Solar Cycles in the Last Centuries in ^{10}Be and δ^{18}O in Polar Ice and in Thermoluminescence Signals of a Sea Sediment (*).

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Summary. — The cyclogram method of time series analysis has been used to analyse ^{10}Be data (1181-1800 AD) and δ^{18}O data (1181-1960 AD) from an artic ice core and thermoluminescence data (1181-1960 AD) from a Mediterranean sediment core. The ^{10}Be concentrations were determined at the ETH Zurich. The δ^{18}O values were measured at the University of Copenhagen. The TL measurements were performed at the Istituto di Cosmo-geofisica del C.N.R., Torino. Common mean periodicities of 10.75 y are found for the period 1505 to 1710 AD in TL and ^{10}Be and of 11.4 y for the period 1715 to 1880 in TL and δ^{18}O. This periodicity was found in the solar sunspot (R_z) series analysed in the same way, from 1825 to 1905. This supports the argument that the common periodicities found in the long-running series are peculiar of the solar activity in the past.

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1. – Introduction.

In the recent years great progress has been achieved in the field of solar-terrestrial physics at least for what concerns the direct observations of the solar phenomena. Measurements of the solar-activity indices, of the solar constant, of the emission at different wave-lengths, of the interplanetary magnetic field and plasma have been performed on board of spacecraft, while on the Earth a great number of solar, climatic and geomagnetic parameters were continuously monitored. However, the short length of time over which the records are taken still do not allow a full understanding of the complex physical processes visible on the Sun and of how their variations influence the terrestrial environment. Long-running terrestrial series may, therefore, provide valuable information.

Furthermore, the signals are often buried in the noise and *ad hoc* techniques of numerical analysis have to be investigated in order to separate signal from noise. As a classical example we can refer to the 27 day recurrence of the geomagnetic effects related to the *M* regions of the Sun. CHAPMAN and BARTELS (1) proved its existence by the harmonic analysis of the « international magnetic character, figure *C* data » plotted not in the usual way, but in a sequence of vectors called « summation dial ».

We stress the fact that, by suitable numerical analysis of the time series, it was possible to infer the solar-terrestrial forcing effects.

The time series of the sunsposts (R_z) has also been extensively studied in order to infer models of the Sun and in order to determine the periodicities, which should be reflected in the terrestrial records.

The 11 y cycle is the most persistent feature observed. In order to investigate solar-terrestrial relations in the past, records in appropriate terrestrial archives must be analysed. The ^{14}C concentration in tree rings, which covers a long time interval ($\sim$ 7000 y), has been often proposed as a test for demonstrating the presence of the Sun imprint stored in a terrestrial reservoir, as well as the width of the rings themselves. But the exchange processes between the time of production of ^{14}C in the atmosphere and of the absorption in the trees involve the damping of the signals and somehow make it difficult to detect the most important of the Sun long periodicities, the 11 y cycle.

^{10}Be, due to its relatively short mean atmospheric residence time and the absence of exchange processes, is the cosmogenic isotope better suited for studying solar-terrestrial relations. In fact, the 11 y solar cycle has been de-

(1) S. CHAPMAN and J. BARTELS: *Geomagnetism* (Oxford, 1940), p. 545.

tected in the data running from 1900 to 1976 ([2]) and also in the Milcent core from 1181 up to 1808 ([3]).

The thermoluminescence (TL) signals from the different layers of a sea sediment supposed to have a contribution from the atmospheric dust irradiated before deposition may be used for the investigation of the irradiation of the Earth in the past. The 11 y solar cycle has been detected there also, during the 17th century ([4]).

Beside these two time series, the series of $\delta^{18}O$ in polar ice has been chosen for this investigation as a test for climatic variations, its deposition in the polar regions being sensitive to the changes of the circulation pattern of the Earth atmosphere and to its temperature. The numerical analysis of the time series has been performed by both the power spectrum and the cyclogram methods; the conventional power spectrum alone is not suited for the analysis of the continuously changing periodicities, while the cyclogram method allows us to follow them in detail ([5]).

