ON ROTATIONAL PATTERNS OF THE SOLAR MAGNETIC FIELD

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ABSTRACT

Solar magnetic field variations (NSO/Kitt Peak data) through solar cycle 23 with respect to rotational modulations are analyzed. A comparative study to solar cycles 21 and 22 is performed. The results are compared to the rotational behavior of activity tracers like sunspots and solar Hα flares. Periodical occurrences of flares often match the 27-day solar rotation due to recurrent stable sunspot groups and complexes of activity which likely produce more flare events than short-living small sunspots. However, periods with strong deviations from the solar rotation are obtained for higher energetic flares. The solar magnetic field is found to vary on similar time scales, which suggests a close relation to the occurrence of strong flare events.

1. INTRODUCTION

The solar cycle is produced and modulated by the emergence of magnetic fields along with the interaction of the differential rotation leading to an array of activity over a large range of spatial and time scales. What we are able to observe at the solar surface are just results and reactions to these unknown processes in the interior (Harvey, 1993). Detailed analyzes of activity tracers like sunspots and flares together with the global magnetic field may help compensating the impossibility of a direct look into the Sun. The investigation of the behavior of the dynamic surface especially on time scales in the order of the solar rotation is aimed in the presented study.

Periodical occurrence rates in the range of ~27 days[1] obtained from Sunspot Numbers, as well as flares and magnetic surface flux are well known and studied (see, e.g., Howard, 1986 for a review; Bai, 2003 and references therein; Henney and Harvey, 2002 and references therein). Strong deviations from this dominant signal are revealed by analyzing high-energetic flare events observed in the light of Hα as well as soft and hard X-ray. By including solar cycles 21, 22 and the increasing phase of cycle 23 periods of major flares in the range of ~ 24 days are obtained. This behavior is not observed for less energetic events (Temmer et al., 2003 and references therein; Bai, 1987).

During the solar cycle minimum the global magnetic field of the quiet Sun is the dominant factor in magnetic flux measurements. However, during the maximum phase of the cycle active regions dominate the total magnetic flux by up to a factor of 3 (Harvey, 1994). In the following, rotational features within a comparative analysis for the global solar magnetic field, high-energetic solar Hα flares (importance classes ≥ 1), and Sunspot Numbers applied on phases around the maximum of solar cycles 21, 22 and 23 are studied. This should provide information on the different kinds of interaction between solar activity tracers and the magnetic field as well as its variability through the 11-year cycle.

2. DATA AND METHODS

Full-disk averages of the daily line-of-sight component of unsigned magnetic field strength measurements (National Solar Observatory/Kitt Peak (NSO/KP)), daily numbers of solar flares observed in Hα (Solar Geophysical Data), and daily International Sunspot Numbers (Sunspot Index Data Center) are taken for the following study. The time span from January 1977 until December 2001 is covered by the analysis.

The magnetic flux data set by NSO/KP does not steadily cover the overall period, rather 30% are missing values. These temporal gaps are reconstructed by performing a linear interpolation on the daily values. A detailed description of the instruments used at NSO/KP can be found in Jones et al. (1992). The number of the occurrence of Hα flares is taken for higher energetic events only (≥ 1), i.e. subflares amounting up to 90% of the data are excluded from the analysis.

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

As mathematical tools investigating rotational patterns in time series, periodogram and wavelet analyzes are applied. Both are carried out for a period range from 10–40 days in order to cover periods related to the solar differential rotation. The significance of a peak in the periodogram is estimated via a false-alarm probability (FAP) (for details see Lomb, 1976; Scargle, 1982; Horne and Baliunas, 1986). For the wavelet power spectra presented in this paper, confidence levels at 80% and 99% are applied as significance test. The computation of all the wavelet parameters is performed in the way as described by Torrence and Compo (1998).

Figure 1. Wavelet power spectra calculated for the NSO/Kitt Peak magnetic field data including the time span 1977–2001. Grey-scale coding from white to black represents the square root of power in a linear scale. The COI is given as crossed lines. Dashed and solid vertical lines indicate the solar cycle minima and maxima. The dashed horizontal line indicates a 27-day period. Black/white contour lines show a 80%/99% confidence level.

