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Short-Term Periodicities in Sunspot Activity and Flare Index Data during Solar Cycle 23

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Abstract The short-term periodicities in sunspot numbers, sunspot areas, and flare index data are investigated in detail using the Date Compensated Discrete Fourier Transform (DCDFT) for the full disk of the Sun separately over the rising, the maximum, and the declining portions of solar cycle 23 (1996 – 2006). While sunspot numbers and areas show several significant periodicities in a wide range between 23.1 and 36.4 days, the flare index data do not exhibit any significant periodicity. The earlier conclusion of Pap, Tobiska, and Bouwer (1990, *Solar Phys.* **129**, 165) and Kane (2003, *J. Atmos. Solar-Terr. Phys.* **65**, 1169), that the 27-day periodicity is more pronounced in the declining portion of a solar cycle than in the rising and maximum ones, seems to be true for sunspot numbers and sunspot area data analyzed here during solar cycle 23.

Keywords Flares · Short periodicities · Sunspot activity

1. Introduction

Sunspot activity indices display variations from a few days to several years; the best known oscillations are the 27-day (short-term) and 11-year (long-term) periodicities. These periods are attributed to the modulation of solar features from solar rotation and solar magnetic activity, respectively. Many authors have reported the short-term periodicities in a wide range between 13.5 and 40 days in various solar data and geomagnetic indices during different solar cycles. Bai (1987) found a period of 26.75 days for the rotation period of the active zones during cycle 21. Pap, Tobiska, and Bouwer (1990) analyzed the solar irradiance and solar activity indices, discovering several peaks at 13.5, 22, 23.5, 29, and 30 days for the solar irradiance and at 25, 27, and 28 days for the solar activity indices for a time interval from 1978 to 1988. They also showed that the 27-day periodicity is more pronounced in the descending phase of the solar cycle than in the ascending phase. For 10.7-cm radio emission (F10) during solar cycle 22, Vats *et al.* (1998) suggested that the sidereal rotation period

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varies from 24.07 to 26.44 days with no systematic relation with sunspot numbers and that the solar corona rotates slightly faster than photospheric features. Kane, Vats, and Sawant (2001) studied the 27-day periodicity in solar radio emissions, solar radio flux, and sunspot number during June 1997 to July 1999 for six time intervals and it has been seen that this periodicity shows considerable variation from one interval to the next. During solar cycles 22 – 23, a study of the F10 index made by Kane (2003) reveals fluctuations with peak spacings in a very wide range between 13 and 40 days and shows that the 27-day rotation period is more pronounced in the declining portion of a solar cycle. The 27-day and 13.5-day periodicities are also observed in most solar – terrestrial parameters. These periods are found in solar wind, geomagnetic activity, IMF, and ionospheric parameters (Donnelly and Puga, 1990; Mursula and Zieger, 1996; Nayar *et al.*, 2001, 2002).

In this study, the short-term periodicities in sunspot activity (sunspot numbers and sunspot areas) and flare index data during solar cycle 23 are investigated. To see the periodical behavior of dominant peaks in different phases, all data sets are divided into three time intervals as the rising, maximum, and declining portions. For spectral analysis of these data sets, the Date Compensated Discrete Fourier Transform (DCDFT) is used and this technique is applied separately for the data sets.

2. Data and Analysis

We here study the full disk of the Sun for three kinds of solar data series: sunspot numbers of the Sun provided by the Brussels World Data Center for Sunspot Numbers (SIDC),[1] sunspot areas of the Sun provided by the Royal Greenwich Observatory – USAF/NOAA Sunspot Data,[2] and flare index data taken by the Kandilli Observatory[3] and by the National Geophysical Data Center (NGDC).[4] The data sets cover a time interval from 1 May 1996 to 31 December 2006, which includes the rising, maximum, and declining branches of solar cycle 23. Periodicities of the data series considered here are calculated separately for the three portions. The time intervals cover from 11 May 1996 to 31 January 1999 for the rising portion, from 1 February 1999 to 30 November 2002 for the maximum portion, and from 1 December 2002 to 31 December 2006 for the declining portion. Thus, the time spans of there portions are 1006, 1399, and 1492 days, respectively.

