Pergamon
www.elsevier.com/locate/asr

Adv. Space Res. Vol. 29, No. 12, pp. 1979–1984, 2002

Printed in Great Britain
0273-1177/02 $22.00 + 0.00
PII: S0273-1177(02)00244-2

A 22-YEAR CYCLE IN SUNSPOT ACTIVITY

K. Mursula[1], I.G. Usoskin[2†], G.A. Kovaltsov[3]

[1]*Department of Physical Sciences, P.O.Box 3000, FIN-90014 University of Oulu, Finland*
[2]*Sodankylä Geophysical Observatory (Oulu unit), FIN-90014 University of Oulu, Finland*
[3]*Ioffe Physical-Technical Institute, RU-194021 St. Petersburg, Russia*

ABSTRACT

We study the recently presented group sunspot number series and show that a persistent 22-year periodicity exists in sunspot activity throughout the entire period of about 400 years of direct sunspot observations. The amplitude of this periodicity in total cycle intensity is about 20% of the present intensity level. A 22-year periodicity in sunspot activity is naturally produced by the 22-year magnetic dynamo cycle in the presence of a relic magnetic field. Accordingly, a persistent 22-year periodicity in sunspot activity gives strong evidence for the existence of such a relic magnetic field in the Sun. The stable phase and the roughly constant amplitude of this periodicity during times of very different sunspot activity level strongly support this interpretation.

INTRODUCTION

Magnetic activity in the Sun is mostly determined by the dynamo mechanism (Babcock, 1961). However, a weak relic magnetic field may exist in the Sun's interior since its formation (Cowling, 1945). Sonett (1983a, 1983b) tried to find a signature of such a relic field in sunspot activity. Assigning a negative sign to odd solar cycles, he fitted the Wolf sunspot series with a model consisting of two harmonics with periods of 22 and 90 years, and found a small negative offset in the running mean of the model during the last 150 years. Such an offset gives evidence for a relic solar field. However, as discussed above, his results for the earlier period from the 18^{th} century to mid-19^{th} century were not conclusive since the offset changed sign in late 1700's. Because of this reason, Sonett's results, and the implied evidence for a relic magnetic field remained rather unconvincing. More recently, Bravo & Stewart (1995) studied the difference in the Sun's polar coronal field during subsequent minima, finding evidence for an inclined dipole relic field. However, the available data covered only two solar cycle minima which is insufficient to allow a statistically significant conclusion (Boruta, 1996).

It has been argued (Levy & Boyer, 1982; Boyer & Levy, 1984) that the solar dynamo with its 22-year magnetic polarity (Hale) cycle must result, in the presence of a dipole relic field, in a 22-year periodicity of sunspot activity. Accordingly, a 22-year periodicity in sunspot activity would provide compelling observational evidence for the existence of a relic field in the Sun. However, no convincing evidence for such a periodicity has been found in sunspot activity when using the famous Wolf sunspot series. This is probably because of the rather poor quality of Wolf sunspot data before mid-19^{th} century (Hoyt & Schatten, 1998; Wilson, 1998; Letfus, 1999), and because of the large long-term variations of sunspot activity level (the secular Gleissberg cycle). The poor quality of Wolf sunspot data is also a likely reason for the inconclusive results by Sonett (1983b) for the early times.

In this paper we perform a detailed analysis of the 22-year periodicity in sunspot activity using the new group sunspot numbers (GSN). The GSN series, depicted in Fig. 1a, includes all known archival records of sunspots starting from the observations of G. Galilei in 1610, and gives a more correct measure of early sunspot activity than the Wolf sunspot numbers (Hoyt & Schatten, 1998). Contrary to Sonett (1983a, 1983b), we do not fit the data to any model but rather analyse the raw sunspot data directly.

