PERSISTENT 22-YEAR CYCLE IN SUNSPOT ACTIVITY: EVIDENCE FOR A RELIC SOLAR MAGNETIC FIELD

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Abstract. We use the recently presented group sunspot number series to show that a persistent 22-year cyclicity exists in sunspot activity throughout the entire period of about 400 years of direct sunspot observations. The amplitude of this cyclicity is about 10% of the present sunspot activity level. A 22-year cyclicity in sunspot activity is naturally produced by the 22-year magnetic polarity cycle in the presence of a relic dipole magnetic field. Accordingly, a persistent 22-year cyclicity in sunspot activity gives an evidence for the existence of such a relic magnetic field in the Sun. The stable phase and the roughly constant amplitude of this cyclicity during times of very different sunspot activity level strongly support this interpretation.

1. Introduction

While magnetic activity in the Sun is determined by the dynamo mechanism, a weak relic magnetic field may exist in the Sun's interior since its formation (Cowling, 1945). Sonett (1982, 1983a) tried to find a signature of such a relic field in sunspot activity (SA). Assigning a negative sign to odd solar cycles, he fitted the Wolf sunspot number (WSN) series with a bi-harmonical model with periods of 22 and 90 years. He found a small offset in the running mean of the model during the last 150 years, providing evidence for a relic solar field. However, his results for the earlier period before mid-19th century were not conclusive since the offset changed sign in late 1700s. Therefore, Sonett's results, and the implied evidence remained rather unconvincing. More recently, Bravo and 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 significant conclusion (Boruta, 1996).

It has been argued (Levy and Boyer, 1982; Boyer and 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 cyclicity of SA. Due to a strong amplification by the dynamo fluid motions in the convection zone, such a weak constant field can

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interact with the poloidal/toroidal dynamo field and hence play a considerable role in the formation of a sunspot cycle (Levy and Boyer, 1982; Boyer and Levy, 1984). The total magnetic field in the convection layer is enhanced when the dynamo field has a favorable 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 cyclicity in SA with the period of the magnetic polarity cycle. Accordingly, a 22-year cyclicity in SA would provide compelling experimental evidence for the existence of a relic field in the Sun. However, no convincing evidence for such a cyclicity has been found in sunspot activity when using the famous WSN series. This is probably because of the rather poor quality of WSN data before mid-19th century (Hoyt and Schatten, 1998; Letfus, 1999), and because of the large long-term variations of SA level (the secular Gleissberg cycle). The poor quality of WSN data is also a likely reason for the inconclusive results by Sonett (1983a) for the early times.

Here we perform a detailed analysis of the 22-year cyclicity using the new group sunspot numbers (GSN). The GSN series, depicted in Figure 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 WSN (Hoyt and Schatten, 1998). Contrary to Sonett (1982, 1983a), we do not fit the data to any model but rather analyze the raw sunspot data directly.

2. 22-Year Cyclicity in Sunspot Activity

An empirical Gnevyshev–Ohl (G–O) rule (Gnevyshev and Ohl, 1948) orders 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 WSN series is only valid since solar cycle 10 and fails for cycle pairs 4–5 and 8–9 (Gnevyshev and Ohl, 1948; Wilson, 1988; Storini and Sykora, 1997). In analogy with G–O rule, we define the intensity $I_{\mathrm{GO}}(k)$ of the sunspot cycle number k as the sum of sunspot numbers over the cycle:

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

where $R_g(j)$ is the GSN value for the month number j and $J(k)$ is the month starting cycle k. (Cycle minima are defined as 12-month running mean minima. The constant factor $\frac{1}{132}$ in Equation (1) scales the intensity values to correspond to the normal sunspot number values.) The monthly GSN series has some gaps until the end of 18th century. Most data gaps are rather short, but a few gaps are longer than one year. 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%