The spectral analysis of data sets considered here are performed by using the DCDFT method first derived by Ferraz-Mello (1981). The method, a lesser known but very useful technique for periodic analysis of time series, was modified and implemented as the CLEANest algorithm by Foster (1995) specifically to analyze the long-term visual data of variable stars such as supplied from the American Association of Variable Star Observers (Templeton, 2004). However, the analysis method was applied to the solar time series for the first time by Kiliç (2008) and it was seen that it is a very useful tool also for solar data. Details and superiorities of the analysis method are given elsewhere by Foster (1995) and Templeton (2004).

As the sunspot or flare data are not statistically independent but correlated, the power P_N follows an exponential distribution (Horne and Baliunas, 1986); that is, the probability of

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[1] http://sidc.oma.be/DATA/DAILYSSN.

[2] http://solarscience.msfc.nasa.gov/greenwch/daily_area.txt.

[3] ftp://ftp.koeri.boun.edu.tr/pub/astronomy/flare_index.

[4] ftp://ftp.ngdc.noaa.gov/stp/solar_data/solar_flares/index.

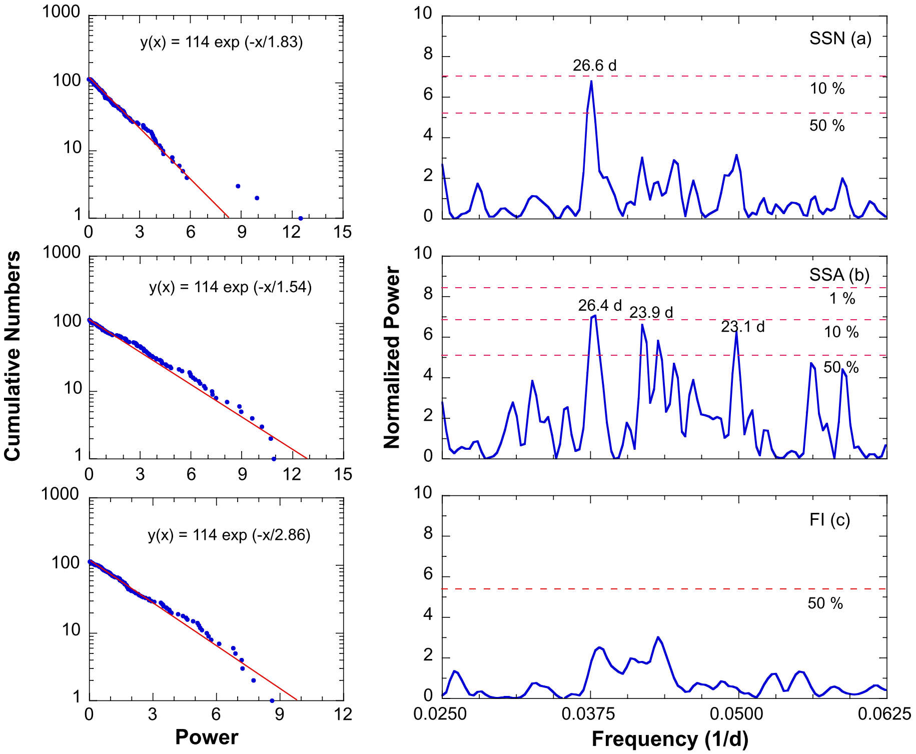

Figure 1 Cumulative numbers and normalized power spectra of (a) sunspot numbers (SSN), (b) sunspot area (SSA), and (c) flare index data (FI) for the rising portion. The dotted lines in the right-hand-side panels show the FAP significance levels.

the power density at a given frequency being greater than k by chance is given by

$$P_r\left[P_N(w_0) > z\right] = \exp(-z/k), \tag{1}$$

where the normalization factor k, which is due to event correlation, should be determined empirically (Delache, Laclare, and Sadsoud, 1985; Bai and Cliver, 1990).

Since the DCDFT uses an algorithm that allows us to scan a part of the periodogram with any desired resolution in frequency (or period), the data sets are analyzed for the period interval of 16 – 40 days. We then obtain a simple estimate of the statistical significance of the height of a peak in the power spectra by using the false alarm probability (FAP) described by Horne and Baliunas (1986). The FAP formula applied here is given by

$$F = 1 - \left[1 - \exp(-Z_{\mathrm{m}})\right]^N, \tag{2}$$

where Z_{m} is the height of the peak in the normalized power spectrum and N is the number of independent frequencies (nif). F displays the probability that the power at one or more of these frequencies will exceed Z_{m} by chance. As shown in the left-hand-side panel of Figure 1a, we then studied the cumulative power distribution of sunspot numbers for the total disk derived using the DCDFT. This figure shows that for all 114 frequencies the power exceeds zero. Except for the maximum value of power (12.50) at only one frequency as