2. – The cyclogram method.

We briefly recall the numerical procedure used to make the graphs: from the series of N equispaced data $\{x_t;\ t = 1, 2, \ldots, N\}$ a subseries of length T is chosen starting from the t-th datum.

In a moving way the complex harmonic amplitude of a period $\tau \leqslant T$ is then computed by the fast Fourier transform:

$$\left\{\boldsymbol{a}_t = \frac{2}{T}\sum_{k=t}^{t+T-1} x_k \exp\left[i2\pi k/\tau\right];\ t = 1, 2, \ldots, N - T + 1\right\}$$

and summed progressively in the harmonic dial.

The unit vectors having the same phases as the amplitudes are also represented in the same way. We call the first and the second curve the *phase* and the *amplitude* cyclograms, respectively. A sine wave of period τ_0 will

([2]) J. Beer, M. Andrée, H. Oeschger, B. Stauffer, R. Balzer, B. Bonani, Ch. Stoller, M. Suter, W. Wolfli and R. C. Finkel: *Radiocarbon*, **25**, 269 (1983).
([3]) J. Beer, H. Oeschger, M. Andrée, R. Finkel, G. Cini Castagnoli, G. Bonino, M. R. Attolini and M. Galli: in preparation.
([4]) G. Cini Castagnoli, G. Bonino, M. R. Attolini and M. Galli: *Nuovo Cimento C*, **7**, 69 (1984).
([5]) *a*) M. R. Attolini, S. Cecchini and M. Galli: *Proceedings of the XVII International Cosmic-Ray Conference*, Vol. **8**, 202; *b*) M. R. Attolini, S. Cecchini and M. Galli: *Nuovo Cimento C*, **7**, 245 (1984).

appear as a straight line if $\tau_0 = \tau$, whereas it will appear as an arc of a circle bent to the right or to the left according to $\tau_0 > \tau$ or $\tau_0 < \tau$. If considerations are to be made about the existence of nonrandom periodicities, the phase cyclogram is preferred because it is less variable and it is not affected by the statistical dependence between the amplitudes. For the sake of convenience every sum of T consecutive vectors is divided by T for the phases and by $\bar{a}T$ for the amplitudes and then marked with a circle ($\bar{a}$ is the r.m.s. amplitude). Furthermore, the vector connecting two successive marks will represent the average amplitude in the amplitude cyclogram and the average phases in the phase cyclogram. Obviously, when analysing the variation of geophysical and astrophysical phenomena in which instability and turbulence are present or regular variability may appear at random, the power spectrum analysis is not suitable because the time and phase information is destroyed. With the cyclogram analysis, instead, it is possible to discover significant trains of periodicities among random variations and also to evaluate the time variation of the amplitude. The relation of the cyclogram method to the power spectrum consists in the fact that to a stretched part of the cyclogram corresponds a peak in the p.s. calculated over the same time interval. The straighter is the cyclogram, the narrower is the peak. The centre of the peak represents obviously the average periodicity over the considered time interval.

3. – Experimental data and results.

The data series, covering the last centuries, are

a) the ^{10}Be concentration in the Milcent core [6],

b) the δ^{18}O in the same core [7],

c) the thermoluminescence intensity from the different layers of the Tyrrhenian Sea sediment core CT75 [4,8].

In fig. 1 the two phase cyclograms of ^{10}Be and of TL from the year 1180 up to 1780 are shown for the period $\tau = 10.75$ y. TL data are sampled every 4.35 y between 1500 and 1780; previous measurements are at 8.7 y intervals. ^{10}Be data are measured at intervals varying from 3 to 8 y. Along the cyclograms the small-circle marks are at $T = 50$ y intervals: the vectors 50 y apart are completely independent of each other.

