ON THE RELATION BETWEEN THE CORONAL FREE ENERGY AND SOLAR FLARE OCCURRENCE

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Abstract. A significant delay with a 22-year modulation in solar flare occurrence was found by Temmer et al. (2003) with respect to the solar cycle defined on the basis of the relative sunspot number. These observational results were modelled by Litvinenko and Wheatland (2004) through a time-dependent balance of the magnetic free energy in the solar corona. The free magnetic energy is assumed to be depleted mainly by flares and lags behind the variation of the energy supply (emerging magnetic flux - proxy: relative sunspot numbers) to this system. For solar cycles 21 and 23, in accordance with the delay obtained for flare rates, the rate of sunspot group numbers lags behind the solar cycle maximum. Theses findings suggest that the energy supply itself is delayed, most prominent in odd numbered solar cycles which subsequently causes the delay observed for flare and sunspot group occurrences.

Key words: solar flares - sunspot areas - solar cycle - coronal energy balance

1. Introduction

The temporal behaviour of the solar cycle is defined on the basis of the number of sunspots observed on the visible solar disk, indicated by the relative sunspot numbers \( R \) (see Equation 1). The remarkable relevance of \( R \) lies in particular in the fact that it represents one of the longest time series of solar activity indices available. Thus, relative sunspot numbers provide the foundation of a continuous data set for research on the solar cycle and its long-term variations. \( R \) is defined by

\[
R = k (10g + f),
\]

(1)
where \( g \) is the number of observed sunspot groups, \( f \) the number of spots and \( k \) is an observatory-related correction factor (the details depending on the actual seeing conditions, the instrument used, and the observer).

In principle, many other activity indices – related to photospheric, chromospheric or coronal activity phenomena (cf. Table I) – closely follow the course of the sunspot cycle. However, exceptions exist which possibly contain interesting clues on the dynamics of the solar cycle. In several studies it was reported that in solar cycle 21, the soft X-ray (SXR) flare occurrence as well as the SXR background flux were significantly delayed with regard to the Sunspot Numbers, revealing a lag of 2–3 years between the peak times (e.g., Wagner, 1988; Aschwanden, 1994; Bromund et al., 1995). This delay has been interpreted in terms of complexity of the coronal magnetic field in the decay phase of the solar cycle (Aschwanden, 1994). However, Wilson (1993) studied solar cycle 22 up to the year 1992 and did not find evidence for such a delay of SXR flare occurrence.

Wheatland and Litvinenko (2001) presented a model for the dynamic energy balance in the corona over the solar cycle that predicts that the magnetic free energy in the corona lags behind the variation in the energy supply to the system. The energy supply to the corona is generally assumed to occur via the emergence of new magnetic flux or by photospheric stressing of coronal fields. Assuming that flares are powered by a coronal energy source and are the dominant mechanism for depleting that source, and using Sunspot Numbers as a proxy for the energy supply rate, the model accounts for a delay of flare occurrence with respect to Sunspot Numbers for \( \approx 11 \) months (Wheatland and Litvinenko, 2001).

2. Motivation

Temmer et al. (2003, hereafter referred to as paper A) tested in detail the model proposed by Wheatland and Litvinenko (2001) applying cross-correlation analyses on the monthly number of H\( \alpha \) and soft X-ray flares against the monthly mean Sunspot Numbers for the period 1976–2002. The solar flare occurrence rate was investigated separately for weak and powerful events, and the relation between flare occurrence and Sunspot Numbers was analysed also as a function of flare importance (cf. Table 1 in paper A). In paper A it was shown that in solar cycles 19, 21 and 23 flare activity is statistically delayed with regard to sunspot activity with
Table I: Activity indices for different solar atmospheric layers, where $^1$ indicates the magnetic field strength and $^2$ the sunspot area (see also Bachmann and White, 1994).

<table>
<thead>
<tr>
<th>Activity Index</th>
<th>Wavelength</th>
<th>Atmospheric Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFS$^1$</td>
<td>–</td>
<td>photosphere</td>
</tr>
<tr>
<td>SA$^2$</td>
<td>–</td>
<td>photosphere</td>
</tr>
<tr>
<td>Hα</td>
<td>656.3 nm</td>
<td>chromosphere</td>
</tr>
<tr>
<td>Ca II K</td>
<td>393.3 nm</td>
<td>chromosphere</td>
</tr>
<tr>
<td>Mg II</td>
<td>279.9 nm</td>
<td>chromosphere</td>
</tr>
<tr>
<td>He I</td>
<td>1083.0 nm</td>
<td>chromosphere</td>
</tr>
<tr>
<td>Ly α</td>
<td>121.6 nm</td>
<td>upper chromosphere</td>
</tr>
<tr>
<td>F10</td>
<td>10.7 cm</td>
<td>chromosphere, corona</td>
</tr>
</tbody>
</table>

A characteristic lag in the range $10 \lesssim \tau \lesssim 15$ months. This phenomenon shows up more prominently when low-energetic events are discarded from the analysis. In general, the derived lag is consistent with that derived by Wheatland and Litvinenko (2001). However, for solar cycles 20 and 22 no characteristic time lag between Sunspot Numbers and flare occurrence was found. The result that in odd-numbered cycles flare activity lags behind sunspot activity, while in even-numbered cycles it does not, appears to be a manifestation of the 22-year magnetic cycle of the Sun. The model of Wheatland and Litvinenko (2001), based on a 11-year cyclicity in the energy supply rate to the corona, can obviously not account for a 22-year modulation in the time lag between energy supply rate and magnetic free energy in the corona available for flaring.