3. RESULTS

In Fig.1 the result out of the wavelet analysis computed for the daily averaged magnetic field (AMF) during the time span 1977–2001 is given. Overall, a persistent 27-day period indicated by enhanced power levels is seen for times covering 1–2 years before and 2–3 years after maximum of each entire cycle. Additionally, interim small islands of significant (80%) periods ranging from ∼12–∼17 days are obtained. Periods at a level of 80% significance can be found around the maximum as well as for the late declining phase of cycle 21 ranging from ∼23 to ∼29 days. A broader amplitude range is seen in cycle 22, appearing from ∼24 to ∼30 days during the declining phase of the cycle. Solar cycle 23, which is covered by the data through the increasing and maximum phase, is dominated by periods around 25 and 27 days. Highly significant periods at a 99% level are solely revealed right after the maximum phase of solar cycle 22 within 24–28 days. These phases of each cycle appearing in the wavelets within significant signal ranges (80% as well as 99%) are taken for further analyzes by preparing periodograms so as to get discrete periods.

The periodograms shown in Fig.2 present the normalized power (due to event correlation a normalization factor has to be applied; for details see Scargle, 1982) calculated for the AMF (top panels) and the numbers of Hα flare events ≥ 1 (bottom panels), including selected time ranges, i.e. the declining phases of solar cycles 21 and 22, as well as the increasing phase of cycle 23. For the AMF a recurrent rotational period in the range of the Carrington rotation (26.5–27.1 days) is revealed which is not apparent for the occurrence of high-energetic solar Hα flares. Couples of matching periods are given at 25.4 (significant) and 23.6 days (non-significant) for the declining phases of solar cycle 21 and 22, respectively. For the increasing phase of cycle 23 coincident periods in the range of ∼32 days are seen. In general, the number of flares displays a much higher noise ratio than the AMF due to a rather low amount of data by reason of selection.

A comparative study to the daily International Sunspot Numbers applying periodograms is presented in Fig.3. For the declining phase of solar cycle 21 the power signals do not match periods seen within the AMF or flare periodogram analysis. During the declining phase of cycle 22 periods at 26.5 (highly significant) and 25.6 days (significant) are obtained according to those of the AMF as well as high-energetic Hα flares. For the increasing phase of cycle 23 power at 25.6 days matching those of the AMF is revealed.

4. DISCUSSION

Out of the wavelet analysis applied to the AMF a rather coherent signal around the 27-day period for the whole considered time span with significant amplitudes during the maximum phase of a cycle and some years afterwards is revealed. Therefore, the persistence of a periodicity near 27 days in the magnetic field can be confirmed according to Neugebauer et al. (2000). Exception from this behavior is seen during solar minimum for which it should be emphasized that the activity level of the AMF during this phase of the cycle is lowered by a factor of ∼5 which is reflected in the mathematical treating of the data. This dominant 27-day period found might be persistent in order to be stated as preferred longitudes of solar magnetic activity (Neugebauer et al., 2000, and references therein). However, out of the wavelets and periodograms it is revealed significantly just for

Figure 2. Periodograms calculated for the daily averaged magnetic field (AMF) and daily number of Hα flares for importance classes ≥ 1. Decreasing phases of solar cycles 21 (Nov. 80–July 83), and 22 (April 90–Jan. 93) as well as the increasing phase of cycle 23 (Jan. 99–April 01) are shown. Couples of matching periods are indicated in bold type.

the various selected phases of a cycle not longer lasting than 2–3 years. Bumba and Howard (1969) suggested by analyzing magnetic-field synoptic charts in comparison with sunspot groups that rigid periods near the Carrington rotation may come from magnetic active longitudes lasting for 20–40 consecutive rotations.

For Hα flares ≥ 1 no significant signals at ∼27 days are seen. Nevertheless, strong periods at 25.4–25.6 days for the declining phases of cycles 21 and 22, as well as a 23.6-day period seen solely during the declining phase of cycle 22 are obtained which are also detected for the AMF. Bai (1987) found that hard X-ray flares (mainly major flares) for the time span 1980–1985, i.e. during solar cycle 21, rotate with a period of ∼23.7 days. A dominant ∼23.5-day period is also found in irradiance measurements as well as in the areas especially of young and "active" sunspot groups observed mainly during cycle 21 (Pap, Tobiska and Bouwer, 1990). The occurrence of such a period during cycle 21 is not revealed out of this analysis for which we suggest the sensibility of the time range applied. Rotational periods might be strongly dependent on the included time span since the period near 24 days is clearly obtained for Hα flare events ≥1 calculated for the entire period from 1975–2000 (Temmer et al., 2003).

