On the 24-day period observed in solar flare occurrence

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Abstract. Time series of daily numbers of solar Hα flares from 1955 to 1997 are studied by means of wavelet power spectra with regard to predominant periods in the range of ~24 days (synodic). A 24-day period was first reported by Bai (1987) for the occurrence rate of hard X-ray flares during 1980–1985. Considering the northern and southern hemisphere separately, we find that the 24-day period is not an isolated phenomenon but occurs in each of the four solar cycles investigated (no. 19–22). The 24-day period can be established also in the occurrence rate of subflares but occurs more prominently in major flares (importance classes $\geq$1). A comparative analysis of magnetically classified active regions subdivided into magnetically complex (i.e. including a γ and/or δ configuration) and non-complex (α, β) reveals a significant relation between the appearance of the 24-day period in Hα flares and magnetically complex sunspot groups, whereas it cannot be established for non-complex groups. It is suggested that the 24-day period in solar flare occurrence is rather related to a periodical emergence of new magnetic flux than to the surface rotation of sunspots.

1. Introduction

From the longitudinal distribution of hard X-ray (HXR) flares for the time span 1980–1985, Bai (1987) found a predominant period of 23.78 days[1]. He excluded surface rotation as origin of this period but attributed it to sources in the interior of the Sun, like deeper lying active centers. However, a dominant 23.5-day period was also found in irradiance measurements for the time span 1980–1988 as well as in the areas especially of young and "active" sunspot groups (Pap, Tobiska, and Bouwer, 1990, and references therein). Even shorter periods (~22 days) in solar flare occurrence were reported by Jetsu et al. (1997) interpreting this as a signature of a non-axisymmetric component of

[1] All periods stated in this paper are synodic.

the magnetic field below the visible surface. Recent helioseismic studies indicate an increase of the rotation velocity below the surface for low solar latitudes (see the review by Beck, 1999). Based on periodogram techniques, Temmer et al. (2003) found a predominant 23.8-day periodicity in the occurrence rate of major solar flares during 1975–2001 which did not show up in sunspot relative numbers analyzed for the same time span. However, Zięba et al. (2001) found for the rising phase of solar cycle 23 a 23.8-day period in sunspot relative numbers after the removal of strong periods in the original data. By analyzing magnetic flux time series for the time span 1977–2001, Henney and Harvey (2002) obtained a 24.4-day period but considered this as a spurious signal. More detailed studies concerning the $\sim$24-day period in solar flare occurrence and possibly linked activity tracers are still outstanding.

Large flares occur preferentially in association with active regions of complex magnetic configuration. Sammis, Tang, and Zirin (2000) analyzed 8 years of active region observations with respect to solar flare occurrence, and found that most of the major flares occurred in active regions of $\beta\gamma\delta$ structure. Periodical occurrences of major flare events might be related to these magnetically complex active regions, reflecting their rotational behavior. In the frame of the anchoring hypothesis, especially new-borne spots might represent deeper and thus faster rotating layers (see, e.g., Balthasar, Schüssler, and Wöhl, 1982).

Answers to the following questions could give us a better understanding of the $\sim$24-day period. (1) Is the 24-day periodicity a general (i.e. occurring in many solar cycles) or an isolated phenomenon? (2) Is it apparent only for major solar flares? (3) Is it related to the rotation of magnetically complex active regions?

In the present paper solar Hα flares for the entire cycles 19–22 are investigated with respect to synodic occurrence rates in the range of $\sim$24 days, together with their localization in time by means of wavelet power spectra. The investigation is carried out for different flare importance classes as well as separately for the northern and southern hemisphere, respectively. The separation into the solar hemispheres is important to avoid overlapping effects from the activity of both hemispheres, which may occur when studying the whole disk (e.g., Bai, 1987; Temmer, Veronig, and Hanslmeier, 2002). It is worth noting that Bai's analysis of HXR flares comprises only major events. Here we distinguish between small and large flares. In addition to that, for cycles 20–22, a comparative analysis of the occurrence rates of magnetically complex and non-complex active regions, respectively, is carried out.

2. Data

For each hemisphere, time series of daily numbers of Hα flares are constructed using the Hα flare data compiled in the Solar Geophysical Data for the time span 1955–1997. Based on the importance classification of Hα flares, the events are subdivided into low-energetic (subflares) and high-energetic (importance class $\geq$1) flare groups. Because of inadequate importance classifications before 1975, the distinction between low- and high-energetic events is based on the flare duration for the time span 1955–1974 (there is a strong correlation between flare importance and duration, see e.g., Temmer et al., 2001). Flares of duration $d < 50$ min are defined as low-energetic, and flares with $d \geq 50$ min are defined as high-energetic events. The value of $d \geq 50$ min gives us about the same percentage ($\sim$10%) of high-energetic flares as derived from importance classifications $\geq$1 for 1975–1997.