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†on leave from Ioffe Physical-Technical Institute, St. Petersburg, Russia

GNEVYSHEV-OHL RULE IN THE GROUP SUNSPOT NUMBER SERIES

An empirical Gnevyshev-Ohl (G-O) rule (Gnevyshev & Ohl, 1948) orders the sunspot cycles to even-odd pairs so that the intensity of the odd cycle of a pair exceeds that of the preceding even cycle. However, the G-O rule in the Wolf sunspot series is only valid since solar cycle 10 and fails for cycle pairs 4-5 and 8-9 (Gnevyshev & Ohl, 1948; Vitinsky et al., 1986; Wilson, 1988; Storini & Sykora, 1997). In analogy with Gnevyshev & Ohl (1948), we define the intensity $I_{GO}(k)$ of the sunspot cycle number k as the normalized sum of sunspot numbers over the cycle:

$$I_{GO}(k) = \frac{1}{132} \sum_{j=J(k)}^{J(k+1)-1} R_g(j), \tag{1}$$

where $R_g(j)$ is the GSN value for the month number j and $J(k)$ is the month starting cycle k. (As cycle minima we use here the minima of the running 12-month average (see, e.g., Mursula & Ulich, 1998).) The 11-year cycle length (132 months) is used as a normalization factor. The monthly GSN series has some gaps until the end of 18^{th} century. Most data gaps are rather short, but a few gaps are longer than one year. The longest data gap of 27 months was during cycle 0. The data gaps were interpolated using a fit to a binomial curve with a window length of 41 months. The interpolation method was tested with an artificial series (noised 11-year sinusoid with gaps), yielding an accuracy better than 5% even for the longest gaps. The $I_{GO}(k)$ series, depicted in Fig. 1b, allows to examine the validity of the G-O rule in the GSN series. Starting from cycle 6, each even cycle (including cycle 8) is followed by a more intense odd cycle, verifying the G-O rule in the GSN series since the Dalton minimum in 1790-1830. Before the Dalton minimum, the G-O rule is also valid in a phase-reversed form whereby an odd cycle is followed by a more intense even cycle. It has recently been argued (Usoskin et al., 2001) that the irregularity of solar activity evolution known as the phase catastrophe (Vitinsky et al., 1986; Kremliovsky, 1994) of the Schwabe cycle in the beginning of the Dalton minimum was due to the fact that a weak solar cycle was missed because of poor and partly unreliable sunspot observations in late 18^{th} century. Without the missing weak cycle the parity of cycle numbering is erroneous across the Dalton minimum, resulting in the observed phase change in the G-O rule. Note that this phase-reversed G-O rule applies even for the time before the Maunder minimum which occurred from 1645 to 1715. (Noting that the time difference between the last maximum in 1639-1640 before the deep minimum and the first maximum in 1705 after it was roughly six 11-year cycles, we have numbered the three cycles before the minimum as -12, -11 and -10). As a quantitative measure of the G-O rule we have depicted in Fig. 1c the difference $D(k) = I_{GO}(k+1) - I_{GO}(k)$ between the intensities of the two cycles forming a pair. These differences are roughly constant, about 10-20, throughout most of the GSN interval, including $D(-11)$, the only value before the Maunder minimum. It is important to note that the $D(k)$-values do not correlate with sunspot activity. The correlation coefficient between $D(k)$-values and average pair intensities $((I_{GO}(k) + I_{GO}(k+1))/2)$ is -0.09 ± 0.25 for solar cycles -4 to 21.