Based on the derived results from paper A, a revised model of the flaring corona was developed by Litvinenko and Wheatland (2004). The primary model by Wheatland and Litvinenko (2001) is based on a time-dependent balance equation for the magnetic free energy in the solar corona, which follows from the assumptions that flares derive their energy from a source in the corona and that flares are the dominant mechanism for depleting that source. In the revised model (Litvinenko and Wheatland, 2004) they assume that the flaring rate is a more complicated function, defined not only by the instantaneous energy in the corona but also by the dynamics of the energy supply rate, i.e. the driving function. For weak driving, it might
be expected that there are sufficient flaring sites to dissipate the supplied energy essentially immediately, so that the flaring rate is proportional to the driving rate. It is reasonable to assume in this case that the rate is also proportional to the free energy, because the number of flaring sites is defined by the magnetic field already present. For very large energy supply rates, it might be possible that there are insufficient flaring sites to immediately dissipate the supplied energy, and so the flaring rate is then proportional just to the free energy. This assumption can explain why delays are found for large odd-numbered cycles like 19 and 21, and why there are no delays for weaker cycles, like 20 and 22.

In the following we investigate whether the energy supply rate itself, using the occurrence rate of sunspot groups as a proxy, reveals a delay with respect to the relative sunspot numbers.

3. Data and Methods

For the time span 1955–2003 covering solar cycles 19 to 23 we apply cross-correlation analyses to the monthly number of sunspot groups with respect to the mean monthly Sunspot Numbers. Sunspot group data are from the Royal Greenwich Observatory; Sunspot Numbers are from the Sunspot Index Data Center (SIDC) in Brussels; The cross-correlation function is calculated up to a time lag of ±30 months. In order to accord to the different flaring groups of paper A (defined by their different importance classification) we divide the sunspot groups with respect to their observed areas. Area group I includes the number of sunspot groups with areas > 0 msh (corrected whole spot area in millionths of the solar hemisphere) and area group II the number of sunspot groups with areas > 650 msh, respectively.

4. Results

In Figure 1 it can be seen that the number of area group I shows no delay with respect to the relative sunspot numbers, quite similar to the low-energetic Hα flare group I in paper A. Sunspot group II shows for cycle 19 higher cross-correlation coefficients in comparison to monthly mean Sunspot Numbers for cycle 20 but no delay is obvious. This result is contrary to the Hα flare rates where a delay of $\tau \sim 10$ months is obtained for cycle 19 (see paper A). However, for cycle 21 shown in Figure 2, a delay
Figure 1: Cross-correlation coefficients derived from monthly numbers of daily sunspot areas (for selected groups) and monthly mean Sunspot Numbers for solar cycles 19 (thick lines) and 20 (thin lines). The cross-correlation function is up to a time lag of ±30 months.

Figure 2: Same as Fig. 1 but for solar cycles 21 (thick lines) and 22 (thin lines).

in the range of $\tau \sim 10$ months is revealed for area group II whereas for group I no delay is visible. For cycle 22 no delay for both groups is obtained. Figure 3 shows the cross-correlation coefficients for solar cycle 23 revealing enhanced values between $10 \sim \tau \sim 20$ months which indicates a lag with respect to the solar cycle maximum defined by the relative sunspot numbers.

Summarizing, in 2 out of 3 cases where a delay in the occurrence rate of Hα flares with importance classes $> 1$ and SXR flare events was found in paper A, a delay in the same order of magnitude is found for sunspot groups of large areas.
5. Discussion and Conclusions

In the present analysis we have shown that also the energy supply rate itself, using the occurrence rate of sunspot groups as a proxy, reveals a delay with respect to the sunspot numbers. This result is obtained for solar cycles 21 and 23 in accordance with the delay for the flare rate in paper A. In contradiction is the delay found for cycle 19 for flare occurrences (paper A) but not for sunspot areas. However, Kuklin and Kopecky (1988) found in a 100-year long data set that the maxima of sunspot group occurrences with areas > 1500 msh are shifted to later phases of the cycle which is more distinct in odd cycles. Furthermore, 90% of major flares are produced by only 10% of sunspot groups of complex magnetic field and large areas. Regions larger than 1000 msh and classified as $\beta\gamma\delta$ had nearly 40% probability of producing flares classified X1 or greater (Sammis et al., 2000).

Durney (2000) interprets the differences between odd and even cycles as a nonlinear mechanism stabilizing the cycles amplitude. Using the new group sunspot numbers (Hoyt and Schatten, 1998a,b), Mursula et al. (2001) revisited the Gnevyshev-Ohl rule (Gnevyshev, 1963), finding a systematic variation with the 22-year magnetic cycle in the intensity of successive sunspot cycles in a record of almost 400 years. These authors stress that this result provides strong experimental evidence for a persistent relic magnetic field (a hypothesis first proposed by Cowling, 1945). Such a stationary external field can interact with the poloidal/toroidal dynamo field of the Sun which plays an important role in the manifestation of the sunspot cycle. In particular, in the presence of a dipole relic field the symmetry of the dynamo states are broken, which manifests itself in a 22-year modulation.
of the intensity of the 11-year activity cycle (see Levy and Boyer, 1982; Boyer and Levy, 1984).

From this we conclude that the delay observed in flare rates (high-energetic Hα as well as SXR flare events) and also in sunspot groups of large areas might not be invariably effected by the dynamic energy balance of the solar corona as proposed by Wheatland and Litvinenko (2001) and Litvinenko and Wheatland (2004). Rather it might be the result of a different activity behaviour of odd and even solar cycles, i.e. of the two parts of the magnetic 22-year solar periodicity.

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References

VEZA IZMEĐU SLOBODNE ENERGIJE KORONE I POJAVE SUNČEVIH BLJEŠKOVA

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Izlaganje sa znanstvenog skupa


Ključne riječi: Sunčev bljeskovi - površine pjega - Sunčev ciklus - ravnoteža energije u koroni