Furthermore, daily numbers of magnetically classified active regions are analyzed using reports from the Mount Wilson Observatory available for the time span 1964–1997, i.e. fully covering solar cycles 20–22. Considering the magnetic classifications of sunspot groups a subdivision into magnetically non-complex (α, β) and magnetically complex (i.e. all classifications including γ and/or δ) groups is prepared. Magnetically complex groups account for $\sim$15% of all active regions.

3. Methods

The wavelet transform can be used to analyze time series that contain non-stationary power at many different frequencies (Daubechies, 1990). Therefore, wavelets are an appropriate tool to investigate the time of appearance as well as the temporal evolution of dominant periods in time series. For this purpose several types of wavelets are available. However, the method works best when the analyzing wavelet has a similar shape as the observed data. Thus, we have chosen the Morlet wavelet (Grossman and Morlet, 1984) representing a sinusoidal oscillation contained within a Gaussian envelope as the analyzing wavelet function $\psi(\tau)$, where τ is a non-dimensional time parameter. The continuous wavelet transform is defined as the convolution of a time series, $\{x_n\}$, with equal spacing in time, δt, and N data points. It can be written as

$$W_n(s) = \sum_{k=0}^{N-1} \hat{x}_k \hat{\psi}^*(s\omega_k) e^{i\omega_k n \delta t}\,, \tag{1}$$

where $\hat{x}_k$ is the discrete Fourier transform of x_n and $\hat{\psi}^*(s\omega_k)$ is the scaled and translated version of $\psi(\tau)$; (*) indicates the complex conjugate. By varying the scale s and translating along the localized time index n one can construct a descriptive three-dimensional plot showing the amplitude of any feature versus the scale as function of time. The angular frequency ω_k is defined as

$$\omega_k = \begin{cases} \frac{2\pi k}{N\delta t} & : \quad k \leq \frac{N}{2} \\ -\frac{2\pi k}{N\delta t} & : \quad k > \frac{N}{2} \, . \end{cases} \tag{2}$$

All wavelet power spectra presented in this paper were calculated for the period range 10–40 days. As significance tests confidence levels at 95% and 99% are applied, respectively. Since daily flare data are assumed to be correlated (Oliver and Ballester, 1995) the background spectrum is modeled with red noise. Regions where edge effects become important due to dealing with finite-length time series, such as the beginning and the end of the wavelet spectrum, are labeled as cone of influence (COI). The computation of all these parameters is performed in the way described by Torrence and Compo (1998).

4. Results

4.1. Hα FLARE EVENTS

Figures 1–4 show the wavelet power spectra calculated for daily numbers of northern/southern flare events occurred during solar cycles 19–22. **In general, the strongest power is seen in the range of about 27 to 30 days. This signal is very probably caused by the differential rotation of the Sun. Mean periods reported are from ∼26.5 days near the solar equator to ∼29.5 days around 40° latitude (e.g.,** Howard, 1984; Balthasar, Vázquez, and Wöhl, 1986**). In this paper we do not discuss this range of periodicities but concentrate on the distinct power revealed at a period of ∼24 days (see Figs. 1–4).**

In particular, we draw attention to high amplitudes within a confidence level of at least 95% observed for the period range 23.8 ± 0.5 days (a 23.8-day period is reported by Bai, 1987; Zięba et al., 2001; Temmer et al., 2003). Significance levels at 95%/99% are indicated by black/white contour lines in the wavelet power spectra. Applying these criteria, the results obtained for each solar cycle and the different subdivisions are summarized in Table I.