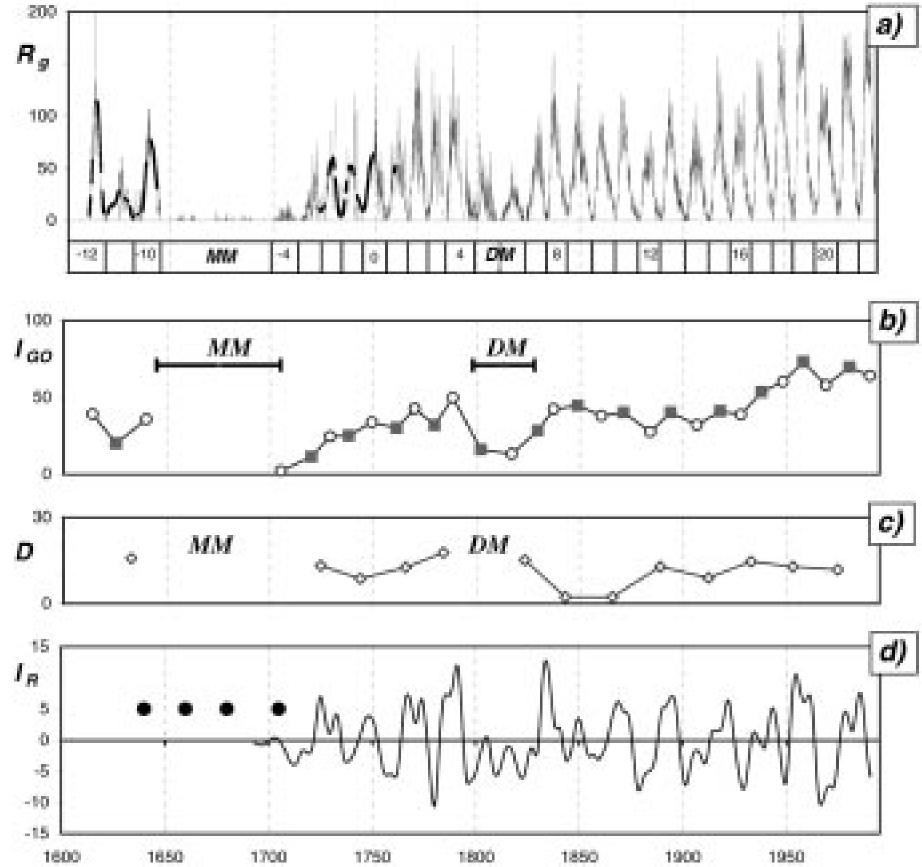

Figure 1. (a) Monthly group sunspot number series R_g (*thin line*) with interpolated gaps (sections of *thick line*). Sunspot cycle numbers are shown in the lower panel together with the location of the Maunder (MM) and Dalton (DM) minima. (b) Sunspot cycle intensities I_{GO} (see Equation (1)) for odd (*black 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 Equation (3)). The times of the 22-year cycle maxima before and during the Maunder minimum are noted by black circles.

even for the longest gaps. The $I_{GO}(k)$ series (Figure 1(b)) allows us 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. This phase-reversed G–O rule applies even for the time before the Maunder minimum which occurred in 1645–1715. (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 Figure 1(c) the difference $D(k) = I_{\rm GO}(k+1) - I_{\rm GO}(k)$ 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 SA. The correlation coefficient between $D(k)$-values and average pair intensities $((I_{\rm GO}(k) + I_{\rm GO}(k+1))/2)$ is -0.09 ± 0.25 for solar cycles -4 to 21.

In 1830–1930 and 1950–1990, when cycle intensities remained roughly constant (see Figure 1(b)), the odd cycles were more intense than either of the two neighboring even cycles. This behavior 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 cyclicity is hidden at times when the SA 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 1940s. During these times the G–O rule is valid only in the fixed order of cycle pairs. Therefore, in order to avoid this influence of long-term trends in SA when examining the existence of the 22-year periodicity in cycle intensity in more detail, we standardized (e.g., Jenkins and 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 $I_R(i)$:

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

The $I_R(i)$-series (see Figure 1(d)) shows a persistent 22-year cyclicity both between the Maunder and Dalton minima and since the Dalton minimum. The confidence level (Jenkins and 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. We have also checked the stability of the results by varying the smoothing length between 10 and 12 years. The residual of the 11-year cyclicity is larger in the 10- and 12-year smoothed series than in the 11-year smoothed series, but a persistent 22-year periodicity is still the dominant feature. In agreement with results obtained above for the discrete series (see Figure 1(c)), the peak-to-peak amplitude of the 22-year cyclicity in Figure 1(d) is roughly constant and about 10–20, corresponding to approximately 10% of the amplitude 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 cyclicity is independent of the overall SA level. We have proven recently that during the Maunder minimum, when the Schwabe cycle was strongly suppressed, the remaining SA still shows a significant 22-year periodicity (Usoskin, Mursula, and Kovaltsov, 2000). Accordingly, a persistent 22-year cycle exists in SA throughout the whole time interval of nearly 400 years of direct solar observations. The sunspot maxima during the Maunder minimum (Usoskin, Mursula, and Kovaltsov, 2000) occur in phase with the maxima of the 22-year cyclicity before and after the minimum (see Figure 1(d)). The 22-year cyclicity was suppressed 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 cyclicity has no sizeable phase change around the Dalton minimum. Therefore, the phase reversal in the G−O rule is not related to the 22-year cyclicity but, most likely, to the known phase catastrophe (e.g., Vitinsky, Kopecký, and Kuklin, 1986; Kremliovsky, 1994) of the Schwabe cycle in the beginning of the Dalton minimum (see also Sonnet, 1983b). (Note that another phase catastrophe occurred after the Maunder minimum (Usoskin, Mursula, and Kovaltsov, 2000)).

3. Conclusions

Concluding, in this paper we have shown that a persistent 22-year cyclicity indeed exists in sunspot activity throughout the whole time interval of about 400 years of direct solar observations. The 22-year cyclicity in SA implies a systematically asymmetric oscillation of the magnetic field intensity in the solar convection zone. Such an asymmetric oscillation is naturally explained by the 22-year magnetic Hale cycle in the presence of a constant (at least at the time scale of several hundred years) relic dipole magnetic field (see, e.g., Levy and Boyer, 1982; Boyer and Levy, 1984). Accordingly, the detected persistent 22-year cyclicity in SA gives evidence for the existence of such a relic magnetic field in the Sun. The orientation of the relic field is southward, in agreement with the suggestion of Bravo and Stewart (1995). The stable phase and the roughly constant amplitude of this cyclicity during times of very different sunspot activity level strongly support this interpretation.

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