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(6) J. BEER, U. SIEGENTHALER, H. OESCHGER and M. ANDRÉE: *Proceedings of the XVIII International Cosmic-Ray Conference*, Late papers OG 7.2 (1983).

(7) C. U. HAMMER, H. B. CLAUSEN, W. DANSGAARD, N. GUNDESTRUB, S. J. JOHNSON and R. RUTH: *J. Glaciol.*, **20**, 3 (1978).

(8) G. CINI CASTAGNOLI, G. BONINO and S. MIONO: *Nuovo Cimento C*, **5**, 488 (1982).

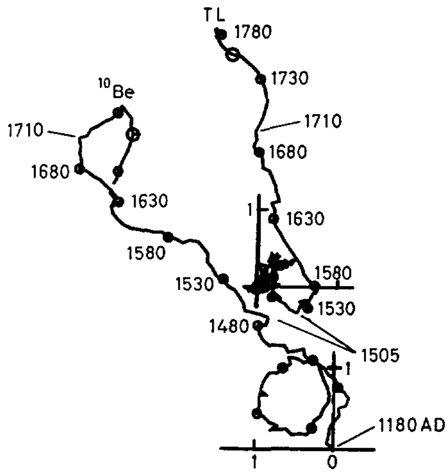

Fig. 1. – Phase cyclogram of ^{10}Be and TL data at $\tau = 10.75$ y with $T = 50$ y. Notice the stretching between 1505 and 1710 AD.

For a series of independent random data one should find that a segment joining two marks should be randomly oriented. Instead we notice that, starting from the year 1505, the vectors tend to be aligned rather straightly.

In order to calculate the stretching probability, we have computed (in 10^6 trials) the empirical frequency (in percent) of a displacement $\geqslant d$ after n unitary steps $(n = (1710 - 1505)/50 \approx 4$ steps).

For ^{10}Be $d = 3.3$ units and for TL $d = 2.4$ units we have found the corresponding probabilities 94.6 % and 73 %, respectively, for ^{10}Be and TL. We must also consider the fact that the displacement of the vectors is achieved as the period approaches 10.75 y with a rather regularly bending path, which gives another factor 2^{-n} in the probability to be at random. All together the straight alignment of ^{10}Be and of TL vectors in fig. 1 has a probability of (at least) 99.6 % and 96.6 %, respectively, to be nonrandom. With this reliability we can say, therefore, that the mean common periodicity during the interval 1505-1710 is 10.75 y. Anyhow toward the end of the Maunder minimum the periodicity in ^{10}Be data seems to change to smaller values around 10 y.

In the same fig. 1 we can see that the path of ^{10}Be from 1180 up to 1500 AD is rather circular, indicating that a different periodicity is present before 1500 AD. In fact, it is shown in ([3]) that the mean periodicity in this interval is 11.4 y with a confidence level of 99.98 %. For TL instead the path is random because the data prior to 1500 AD have been sampled at too large intervals to be able to show the 11 y periodicity by the cyclogram computed with $T = 50$ y.

In fig. 2 we show the cyclogram for $\tau = 11.40$ y for δ^{18}O starting from 1180 up to 1960 AD. The data have the same sampling of the ^{10}Be data. In the early part of the series the path is not regular, however, starting from 1680 AD, the vectors are rather straightly aligned, indicating a periodicity of 11.40 y from 1680 to 1880 AD.

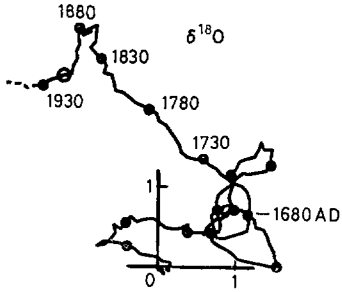

Fig. 2. – Phase cyclogram of $\delta^{18}O$ data at $\tau = 11.4$ y with $T = 50$ y. Notice the stretching between 1680 and 1880 AD.