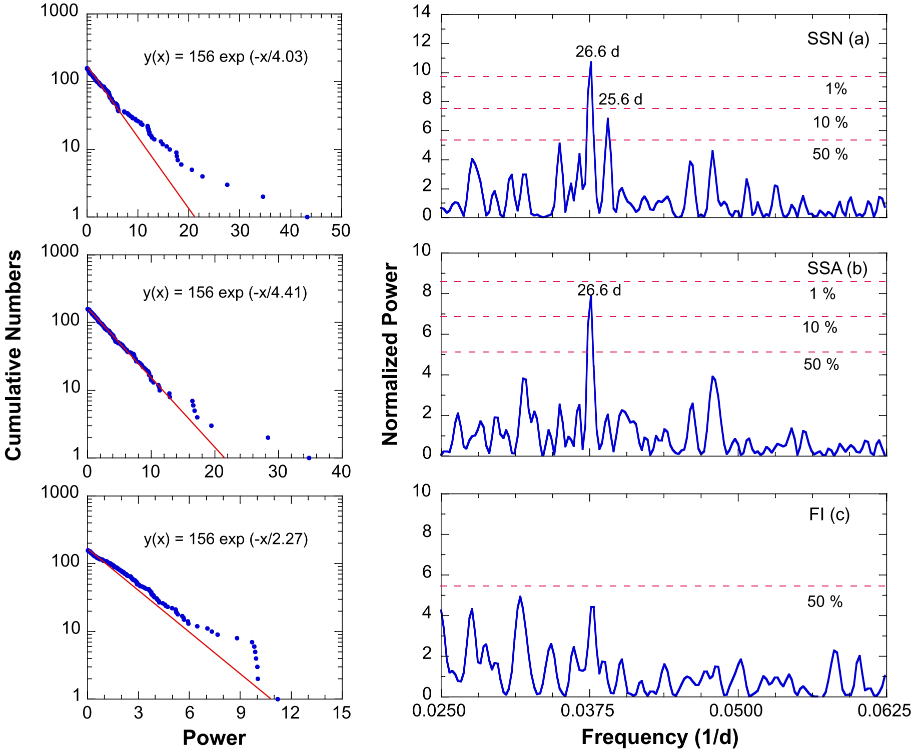

Figure 2 Same as Figure 1, but for the maximum portion.

expected from Equation (1), the distribution can be well fitted for lower values of power by the equation shown in the left-hand-side panel of Figure 1a. Thus, the normalized power spectrum displayed in the right-hand-side of Figure 1a is computed by dividing the powers by 1.83. For the normalization of all power spectra of data sets, the same procedure has been followed.

In contrast, Fourier components computed for frequencies at intervals of the independent Fourier spacing, $\Delta f_{\mathrm{nif}} = t^{-1}$, where t is the time span of the data, are totally independent (Scargle, 1982). However, de Jarger (1987) has shown by Monte Carlo simulations that the Fourier powers obtained at intervals of one-third of the independent Fourier spacing are still statistically independent. For the data sets, the number of independent frequencies N in the chosen window from frequency f_1 to f_2 is calculated to be $f_2 - f_1/f_{\mathrm{nif}}$. In the case of our study for frequency ranges $f_1 = 0.0250$/day (40 days) and $f_2 = 0.0625$/day (16 days), we obtain 38, 52, and 56 for the number of independent frequencies for the rising, maximum, and declining portions, respectively [using, according to de Jarger (1987), 114, 156, and 168]. In this manner, if the height of the peak and the number of independent frequencies in Figure 1a for the total disk are considered, we obtain, by oversampling, a power spectrum in which the normalized height of the peak at 26.6 days is 6.79. The oversampling tends to estimate the peak value more accurately. Therefore, if $Z_{\mathrm{m}} = 6.79$ and $N = 114$ are substituted in Equation (2), the FAP $F = 0.12$ is obtained; that is, the probability of finding such a high peak by chance is about 12%. To estimate the statistical significance levels of evident peaks in the power spectra, the same analysis method has been applied to all data sets of

