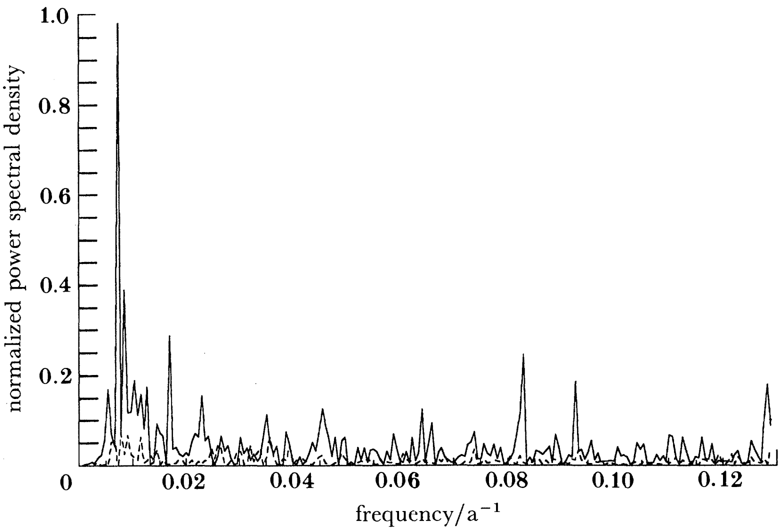

FIGURE 2. Power spectrum of the TL signal.

To further explore whether the 11-year cycle is present over the whole time interval spanned by the TL data we consider the cyclogram analysis for the 10.8-year and 12.06-year waves. The cyclogram method allows a time series to be analysed interval-wise by plotting running averages of the complex amplitudes of the Fourier transform for a given periodicity (Galli 1988). A window is moved along the time series, continuously testing for the chosen periodicity. When the chosen periodicity is present and correctly determined, the cyclogram tends to a straight line. For test periods shorter than a 'true' period present in the data the cyclogram tends to turn anticlockwise, while for test periods larger than the true period the cyclogram turns clockwise. If no regular oscillation with periodicity around the chosen test period is present in the data, then the cyclogram has the appearance of a random walk on the plane of the complex Fourier amplitudes. Thus computing several cyclograms for different test periods around a periodicity of interest allows (1) for its careful determination and (2) for testing its stability along the time series.

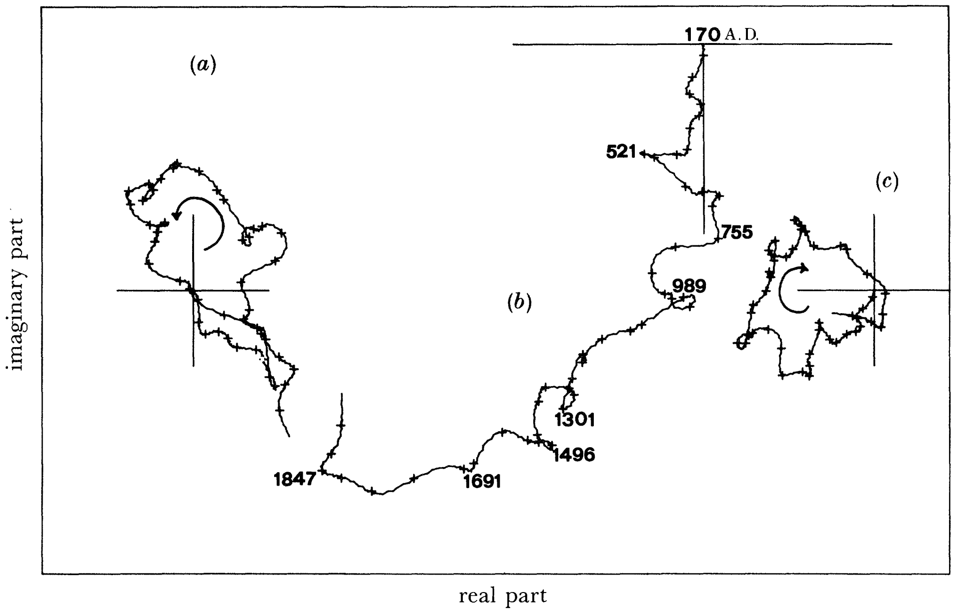

FIGURE 3. Cyclograms obtained from the TL signal using a window of period $T = 39$ years and test periods (*a*) $\tau = 10.7$ years, (*b*) $\tau = 10.8$ years, and (*c*) $\tau = 10.85$ years.