In fig. 3 we show the phase cyclogram for TL at $\tau = 11$ y as a good example of how this method can give evidence to a change of periodicity in the time series. In 1705 AD, in fact, we can see a turning point between two arcs of different curvature radii. The arcs correspond, respectively, to data having the afore-mentioned mean periodicity of 10.75 y prior to 1705 AD and the mean periodicity of 11.4 y, from 1705 up to 1860 AD, the same found in $\delta^{18}O$.

It is interesting to notice that, during the time interval 1825-1905 AD, also

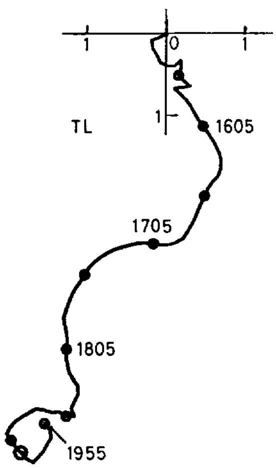

Fig. 3. – Phase cyclogram of TL data at $\tau = 11$ y with $T = 50$ y. Notice the two arcs bent clockwise between 1505 and 1705 corresponding to a mean periodicity of 10.75 y and anticlockwise between 1705 and 1860.

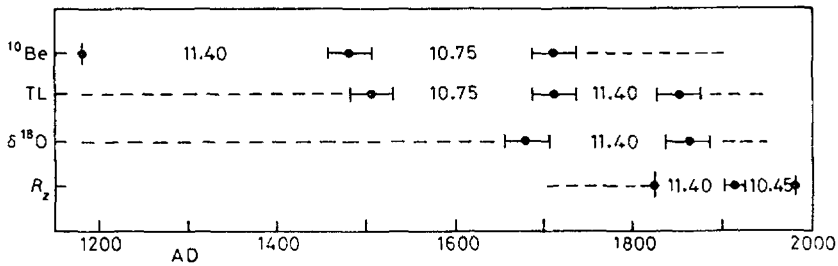

Fig. 4. – Graphic of the significant *mean* periodicities detected in the series ^{10}Be, δ^{18}O, TL. The Zurich sunspot number (R_z) periodicities are also shown.

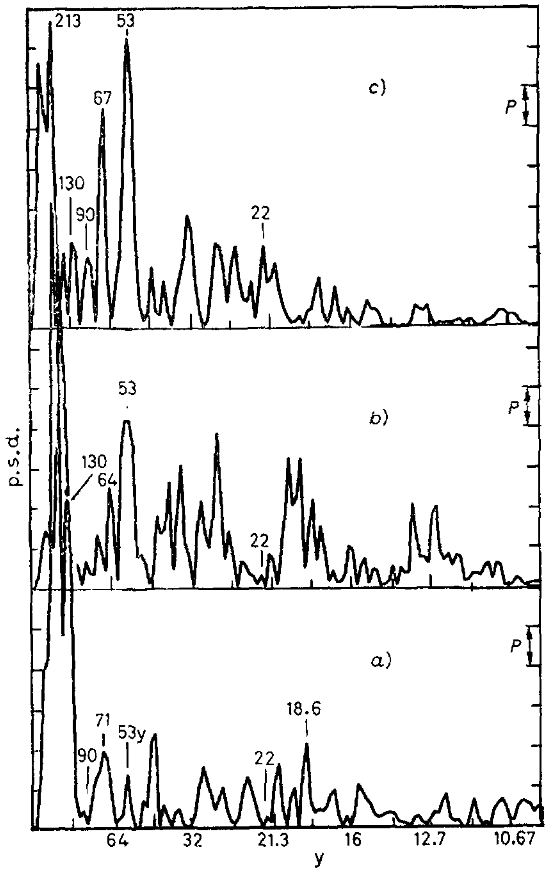

Fig. 5. – Power spectral density of *a*) ^{10}Be, *b*) δ^{18}O and *c*) TL for the period 1181-1808 AD. The data have been 5 y linearly interpolated and detrended with a second-degree polynomial.

the sunspot number (R_z) series analysed in the same way ([9]) shows the vector alignment at the same periodicity of 11.4 y. After 1905 up to 1945 AD a smaller mean value is found.