However, Sturrock and Bai (1992) found by analyzing Zürich Sunspot Numbers for the time interval 1849 to 1970 that the 154-day periodicity and other related periods of 51, 77, 103, and 129 days discovered in solar flares are multiples of a period of about 25.5 days which may be interpreted as the period of the hypothetical "clock" (Bai and Sturrock, 1991, 1993). Therefore, Bai and Sturrock (1991, 1993) suggested a rotating wave pattern about an oblique axis for which they further concluded that oblique rotating structures enhance flare activity when there are active regions on the surface. Periods presented here for the AMF range from 25.4–25.6 days detected during all selected phases in the periodogram analysis. Hα flares with importance classes ≥ 1 display these periods, too, with exception of the increasing phase of cycle 23. For Sunspot Numbers comparable periods are seen for the declining phase of solar cycle 22 and the increasing phase of cycle 23. Thus, the AMF, Sunspot Numbers, and flares match in a 25.6-day period solely for the declining phase of cycle 22. A differing activity behavior between solar cycles 21 and 22 is given on the one hand by a conspicuously higher rate of subflares for solar cycle 21 and on the other hand by a bigger amount of high-energetic flares (importance classes ≥1) observed for cycle 22 (Temmer et al. 2001).

Besides, an additional strong signal at ∼32 days during the increasing phase of solar cycle 23 is revealed for flare events and the AMF pointing out the beginning of a new cycle that features active regions in higher solar latitudes.

Figure 3. Periodograms calculated for the daily International Sunspot Number. Decreasing phases of solar cycles 21 (Nov. 80–July 83), and 22 (April 90–Jan. 93) as well as the increasing phase of cycle 23 (Jan. 99–April 01) are shown. Periods matching those of the AMF are indicated in bold type.

5. CONCLUSION

Concluding, in this paper we have shown how the variability of rotational patterns observed for the solar global magnetic field over the time span 1977–2001 behaves. A rather coherent signal around 27 days assumed to display the persistence of preferred longitudes of magnetic activity is revealed (Bumba and Howard, 1969, Neugebauer et al., 2000). Besides, a strong signal at 25.6 days is seen in the AMF. In comparison to high-energetic Hα flares and Sunspot Numbers this low rotational period is revealed for the declining phase of solar cycle 22, too. Oblique rotating structures as they are suggested for the 25.5-day period within the magnetic field may enhance flare activity when there are active regions on the surface (Bai and Sturrock, 1991, 1993). Indeed during cycle 22 a much higher rate of major flares than during cycle 21 is observed (Temmer et al. 2001).

The result of a 23.6-day period calculated for the AMF and high-energetic flare events during the declining phase of solar cycle 22 might not be persistent but rather interim.

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REFERENCES

Bai T., 1987, ApJ 314, 795

Bai T., 2003, ApJ 585, 1114

Bai T. and Sturrock P.A., 1991, Nature 352, 360

Bai T. and Sturrock P.A., 1993, ApJ 409, 476

Bumba V. and Howard R., 1969, Solar Phys. 7, 28

Harvey K.L., 1993, in *Solar Surface Magnetism*, Rutten R.J., Schrijver C.J. (eds.), Kluwer Academic Publishers, NATO ASI Series 433, 347

Harvey K.L., 1994, in *The Sun as a Variable Star*, Pap J.M., Fröhlich C., Hudson H.S., Solanki S.K. (eds.), Cambridge Univ. Press, IAU Coll. 143, 217

Henney C.J. and Harvey J.W., 2002, Solar Phys. 207, 199

Horne J.H. and Baliunas S.L., 1986, ApJ 302, 757

Howard R., 1984, ARA&A 22, 131

Jones H.P., Duvall T.L., Harvey J.W., 1992, Solar Phys. 139, 211

Lomb, N., 1976, ApJSS 39, 447

Neugebauer M., Smith E.J., Ruzmaikin A., Feynman J., Vaughan A.H., 2000, Geophys. Res. 105, A2, 2315

Pap J., Tobiska W.K., Bouwer A.D., 1990, Solar Phys. 129, 165

Scargle J.D., 1982, ApJ 263, 385

Sturrock P.A. and Bai T., 1992, ApJ 397, 337

Temmer M., Veronig A., Hanslmeier A., Otruba W., Messerotti M., 2001, A&A 375, 1049.

Temmer M., Veronig A., Rybak J., Hanslmeier A., 2003, Hvar Obs. Bull., in press.

Torrence C. and Compo G.P., 1998, Bull. Am. Meteorol. Soc. 79, 61