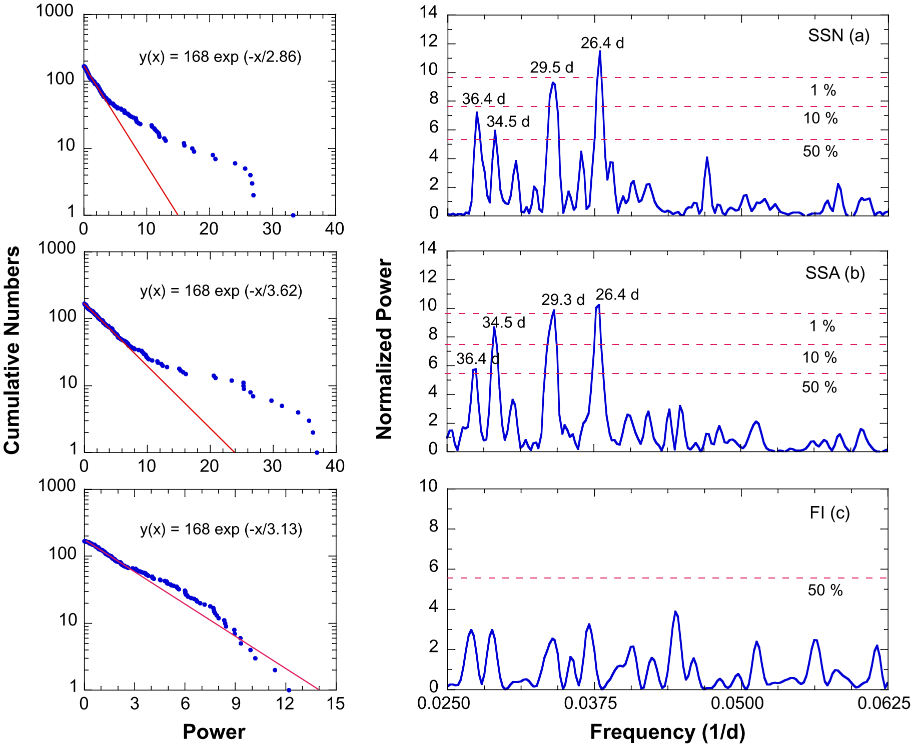

Figure 3 Same as Figure 1, but for the declining portion.

time series considered here and significant peaks computed are given in Figures 1, 2, and 3 and Table 1.

Since peaks in a spectrum may appear from aliasing, the FAP criterion, alone, is insufficient for evaluating whether or not a strong peak in a spectrum is a real periodicity in the time series (Lean and Brueckner, 1989). One useful method of evaluating this is to subtract the sine curves of their periods from the original time series and then to recompute the periodogram (Horne and Baliunas, 1986). A good computational way for this method is given by Ferraz-Mello (1981). After removal of the sine curves of significant peaks form the original time series spectra, we see that no significant peak appears in normalized power spectra.

3. Results and Discussion

In this paper, we present the results of the short-term periodic analysis of the sunspot activity and solar flare index during solar cycle 23. While the spectral analysis of daily sunspot numbers and sunspot areas at successive time intervals in solar cycle 23 display the presence of highly significant short-term periodicities, the power spectra of daily flare index for the same intervals do not show any important peak with a FAP value below 50% (Figures 1, 2, and 3). Table 1 summarizes the significant peaks computed in these time series.

As given in Figures 1, 2, and 3 and Table 1, neither the period 26.4 nor 26.6 days detected in sunspot numbers and areas during all portions of current solar cycle 23 is more prominent

Table 1 Periodicities (in days) detected by spectral analysis of sunspot activity and solar flare index during the rising, maximum, and declining portions of solar cycle 23 and false alarm probability values (%) in parentheses.

Periodicities			
	Rising portion	Maximum portion	Declining portion
Sunspot numbers	–	–	36.4 (12)
	–	–	34.5 (36)
	–	–	29.5 (2.0)
	26.6 (12)	26.6 (0.3)	26.4 (0.2)
	–	25.6 (16)	–
Sunspot areas	–	–	36.4 (41)
	–	–	34.5 (3.0)
	–	–	29.3 (0.9)
	26.4 (9.0)	26.6 (6.0)	26.4 (0.6)
	23.9 (14)	–	–
	23.1 (29)	–	–
Flare index	–	–	–

and stable than the other short periodicities, especially in the maximum and declining portions. The other peaks occur at 23.1 and 23.9 days in sunspot areas during the rising portion, at 25.6 days in sunspot numbers during the maximum portion, and at 29.3, 29.5, 34.5, and 36.4 days in both sunspot numbers and sunspot areas during the declining portion. Whereas both time series exhibit very similar periodicities in the declining portion, they show some different periodic behavior during the rising and maximum portions. Though main periodicity at ≈26.6 days is close to the solar rotation period of 27 days, sunspot number and sunspot area data demonstrate several periodicities in a widespread range ≈23 – 36 days during solar cycle 23.