Positive results on significance levels of 95% (and partially even 99%), are obtained for low- as well as high-energetic flares for each of the studied cycles. High-energetic flare events show a ∼24-day period nearly twice as much as low-energetic ones. For flares occurring on the

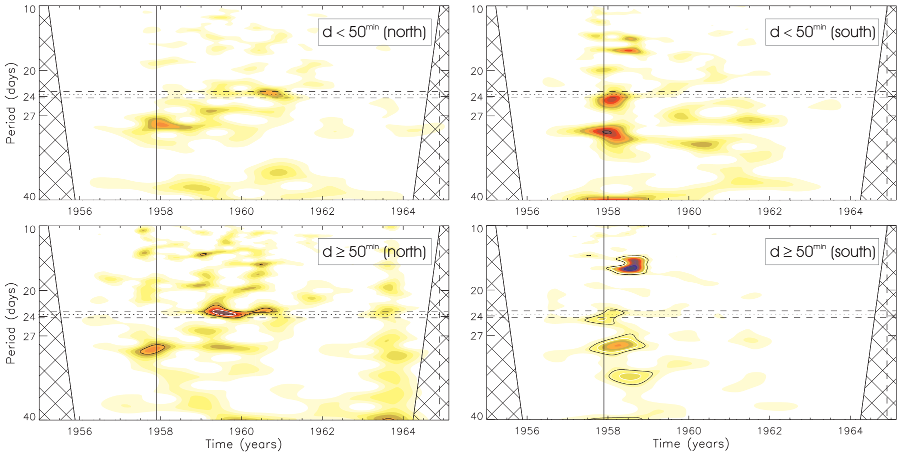

Figure 1. Wavelet power spectra derived from Hα flare events observed during cycle 19 (*left panels*: northern hemisphere, *right panels*: southern hemisphere, *top panels*: low-energetic flares, *bottom panels*: high-energetic flares). Grey-scale coding from white to black represents the square root of power in a linear scale. Dashed/solid vertical lines indicate the solar cycle minima/maxima. Black/white contour lines denote a 95%/99% confidence level. Cross-hatched lines indicate the COI's. Dashed/dotted horizontal lines at 23.3, 23.8, and 24.3 days are drawn.

southern hemisphere the occurrence of the ~24-day is more prominent than for those on the northern hemisphere. Events on the northern hemisphere feature the ~24-day period around the solar cycle maxima ($-1.5 \lesssim$max.$\lesssim +2.5$ years). For the southern events it appears within a closer range to the solar cycle maxima ($-0.5 \lesssim$max.$\lesssim +2.0$ years).

In general, the 24-day period is intermittent and reveals higher significance for high-energetic flares. It is important to note that this periodicity occurs also in low-energetic events, but more prominently in major flares. For cycles 19–22, in major flare occurrence the 24-day period can be found in 7 out of 8 cases (cf. Table I).

4.2. Magnetically complex active regions

It was pointed out that there is a strong tendency of major flares to be associated with active regions of a complex magnetic configuration (Sammis, Tang, and Zirin, 2000). Here, we find a 24-day period primarily in the occurrence rates of major flares. Since major flares account only for ~10% of the total of events (cf. Temmer et al., 2001; Veronig et al., 2002; and references therein) the fact that this periodicity is found in the occurrence of major flares might be due to a selection effect towards magnetically complex active regions and their rotational behavior. Here we test this hypothesis by analyzing time series of occurrences of magnetically complex active regions (i.e. including a γ and/or

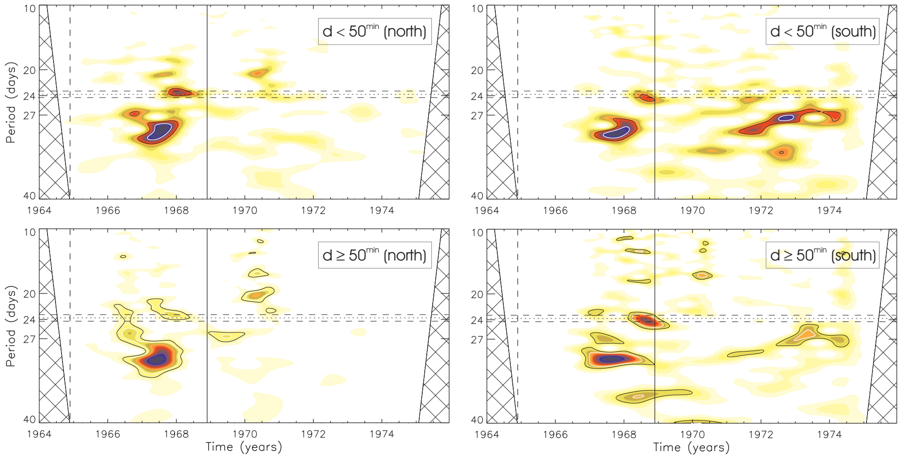

Figure 2. Same as Fig. 1 but for cycle 20.