22-YEAR CYCLICITY IN THE GROUP SUNSPOT NUMBER SERIES

We note first that in 1830-1930 and 1950-1990, when cycle intensities remained roughly constant (see Fig. 1b), the odd cycles were more intense than either of the two neighboring even cycles. Similarly, in 1740-1790 the even cycles were larger than the two neighboring odd cycles. This behaviour suggests that a 22-year periodicity in cycle intensity is the underlying pattern behind the G-O rule. However, the visibility of the 22-year periodicity is hidden at times when the sunspot activity level is rapidly changing, e.g., during the recovery of activity after the Maunder minimum, around the Dalton minimum and at the start of the recent high cycles in 1940's. During these times the G-O rule is valid only in the fixed order of cycle pairs. Therefore, in order to examine the existence of the 22-year periodicity in cycle intensity in more detail we standardized (Jenkins & Watts, 1969) the monthly GSN series by subtracting the long-term (30-year) trend:

$$U_g(i) = R_g(i) - \frac{1}{361} \sum_{j=-180}^{180} R_g(i+j) \tag{2}$$

and suppressed the dominant 11-year Schwabe cycle by calculating the running 11-year average intensity $I_R(i)$:

$$I_R(i) = \frac{1}{132} \left(\sum_{j=-65}^{65} U_g(i+j) + \frac{1}{2} U_g(i \pm 66) \right) \tag{3}$$

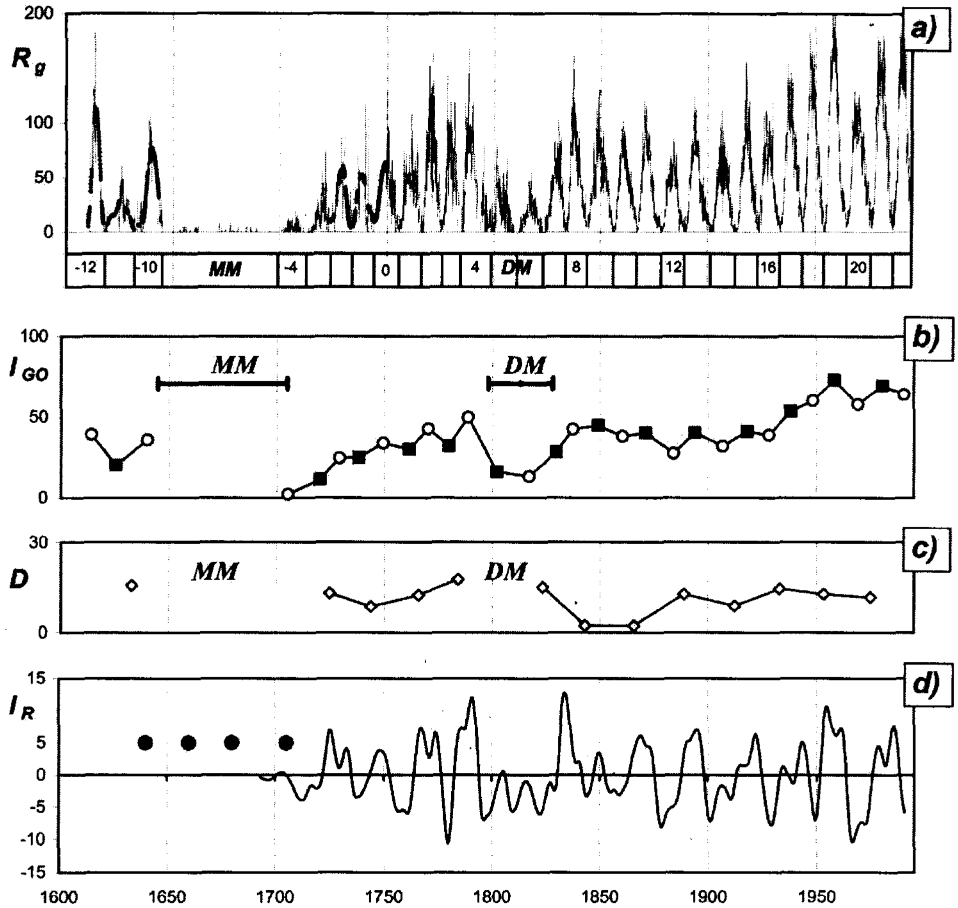

Fig. 1. (a) Monthly group sunspot number series R_g (thin line) with interpolated gaps (sections of thick line). Sunspot cycle numbers are shown in the lower panel together with the location of the Maunder (MM) and Dalton (DM) minima. (b) Sunspot cycle intensities I_{GO} (see Eq. (1)) for odd (grey squares) and even (open circles) sunspot cycles. (c) Intensity differences D between the two sunspot cycles forming a G-O pair. (d) Running standardized and 11-year averaged GSN series I_R (see Eq. (3)). The times of the 22-year cycle maxima before and during the Maunder minimum (Usoskin et al., 2000) are noted by black circles.