In conclusion it seems that the periodicities found in our series around 11 y are peculiar of the solar activity and change from time to time in concordance with one another (see fig. 4).

Concerning the method of spectral analysis we show in fig. 5 the power spectral density (p.s.d.) for the three series from 1181 up to 1808 AD: the

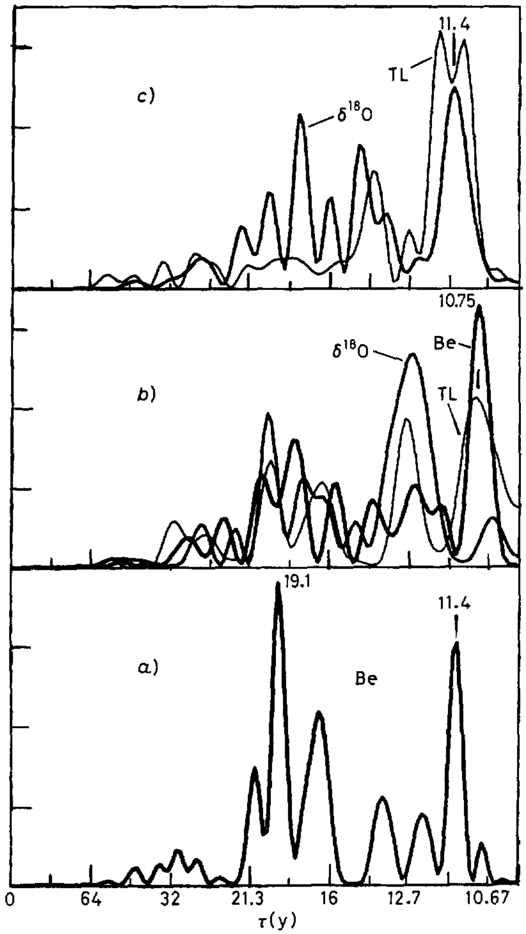

Fig. 6. – Power spectral density of ^{10}Be, δ^{18}O, TL data for the following intervals: *a*) 1180-1500 AD, *b*) 1505-1710 AD, *c*) 1710-1920 AD. In order to avoid a possible power leakage, the spectra have been computed on the difference between the original series and the same smoothed with a double procedure of averaging one datum with the next.

([9]) M. R. Attolini, G. Cini Castagnoli and M. Galli: to be submitted to *Sol. Phys.*

data have been interpolated to 5 y intervals. There we can see a significant band between 130 and 500 y covering the long-term oscillations of the series and another band with coincidence peaks at 52.2 y for $\delta^{18}O$ and TL, at a significance level the first of (at least) 99.75 % and the second of 99.96 %. The probability of random overlapping is about 3 %, increasing the confidence on the reality of their existence. Furthermore, it is worth noticing that a small peak in ^{10}Be is present at the same period of 53 y.

In order to be able to see by the p.s.d. methods the periodicities that we have analysed by the cyclogram method, we divided the data according to the results of the cyclograms into three intervals: 1) 1180-1500 (medieval), 2) 1505-1710 (baroque), 3) 1710-1920 AD (modern).

The power spectral density has been computed by using the differences between the original series and the same smoothed with a double procedure of averaging one datum with the next so to see only the high-frequency part of the spectrum, *i.e.* from about 1 cycle/30 y to 1 cycle/10 y. The results shown in fig. 6 clearly reflect what we have found by the cyclogram method: during the medieval period ^{10}Be shows the 11.40 y peak at a significance level of 99.99 % (together with a peak at 19.1 y at 97.8 %); during the baroque period the ^{10}Be and TL data show the peak at 10.75 y, respectively at a level of 99.3 % and 98 %; during the modern period TL and $\delta^{18}O$ both have the 11.4 y peak at a level of 98 % and 99.55 %. It may be noticed that the 11.4 y peak during the medieval period is narrower than the 10.75 y peak during the baroque period. To the first peak corresponds a straighter cyclogram with respect to the second one, as reported at the end of sect. **2**.