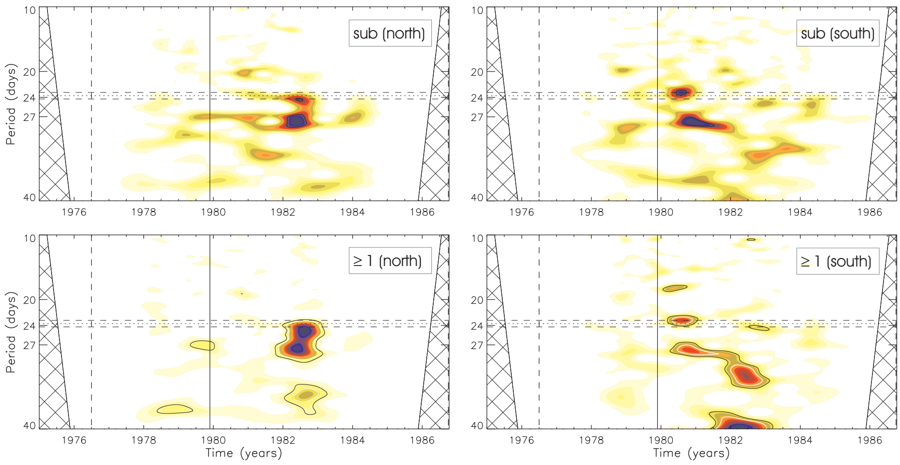

Figure 3. Same as Fig. 1 but for cycle 21.

δ configuration) in comparison to unipolar and bipolar active regions (α, β).

Figures 5–7 show the wavelet power spectra for solar cycles 20–22 calculated from daily numbers of northern/southern active regions for different magnetic configurations. Again the attention was drawn to high amplitudes with at least 95% significance in the period range 23.8 ± 0.5 days, occurring simultaneously with corresponding periods observed in Hα flares. For magnetically non-complex active regions (α, β), the wavelet power spectra do not reveal a significant signal in the 23.8 ± 0.5-day period range. On the other hand, for complex active regions (γ/δ) on the northern hemisphere highly significant $\sim$24-day periods simultaneously with that found for high energetic Hα flares are

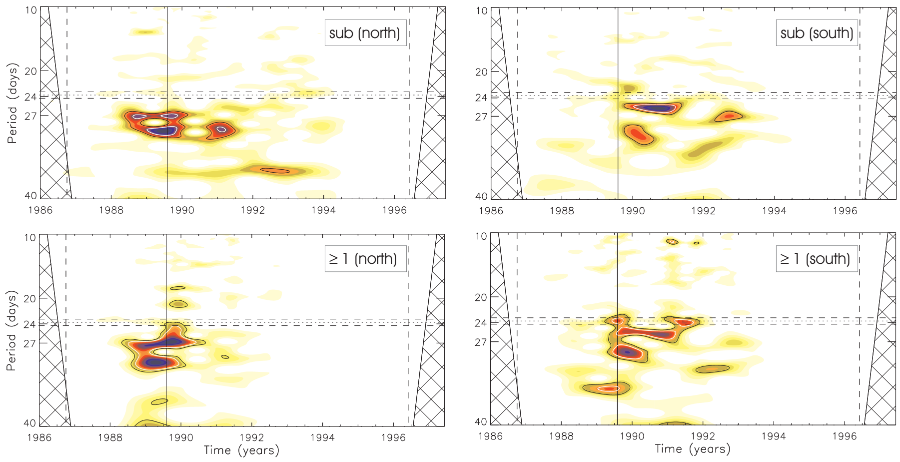

Figure 4. Same as Fig. 1 but for cycle 22.

Table I. Summary of the wavelet analysis regarding the $\sim 24^d$ period in solar cycles 19 to 22 ("✓" indicates existence, "×" non-existence of the $\sim 24^d$ periodicity – attention was drawn to high amplitudes within a confidence level of at least 95% observed for the period range 23.8 ± 0.5 days). The results are listed separately for the northern and southern hemisphere, as well as separately for low- and high-energetic flares.

Cycle no.	$\mathrm{low_{north}}$	$\mathrm{low_{south}}$	$\mathrm{high_{north}}$	$\mathrm{high_{south}}$
19	×	×	✓	✓
20	✓	✓	✓	✓
21	✓	✓	✓	✓
22	×	×	×	✓

obtained in cycles 20 and 21 (left bottom panels in Figs. 5 and 6). For the southern hemisphere, a coincident 24-day period of complex active regions and high-energetic flares is obtained during cycle 22 (Fig. 7, right bottom panel).