The $I_R(i)$-series (see Fig.1d) show a persistent 22-year periodicity both between the Maunder and Dalton minima and since the Dalton minimum. The FFT power spectra of these two parts of the $I_R(i)$-series are shown in Fig. 2 separately. The confidence level (Jenkins & Watts, 1969) of the 22-year peak in the power spectrum of $I_R(i)$-series is 0.99 for 1720-1800 and better than 0.9999 for 1830-1996. The zero hypothesis was formed by colored (correlated) noise corresponding to the observed slope of the sunspot power spectrum (see, e.g., Ostryakov & Usoskin, 1990; Oliver & Ballester, 1996) and filtered using the equations (2,3). When calculating the confidence level, the reduced number of degrees of freedom due to filtering was taken into account. Note that some power from the Schwabe cycle still remains in the $I_R(i)$-series forming the second peak with a period slightly less than 10 years. In agreement with results obtained above for the discrete series (see Fig. 1c), the peak-to-peak amplitude of the 22-year periodicity in Fig. 1d is roughly constant and about 10-20, corresponding to approximately 20% of the intensity of recent solar cycles. Also, the correlation coefficient between the monthly $I_R(i)$-series and the monthly GSN series is roughly zero (0.05 ± 0.04 and 0.07 ± 0.07 for 1830-1996 and 1720-1790, respectively), implying that the 22-year periodicity is independent of the overall sunspot activity level. We have recently shown (Usoskin et al., 2000) that during the Maunder Minimum, when the Schwabe cycle was strongly suppressed, the remaining, seemingly sporadic sunspot activity still shows a significant 22-year periodicity. Accordingly, a persistent 22-year cycle exists in sunspot activity throughout the whole time interval of nearly 400 years of direct solar observations. The sunspot maxima during the Maunder minimum (Usoskin et al., 2000) occur in phase with the maxima of the 22-year periodicity before and after the minimum (see Fig. 1d). Moreover, the times of maxima of the $I_R(i)$-series roughly correspond to even periodes before and to odd cycles after the Dalton minimum (see Figs. 1b and 1d), in agreement with the suggested phase reversal in the G-O rule at the Dalton minimum. The 22-year periodicity was not clearly visible during the Dalton minimum. However, the two maxima in the $I_R(i)$-series around the Dalton minimum are separated by about 43 years, implying that the 22-year periodicity has no sizeable phase change around the Dalton minimum. Therefore, the above mentioned phase reversal in the G-O rule is not related to the 22-year periodicity but rather to the irregularity in cycle numbering as suggested in (Usoskin et al., 2001).