Many authors reported the short-term periodicities in sunspot activity, flare index data, 10.7-cm radio flux data, solar irradiance, and geomagnetic indices during different solar cycles including also solar cycle 23. Bai (1987) analyzed the coordinates of energetic solar flares during a period from February 1980 through August 1985 and found that the rotation period of the active zones is 26.75 days, close to the 26.6-day rotation period obtained in this study. For an extensive time interval, Pap, Tobiska, and Bouwer (1990) analyzed the solar total and UV irradiance, 10.7-cm radio flux, Ca-K plage index, and sunspot blocking function. They showed that the modulation of these solar data by the 27-day solar rotation is more pronounced during the declining portion of the solar cycle than during the rising portion. Vats *et al.* (1998) studied time series data of 10.7-cm solar flux for one solar cycle (1985 – 1995). They obtained that the sidereal rotation period varies from 24.07 to 26.44 days and the periodicities of 26.44 days is very close to 26.4 days, which is computed in this study. The analysis of the radio observations at several frequencies by Zieba *et al.* (2001) revealed several rotation peaks such as 23.3, 26.0, 26.8, 29.1, and 30.3 days that are fairly similar to some of our results. A spectral analysis of the time series of daily values of 12 parameters – namely, ten solar radio emissions in the range 275 – 1755 MHz, 2800-MHz solar radio flux, and sunspot numbers for six continuous intervals of 132 values each during June 1997 to July 1999 – showed considerable differences from one interval to the next, indicating a nonstationary nature, and a ≈27-day periodicity was noticed in intervals 2 (≈ 26.8 days), 3 (≈27.0 days), 5 (≈25.5 days), and 6 (≈27.0 days) (Kane, Vats, and Sawant, 2001). A more recent study made by Kane (2002) revealed that the short-term variation of solar indices, though typically near the solar rotation period of 27 days, can often deviate considerably from 27 days, in a wide range $\approx 19-33$ days. During the period 1992 – 2000, another study of Kane (2003) on the daily values of the 10.7-cm (2800-MHz, F10) solar radio flux showed that the most prominent periodicity was generally at $\approx 27 \pm 1$ day. In addition, he confirmed the conclusion of Pap, Tobiska, and Bouwer (1990) that the 27-day solar rotation is more pronounced in the declining phase of a solar cycle and shows fluctuations in a very wide range $\approx 13-40$ days. Mavromichalaki *et al.* (2003) searched for the temporal evolution of cosmic-ray (CR) intensity and flare index in the solar maxima of cycles 21 and 22 and found that the periodicities of 27, 35, and 36 days are close to those of this study. More recently, Özgüç, Ataç, and Rybak (2004) investigated the short-term periodicities in flare index data during the time interval 1966 – 2002 and found several peaks at 25.6, 27.0, 30.2, and 33.8 days in which the 27-day solar rotation is more pronounced during the declining portion of solar cycle than during the rising portion. They have also suggested that the period has an intermittent character.

4. Conclusion

In this study, the short-term periodicities in sunspot numbers, sunspot areas, and flare index data are investigated for the total disk of the Sun during solar cycle 23. For the spectral analysis, the DCDFT is separately applied to the data series for the rising, the maximum, and the declining portions. Whereas sunspot numbers and sunspot areas display several significant periodicities between 23.1 and 36.4 days, the flare index data do not show any significant period with a FAP value below 50%.

The earlier conclusion of Pap, Tobiska, and Bouwer (1990) and Kane (2003), that the 27-day periodicity is more pronounced in the declining portion of a solar cycle than in the rising and maximum ones, seems to be true for sunspot numbers and sunspot area data analyzed here during solar cycle 23. This may be explained by the fact that during the time of maximum and the following decline of a solar cycle the magnetic fields are much more organized and long-lived than at the beginning of a new cycle (Pap, Tobiska, and Bouwer, 1990)

The other conclusion presented here is that although both sunspot numbers and sunspot areas reveal very similar periods in a wide range of spacings at 26.4 – 36.4 days in the declining phase, they show some different behaviors in a narrow range of spacings at 23.1 – 26.6 days during the rising and maximum phases.

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