5. Discussion

Up to now the 24-day period was only reported for the occurrence rate of major solar flares in cycle 21 (Bai, 1987). Here we have shown that the 24-day period in flare occurrence is not a singular phenomenon but occurs in all four solar cycles studied (19–22). It is observed mainly

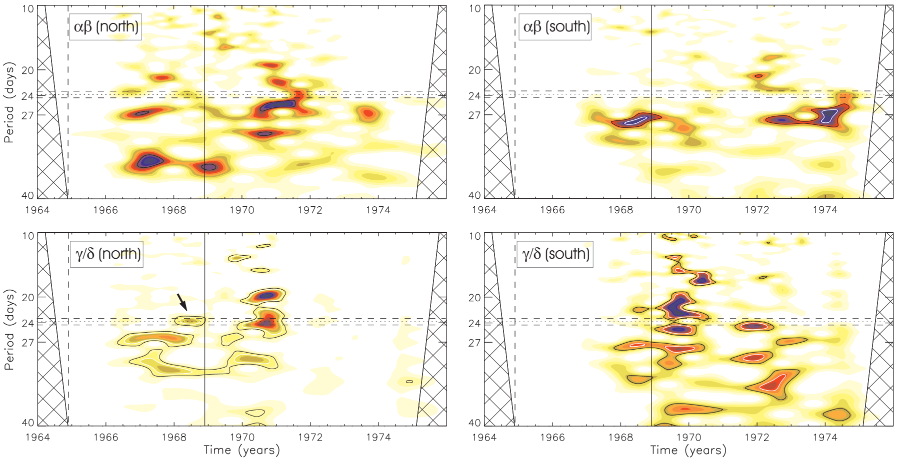

Figure 5. Wavelet power spectra derived for different magnetic classifications of sunspot groups observed during cycle 20 (*left panels*: northern hemisphere, *right panels*: southern hemisphere, *top panels*: non-complex active regions, *bottom panels*: complex active regions). Grey-scale coding from white to black represents the square root of power in a linear scale. Dashed/solid vertical lines indicate the solar cycle minima/maxima. Black/white contour lines denote a 95%/99% confidence level. Cross-hatched lines indicate the COI's. Dashed/dotted horizontal lines at 23.3, 23.8, and 24.3 days are drawn. Arrows mark a simultaneous occurrence of a ∼24-day period revealed for flare events.

during narrow time ranges around the maximum of a solar cycle. Since the activity is highest around solar cycle maxima the most dominant periods are generated during that time. The appearance of the 24-day period is more prominent for major flares but can be seen also in subflares. Further interesting results are obtained from the investigation of daily numbers of magnetically complex (including classification γ and/or δ) and non-complex active regions (α, β), respectively. Covering three solar cycles, only for magnetic complex active regions a 24-day period is observed. In 3 out of 5 cases this feature coincides with that found for solar major flares.

The ∼24-day period observed in solar Hα flare occurrences might be related to the rotational periodicities of sunspots which are the magnetic source of flare eruptions. From solar rotation studies based on tracing sunspots – which present all individual measurements in contrast to the statistical approach in Fourier techniques – a small fraction reveals sidereal rotation velocities of about 16 deg/day (which corresponds to a synodic period of ∼24 days) and even higher (e.g., Godoli, Mazzucconi, and Piergianni, 1998; Pulkkinen and Tuominen, 1998; Suzuki, 1998). Godoli, Mazzucconi, and Piergianni (1998) and Brajša et al. (2002) report an asymmetric distribution on sunspot ro-

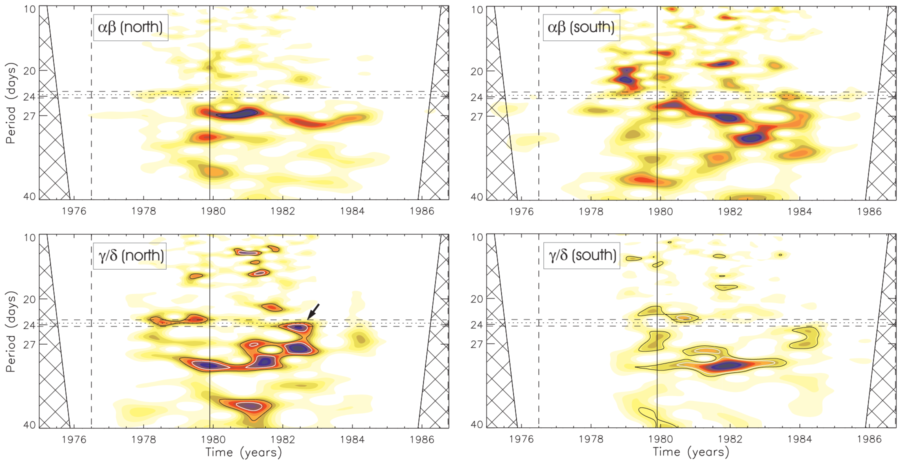

Figure 6. Same as Fig. 5 but for cycle 21.