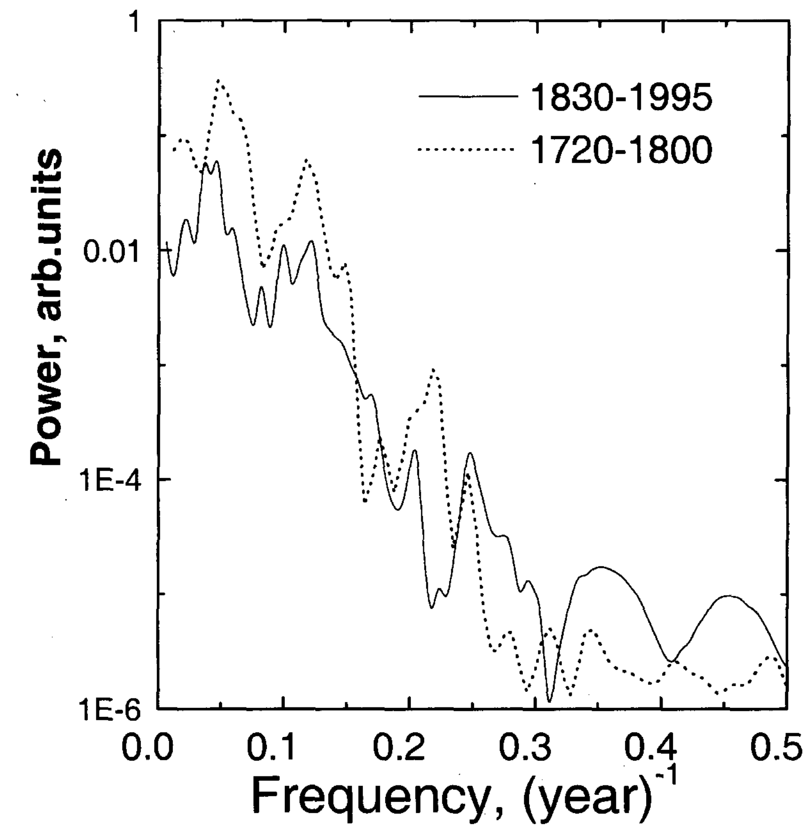

Fig. 2. FFT power spectra of the $I_R(i)$-series before the Maunder minimum (1720-1800) and after it (1830-1996).

DISCUSSION AND CONCLUSIONS

The idea of a weak dipole relic solar magnetic field gives a natural explanation for the observed 22-year periodicity (Levy & Boyer, 1982; Boyer & Levy, 1984). A relic field can, due to the high conductivity in the solar interior, survive in the Sun for a very long time, even over time scales comparable to the solar age (Cowling, 1945). Due to a strong amplification by the dynamo fluid motions in the convection zone, such a weak constant field can interact with the poloidal/toroidal dynamo field and hence play a considerable role in the formation of a sunspot cycle (Levy & Boyer, 1982; Boyer & Levy, 1984). The total magnetic field in the convection layer is enhanced when the dynamo field has a favourable orientation with respect to the relic field, and suppressed during the next sunspot cycle which has an opposite magnetic orientation in accordance with the Hale law. Thus, a constant relic field leads to periodicity in sunspot activity with the period of the magnetic polarity cycle.

Note also that the search for a 22-year periodicity in sunspot activity cannot be straightforwardly extended to times before direct sunspot observations using, e.g., geomagnetic (aurorae) or cosmic ray intensity (cosmogenic isotopes in natural archives) proxy data because of the major effect of the 22-year magnetic polarity cycle to these proxies. For instance, the significant 22-year variation in the cosmic ray intensity is due to charge drift effect which is dependent on the magnetic polarity (e.g., Jokipii & Levy, 1977). Similarly, the 22-year periodicity in geomagnetic data is mainly due to the Russell-McPherron mechanism which couples the interplanetary magnetic field and the magnetosphere differently for the two solar magnetic polarities (e.g., Cliver et al., 1999).

In conclusion we have shown that a persistent 22-year periodicity indeed exists in sunspot activity throughout the whole time interval of about 400 years of direct solar observations. The 22-year periodicity in sunspot activity is naturally produced by the 22-year magnetic Hale cycle in the presence of a relic dipole magnetic field. Accordingly, the detected 22-year periodicity in sunspot activity gives strong evidence for the existence of such a relic magnetic field in the Sun. The stable phase and the roughly constant amplitude of this periodicity during times of very different sunspot activity level strongly support this interpretation.

ACKNOWLEDGEMENTS

The financial support by the Academy of Finland is greatfully acknowledged. We appreciate the electronic service of NOAA for an easy access to sunspot data.

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