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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 which 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 ~2300 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 [1] had been partitioned into six groups based on the varying temporal evolution of the minimum values Bmin [2]. Each group consists of several consecutive Schwabe cycles and approximate equal minimum values as shown in Figure 1.

Maximum and minimum field strength given by

$$Bmax = 1/n\sum_{i=1}^{n} B_i(max) \text{ and } Bmin = 1/m\sum_{i=1}^{m} B_i(min),$$

where n,m are the number of maxima and minima, respectively, per group, 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 field strength increase for each of the two consecutive groups [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 the absolute values Bmin relative to Bmax resulted in introducing the term "visibility", defined as the ratio Br = (Bmax-Bmin)/(Bmax+Bmin) for each group 1 to 6. In contrast to the absolute values, a trend reversal per two consecutive groups occurs for Br. This ratio, a dimensionless quantity, has been plotted in Figure 2 as percent deviations from the group field strength. The short series was found to resemble a dampened oscillation progressing from 1700 AD to the present [2]. This progression shows that it is possible for Br to attain very small values with solar magnetic field strength being very high such as during the modern era. Considering that the reconstructed total magnetic flux encompasses the flux emerging in large bipolar active regions of the photosphere and flux emerging in small bipolar 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 since the active and the ephemeral regions are thought to be products of the general dynamo mechanism [1], the time variation of Br 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, "visibility" 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 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. For example, the observations reported by [3] may actually support this view. The authors were one of the first ones to suggest, that, despite of no sunspots being observed or reported, the modulation of galactic cosmic rays continued during the Maunder minimum, i.e. the solar dynamo did not cease to operate. These conclusions were based on high resolution radiocarbon data, which showed that the C-14 variation (period, phase, amplitude) had to originate from reversals of the solar magnetic field.

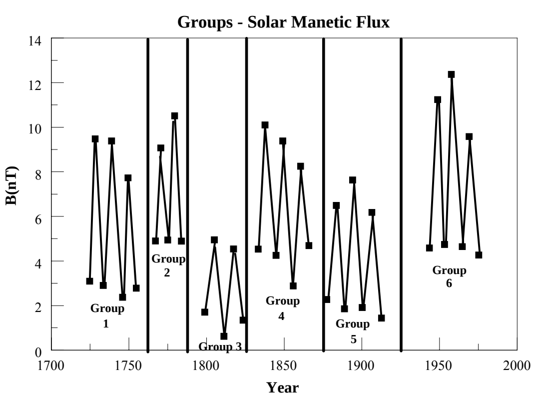

Figure 1: The predicted magnitude of the IMF near Earth derived from [1] where in this case only the groups 1 to 6 have been plotted. The normalization of field strength B(nT) derived from [4]. The secular evolution of the Sun's total magnetic field strength was investigated relative to the periodicities embedded in the data and is indicated by the groups 1 to 6 of several consecutive cycles and approximate equal minimum values.

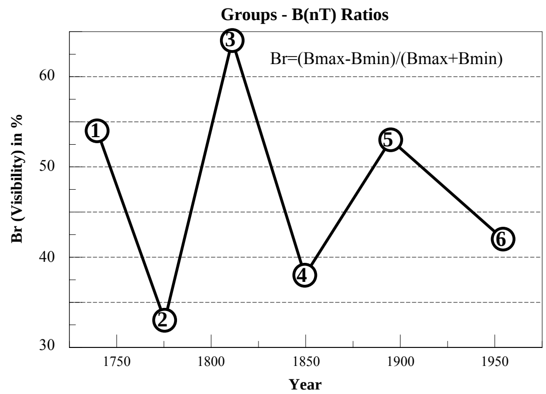

Figure 2: Variation of "visibility" Br has been plotted as percent values of (Bmax-Bmin) relative to the group field strength (Bmax+Bmin) for the time period Maunder minimum to the present. The short data series displays an oscillation where the differences between the Bmax and Bmin values per group oscillate in a 2-step mode relative to average field strengths over the ~300 year time period.

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 ~2300 year Hallstatt cycle present in radiocarbon data throughout the Holocene. As stated by [5], 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 10000 years. The delta C-14 data are plotted in Figure 3 (adapted from [5, 6]), and are superimposed by a spline function representing the Hallstatt cycle. In addition, the individual Hallstatt cycles have been numbered peak 1 through 5, with the latter one representing the most recent, non-completed, cycle. The suggestion is noted, that the Hallstatt cycle may be related to climate forced variations in reservoir parameters, however, the authors 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 [5].

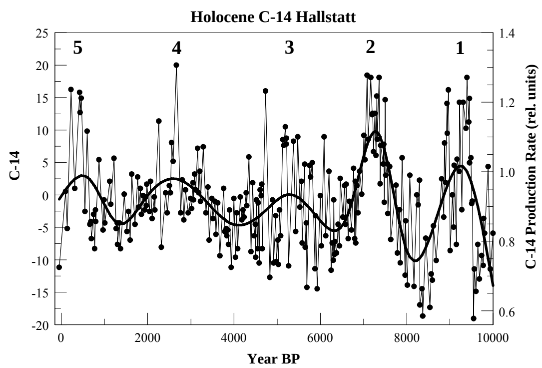

Figure 3: The radiocarbon (delta C-14) record during the Holocene (adapted from [5, 6]), with numbered Hallstatt peaks for the time period 10000 BP to the present (1950). The production rates on the right hand side of the plot have been adapted from [7].