4. – Concluding remarks.

It is worthwhile noticing that it is the information drawn from the cyclograms that gives us the possibility of dividing the data for the p.s.d. computation, so that significant peaks appear in the p.s.d. In fact, when averaging together the spectra, the peaks would sum up in a noise background in which the real signals would have been buried. However, there is an intimate connection between the two methods because the distance from the origin to the end of the amplitude cyclogram is proportional to the square root of the power spectrum relative to the Fourier component of the frequency chosen for the cyclogram analysis.

In summary:

a) The 11 y cycle has been detected in all three time series by both methods.

b) Similar variabilities are shown in the three series reflecting the possible common control agent.

c) The concordance with the periodicity measured in the R_z series between 1825 and 1905 seems to give confidence to the utility of this kind of analysis for inferring mean periodicities of the solar activity in the past over time intervals of the order of a few centuries.

d) During the Maunder minimum the solar cycle did not stop in the terrestrial records. One of the changes of its periodicity seems to have happened at the end of the Maunder interval.

As the presence of the main solar cycle in the data indicates that all the three time series should have some relationship with the solar behaviour, we could expect also to find longer solar periods in these records such as the 22 y and the 80 y Gleissberg cycles. However, there is no evidence for such periodicities. Only a 53 y common periodicity has been found, the origin of which has to be explained.

● RIASSUNTO

Il metodo dei ciclogrammi è stato usato per analizzare i dati delle serie temporali di ^{10}Be (1181-1800 AD) e di δ^{18}O (1181-1960 AD) da carote di ghiaccio artico e i dati della termoluminescenza (TL) di sedimenti marini mediterranei (1181-1960 AD). La concentrazione del ^{10}Be è stata determinata mediante l'acceleratore del Politecnico di Zurigo. I valori di δ^{18}O sono stati invece misurati presso l'Università di Copenhagen. Le misure di TL sono state eseguite presso l'Istituto di Cosmo-geofisica di Torino. Sono state trovate periodicità medie comuni di 10.75 anni nel periodo 1505-1710 AD nella TL e nel ^{10}Be e di 11.4 anni per il periodo 1715-1880 nella TL e δ^{18}O. La periodicità di 11.4 anni è stata anche trovata nella serie delle macchie solari (R_z) analizzata in maniera analoga. Ciò favorisce l'argomento che le periodicità comuni trovate nelle suddette serie siano legate all'attività solare nel passato.

Солнечные циклы в прошлые века на основе анализа ^{10}Be и δ^{18}O в арктическом льду и термолюминесценции осадков.

Резюме (*). — Метод циклограмм для временных последовательностей используется для анализа ^{10}Be данных (за период 1181-1800 г.г.) и δ^{18}O данных (за период 1181-1960 г.г.) из арктического льда и данных по термолюминесценции (за период 1181-1960) осадков Средиземного моря. Концентрации ^{10}Be определялись в ЕТН Цюрихе. Значения δ^{18}O измерялись в Университете Копенгагена. Измерения термолюминесценции проводились в Космо-геофизическом Институте Национального Центра Исследований (Турин, Италия). Обнаружены обычные средние периодичности с периодом 10.75 лет для интервала с 1505 г. по 1710 г. в измерениях термолюминесценции и ^{10}Be и с периодом 11.4 лет для интервала с 1715 г. по 1880 г. в измерениях термолюминесценции и δ^{18}O. Обнаружена периодичность с периодом 11.4 лет в последовательностях солнечных пятен (R_z) для интервала с 1825 г. по 1905 г. Полученные результаты свидетельствуют, что обнаруженные обычные периодичности являются характерными для солнечной активности в прошлые века.

(*) *Переведено редакцией.*