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Paleo-Astrophysical data in relation to temporal characteristics of the solar magnetic field

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Abstract: An analysis of the global solar magnetic field strength (referred to as B(nT)) was based on the temporal evolution of the minimum (Bmin) values in relation to the maximum (Bmax) values of the 300-year data series resulted in the finding of a 2-step cycling mode of the absolute values and the ratio Br = (Bmax-Bmin)/(Bmax+Bmin). Br is a dimensionless quantity exhibiting a characteristic which was defined as "visibility", which, when approaching very small values or zero with almost no sunspots visible, could serve as a diagnostic tool for indicating deep minima. Here it is further suggested that the 2-step mode can be extended from periods of the Schwabe cycle to longer-term periodicities, such as the solar Hallstatt cycle of ~2200 years displayed in the Holocene radiocarbon record.

Introduction and previous work

Previously the 300-year data series of the IMF (field strength in B(nT)) near Earth derived from Solanki et al., [1] had been partitioned into six groups based on the varying temporal evolution of the minimum values Bmin. Each group consists of several consecutive Schwabe cycles and approximate equal minimum values as shown in Figure 1.

The absolute values of maximum field strength (Bmax) and minimum field strength (Bmin) display a 2-step behavior or 2-step cycling mode throughout the 300 years of data going from longer to shorter cycles (~11-year Schwabe cycles) per 2-step group and magnetic flux increase [2]. Group 6 of the modern era occupies a position characterized by a median cycle length, but highest maximum as well as highest minimum values of B(nT). The close approach of Bmin relative to Bmax resulted in introducing the term "visibility". This dimensionless quantity was derived from calculating the ratio Br=(Bmax-Bmin)/(Bmax+Bmin), which is a measure of the difference between the maximum and minimum values per group and expressed in per cent of the maximum magnetic energy flux. The short series resembles a dampened oscillation progressing from 1700 AD to the present (Figure 2). This progression shows that it is possible for Br to attain very small values with solar magnetic flux being very high such as during the modern era. Considering that the reconstructed total magnetic flux encompasses the flux emerging in large active regions of the photosphere and flux emerging in small ephemeral regions which have a much broader distribution in latitude [1], the small ephemeral regions may play a more decisive role, i.e. overlapping ephemeral regions result from considerable flux being present on the surface from the previous cycle when new magnetic flux starts to erupt. Br can effectively be defined as "visibility" in terms of solar magnetic flux emergence at times of solar maximum conditions versus solar minimum conditions and can be viewed as a direct measure of magnetic energy density distribution on the photosphere. It may simply indicate that the temporal evolution of the critical magnetic field Hc at the tachocline (base of the convection zone), which ultimately determines the emergence of magnetic flux at the surface, could reach a limiting value at solar maximum accompanied by increasing contributions at solar minimum as well. At this critical limit, where the two values deviate very little, "visivility" could conceivably approach zero. Such periods would be characterized by a reduction or even the disappearance of sunspots. Using “visibility” as a diagnostic tool, it may be conjectured that a rapid decline in “visibility” indicates a critical threshold

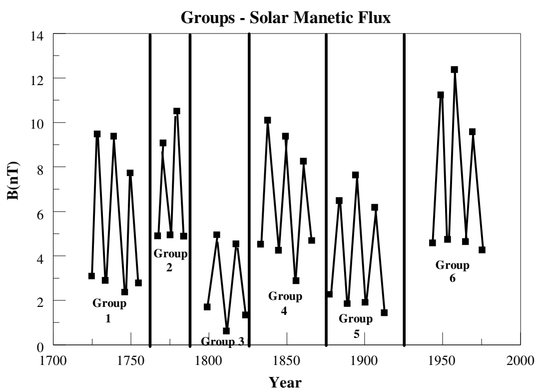

Figure 1: The predicted magnitude of the IMF near Earth derived from [1]. The normalization of field strength B(nT) derived from [3]. The secular evolution of the Sun’s total magnetic field strength was investigated relative to the periodicities embedded in the data and is indicated by the groups 1-6 of several consecutive cycles and approximate equal minimum values.

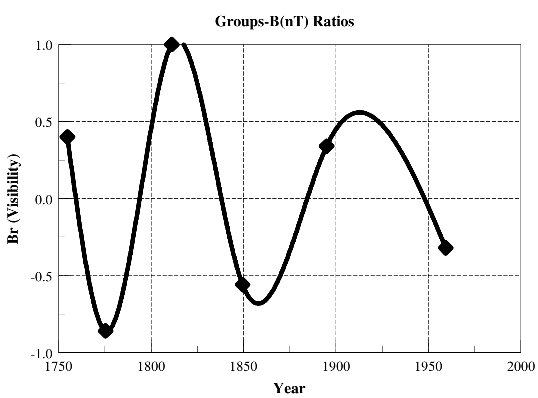

Figure 2: The ratios Br = (Bmax-Bmin) / (Bmax +Bmin) have been plotted as a function of time. A spline has been added. The short data series resembles a dampened oscillation which is amplitude and frequency modulated.

where the minimum values cannot continue indefinitely and the difference between Bmax and Bmin becomes almost negligible. This condition may be applicable to the presence of deep minima such as the Maunder minimum. Two observations may actually support this view. Impulsive nitrate events in polar ice which have been shown to represent individual solar proton events [4, 5] are, with few exceptions, largely absent during the Maunder minimum, but show a major rate increase just preceding the Maunder minimum [6]. This latter result may be explainable by the presence of very high latitudinal gradients of solar rotation just before the disappearance of the sunspots. Based on high resolution radiocarbon data Kocharov et al., [7] suggested further that modulation of GCRs did continue during the Maunder minimum despite of no sunspots being observed or reported.