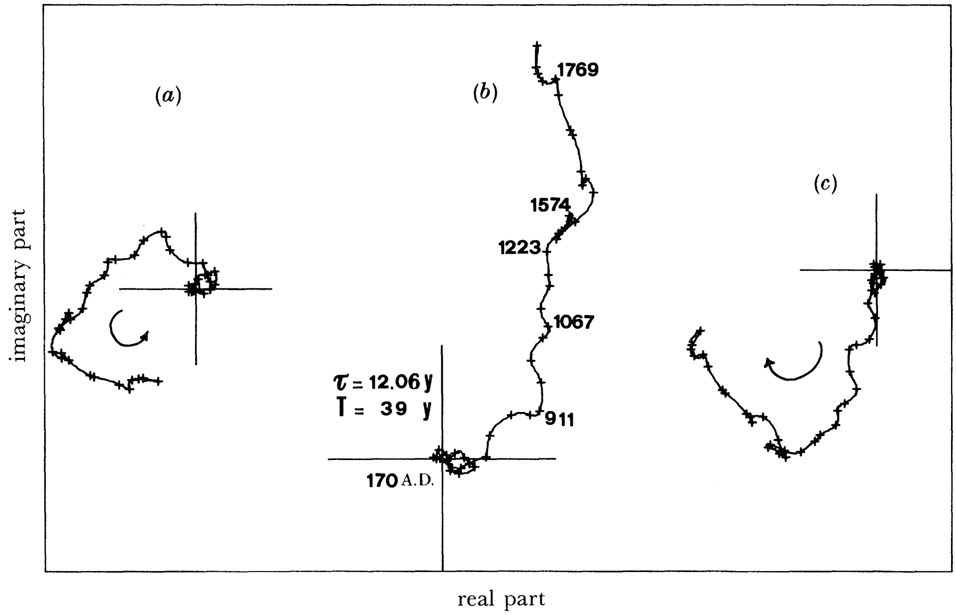

FIGURE 4. Cyclograms obtained from the TL signal using a window of period $T = 39$ years and test periods (*a*) $\tau = 12.0$ years, (*b*) $\tau = 12.06$ years, and (*c*) $\tau = 12.15$ years.

In figure 3*b* we show the cyclogram for the test period $\tau = 10.8$ years with a window of $T = 39$ years (equivalent to 10 data points). The cyclogram is clearly straight and shows that 45 independent vectors (whose extrema are indicated by the crosses) are aligned with the same phase from 170 to 1970 A.D. The cyclograms are anticlockwise when performed on a test period $\tau = 10.7$ years (figure 3*a*) and clockwise for $\tau = 10.85$ years (figure 3*c*), indicating a very regular, non-random character of the 10.8-year cyclicity. In figure 4*b* we show the analogous cyclogram for $\tau = 12.06$ years. Again the cyclogram is straight. The cyclogram is on the other hand anticlockwise for $\tau = 12.0$ years (figure 4*a*) and clockwise for $\tau = 12.15$ years (figure 4*c*). The quantitative significance of the observed periodicities is difficult to assess, however the distance between the first and the last points of the cyclograms of figures 3*b* and 4*b* significantly exceeds the distance that would be attained by a random walk with 45 independent vectors (steps) with non-correlated increments.

4. Relations with the solar cycles

In a previous paper (Cini Castagnoli *et al.* 1988*b*) we discussed how the two high-frequency components of 12.06-year and 10.8-year beat producing a wave train whose carrier has a period of 11.4 years. This wave train is amplitude modulated with a period of approximately 206 years, a periodicity already detected in the $\Delta^{14}C$ data (Beer *et al.* 1988; Cini Castagnoli *et al.* 1989). In Cini Castagnoli *et al.*'s paper the phases and amplitudes of the waves were determined by the method of the superposition of epochs. It is interesting to note that the nodes of the modulated wave train coincide with the well-known secular minima in the yearly sunspot number recorded in 1810 A.D. and in 1913 A.D. The modulated wave train is shown in figure 1*d* for the period 1100–1900 A.D. The beats coincide with the centres of the Maunder and Spörer events, as given by the $\Delta^{14}C$ data. The same approximately happens for the Wolf event. This may well indicate that the presence of small sunspot cycles every 103 years may be a regular feature of the solar output.

The oscillation obtained as the sum of the two long waves of 137.7 and 59 years is shown in figure 1*c*. We notice that the centres of the Maunder and of the Wolf events lie in minima of this oscillation, while the centre of the Spörer event lies in a maximum. We recall that also the sum of the two low-frequency TL waves of 137.7 and 59 years may be rewritten as the product of two component waves of 82.6 and 206 years, plus a residues of 137.7 years (Cini Castagnoli *et al.* 1988*b*).

As a conclusion we thus stress that (1) a few well-defined dominant periodicities are evident in the TL signal; (2) among these two decennial oscillations are present, which have been shown to be stable over the entire time interval spanned by the core; and (3) four of the most energetic significant TL peaks may be rewritten as the sum of two oscillations of 11.4 and 82.6 years, which are amplitude modulated with the same period of 206 years. The two 'carrier' oscillations have periods that are similar to those generally attributed to the Sun as the Schwabe and the Gleissberg cycles, while the amplitude modulation has the same period of a very energetic wave present in the $\Delta^{14}C$ signal (Beer *et al.* 1988; Cini Castagnoli *et al.* 1989). These results thus suggest that the TL profiles of recent sea sediment cores may be successfully utilized as a new line of evidence for the solar variability and encourage to further pursue this type of analysis.

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