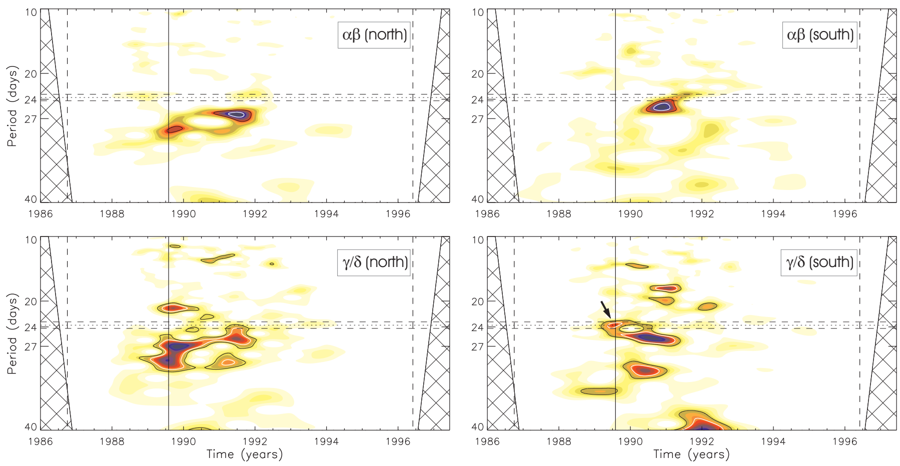

Figure 7. Same as Fig. 5 but for cycle 22.

tation rates from the mean solar rotation of ∼27 days towards shorter periods. However, solar differential rotation is a statistical phenomenon, and individual high rotation velocities might be measurement errors or a consequence of sunspot proper motions. It is important to note that the number of sunspots having sidereal velocities as high as 16 deg/day is only of the order of ∼1%, and thus cannot be the source of the 24-day period found in flare occurrence. This raises the question whether the 24-day signal in flares is related to surface rotation of sunspot groups at all.

The concept of active longitudes (e.g., Bumba and Howard, 1969; Ambrož, 1973; Bogart, 1982; Balthasar and Schüssler, 1983) might be helpful in understanding the 24-day period in solar flare occurrence.

The build-up of a complex of activity as well as large active regions themselves are maintained by pulselike injections of newly emerging magnetic flux rotating in its active lifetime faster than the surrounding regions (Gaizauskas et al., 1983). Signatures of fast-rotating active longitudes can also be found in the "Graphic catalogue of sunspot groups" (Klimeš and Křivsky, 1981, 1983), where the groups are represented by their Carrington longitude, time of observation and latitude. Fast-rotating active longitudes are reported by Rodriguez Taboada and Gil Moreno (1993), too.

6. Conclusions

An important factor triggering the eruption of a flare is the emergence of new magnetic flux that leads to a destabilization of active regions (e.g., review by Aschwanden, 2002). Here we have shown that the 24-day period in solar flare occurrence is not an isolated phenomenon but can be found in each of the studied cycles (19–22), most prominent in the occurrence of major flares. Furthermore, we obtained that the 24-day period exists in the occurrence rate of magnetically complex active regions (γ, δ configurations), whereas it does not occur in magnetically non-complex groups (α, β). In 3 out of 5 cases (cycles 20–22) in which the 24-day period is observed in major Hα flares it occurred also simultaneously in magnetically complex active regions. On the other hand, from solar rotation studies tracing sunspot groups only a marginal fraction ($\sim$1%) of sunspots show rotational periods $\lesssim$ 24 days. Thus, we suggest that the 24-day period is more likely to be related to the periodical emergence of new magnetic flux within already existing active regions than to the surface rotation of sunspots. This hypothesis can explain the observational finding that there is a close relation between the appearance of the 24-day period in solar flares and magnetically complex active regions, which produce most of large flares (Sammis, Tang, and Zirin, 2000), but not in non-complex ones.

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