Two-step characteristics and Holocene Hallstatt-cycle

Emerging from the Maunder minimum, for the last ~300 years the solar magnetic field has been in a general mode of increasing field strength. Since this increase has been shown to be governed by a tendency to repeat in a 2-step fashion over a period of about 2x40 years with an amplitude variation represented by the absolute values Bmax and Bmin [2], the question to ask is if this tendency of progressing in a 2-step mode is also present in longer term periodicities, such as the ~2200-year Hallstatt-cycle present in radiocarbon data throughout the Holocene. As stated by Damon and Sonett [8], with the secular variation due to terrestrial dipole moment removed, the long period of ~2300 years is the most prominent feature in the delta C-14 record of 10 000 years. The data are plotted in Figure 3, i.e. delta C-14, superimposed by a spline function representing the Hallstatt-cycle. In addition, the individual Hallstatt-cycles have been numbered Peal 1 through 5, with the latter one representing the most recent, non-completed, cycle.

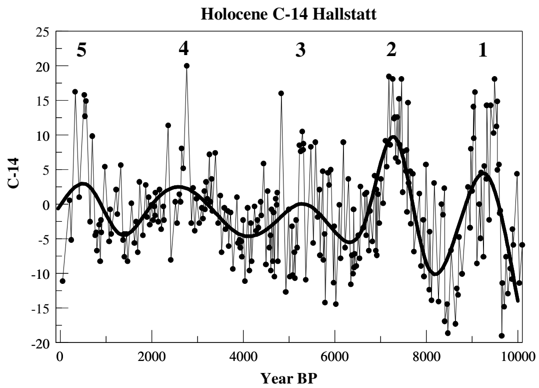

Figure 3: The radiocarbon record during the Holocene (adapted from Damon and Sonett [8]), with numbered Hallstatt Peaks.

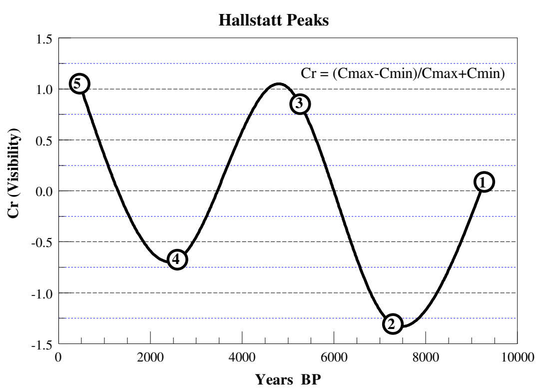

Figure 4: The 2-step oscillatory variation of the Hallstatt Peaks indicated by the ratios Cr termed “visibility” of the magnetic energy minima and maxima in relation to each other.

Similarly to determining Br, the ratio Cr=(Cmax-Cmin)/(Cmax+Cmin) has been determined by calculating the maximum and minimum C-14 values at each Hallstatt peak. For thie purpose, areas of interest were selected by using the absolute values of C-14 within the range of ½ half-width per peak. Obviously, the peaks represent the epochs in C-14 maxima and the minimum epochs in solar activity. The results are shown in Figure 4, indicating the oscillatory, 2-step temporal behavior of the quantity Cr.

It may be concluded that the variation exhibited by the Hallstatt period of ~2200 years during the Holocene is shown to undergo modulation apparently in association with or similar to the 2-step temporal evolution of the solar magnetic field. It is noted that Damon and Sonett [8] suggested that the Hallstatt-cycle may be related to climate forced variations in reservoir parameters, however, they did not exclude C-14 production rate changes on this scale being due to solar activity variations in agreement with this evaluation of the data.

The significance of the two-step characteristics of the solar magnetic field

The cycling in general and the 2-step mode cycling in particular described for the global solar magnetic field (Br) and radiocarbon (Cr), may be related to fundamental properties of the solar energy generating process. It has been proposed that the critical magnetic field Hc at the tachocline is subject to pressure waves and varying magnetic energy contributions, with energy transfer being the result of the hydrogen-helium fusion process itself. Based on these assumptions, the 2-step modes of emerging magnetic flux, which vary apparently on temporal and sparial scales, can be shown to result in a binary sequence [2], which involves cycling from an energetically weaker to a stronger state per two consecutive groups. For example, such a 2-step system can be envisioned, when treating the temporal and spatial evolution of magnetic flux in terms of the physics of “pinch and hoop” forces in magnetized plasmas: the combination of the so-called magnetic vacuum field in a plasma and a local, self-generated magnetic field by local currents represents cycling between a lowest energy state (the vacuum state) and equilibrium states of higher energy, and this self-organization can result in a force-free helical state [9]. However, this local maximum energy state is lost, if the local currents become too high.

Conclusions

The 2-step system permeates the various periods associated with changes in solar activity, where the various periodicity amplitudes are subject to superposition or a type of amplitude modulation [2]. The phenomenon described for the quiet sun may be supported not only by the fact that more than 90% of the ever smaller, tangled magnetic structures are only detectable by the Hanle effect and are invisible to the better known Zeeman effect [10], but also by the fractal nature of the magnetic energy distribution on the quiet sun's photosphere [11].

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