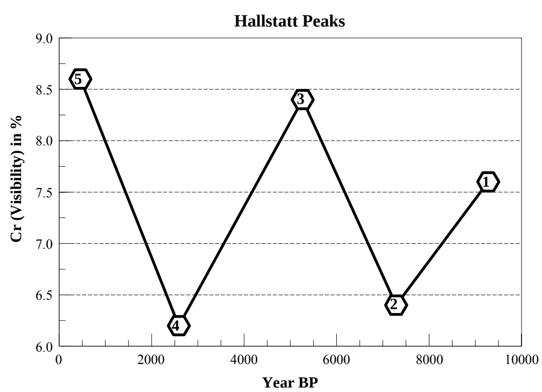

Figure 4: The variation of the ratios Cr, also termed "visibility" patterned after Br "visibility", have been plotted as percent values of (Cmax-Cmin) relative to (Cmax+Cmin) at each spline peak 1 to 5. The time period per peak was selected at the ½ halfwidth of each spline peak averaging 772 years.

Since the production of radiocarbon in the Earth's atmosphere and its variation is a function of cosmic ray intensity changes largely due to solar magnetic field modulation and with the secular terrestrial dipole effect removed, C-14 variability displayed in the 10000 year record can be viewed as a proxy for the temporal evolution of the solar magnetic field and heliospheric conditions for the 10000 year time period. The C-14 variability and associated Hallstatt peak maxima represent periods of extreme states of low solar activity with peak to peak periodicities of ~2300 years, which are superimposed on variations as seen during the last ≥400 years, i.e. including the Maunder minimum type variations. These are the conditions, which have been considered for the analysis of this work.

Whereas the analysis of B(nT), where B(nT) is defined by the Schwabe cycle variability, and of the Br ratios was based on the group-minimum values of B(nT), the analysis of the C-14 data is based on the extreme states of low solar activity defined by the ~2300 year Hallstatt cycles. Similarly to determining the ratio Br, the ratio Cr = (Cmax-Cmin)/(Cmax+Cmin) has been computed from the average maximum and average minimum C-14 values at each Hallstatt peak. First, areas of interest were selected by using C-14 variations within the range of ½ halfwidth per spline peak which corresponds to an average of 772 years for peaks 1 to 5. Second, the delta C-14 values were replaced by production rates for the radiocarbon data series adapted from [7], and have been scaled to the data as shown in Figure 3. The adaptation was made by making use of the peak representing the Maunder minimum, since it can be expected that, in general, this peak is established with reasonably high confidence. Furthermore, by comparing two prominent peaks, Maunder minimum and the characteristic peak around ~2700 yr BP, the relationship between peak amplitudes from three data series differs by less than 12%. It raises the level of confidence for using the approximation of adopting the production rate to the delta C-14 ‰ data as described.

From Figure 4 it may be concluded that during the Holocene the variation exhibited by the Hallstatt period and within the selected time frame, the radiocarbon is shown to undergo modulation apparently also resulting in an apparent 2-step temporal evolution, i.e. the Cr values oscillate with sequentially lower and higher values according to the ~2300 year time scale of the Hallstatt cycle.

Summary and Conclusions

In summary, (1) analyzing the solar magnetic field, group selection is based on Bmin values; (2) The differences (Bmax-Bmin) vary with the group field strength following an oscillatory pattern; (3) A 2-step mode cycling is also found when analyzing the Holocene radiocarbon record. In particular, the differences (Cmax-Cmin) near each peak value of the Hallstatt cycle have been compared to the corresponding group radiocarbon production values and are represented by the ratios Cr which exhibit the oscillation. In other words, the radiocarbon variations associated with the ~2300 year Hallstatt maxima serve as an approximation for the solar magnetic field within the heliosphere under conditions which may be described as minimum levels of solar activity and corresponding residual galactic cosmic ray modulation.

Clearly, there are different effects (magnetic flux emerging at the photosphere, interaction of the solar magnetic field with charged particles as it extends into the outer limits of the heliosphere) operating on very different time scales, with the solar magnetic field however, at the basis of the temporal evolution. The significance of this finding will require further investigations, particularly testing other well-known solar activity periodicities. However, it does not seem that the quantities Br and Cr are totally unrelated, indicating that the 2-step system permeates the various periods associated with changes in solar activity.

References

[1] S.K. Solanki, M. Schussler, M. Fligge. Secular variation of the Sun's magnetic flux. Astron. Astrophys., 383, 706-712, 2002.

[2] G.A.M. Dreschhoff. The Sun's magnetic field characterized by the evolution of its minimum magnetic flux with effects from the core. *Adv.* Space Res., accepted for publ. (2007), doi: 10.1016/jasr.2007.01.084.

[3] G.E. Kocharov, V.M. Ostryakov, A.N. Peristykh, V.A. Vasiliev. Radiocarbon content variations and Maunder minimum of solar activity. Sol. Phys., 159, 381-391, 1995.

[4] K.G. McCracken, G.A.M. Dreschhoff, D.F. Smart, M.A. Shea. A study of the frequency of occurrence of large-fluence solar proton events and the strength of the interplanetary magnetic field. Sol. Phys., 224, 359-372, 2005.

[5] P.E. Damon, C.P. Sonett. Solar and terrestrial components of the atmospheric 14C variation spectrum. In The Sun in Time, (eds. C.P. Sonett ,M.S.Giampapa, M.S.Mathews), University of Arizona Press, Tuscon, 360-388, 1991.

[6] W.E. Dean. The Sun and climate. *USGS Fact* Sheet FS-095-00. US Dept.of Interior, US Geol. Survey, August 2000.

[7] K.G. McCracken, J. Beer. The 2300 year modulation in the galactic cosmic radiation. 30th Int. Cosmic ray Conf., Proceedings, Pre-Conf. Edition, 4 pp., Merida, Mexico, July 2007.