OVERVIEW OF THE FLARE INDEX DURING THE MAXIMUM PHASE OF SOLAR CYCLE 23

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Abstract. Solar activity covers a range of phenomena at all levels in the solar atmosphere and time-scales ranging from seconds and minutes, through months, to the 11 or 22-year solar activity cycle. According to new observations immense cracks sometimes develop in Earth's magnetosphere and remain open for hours during the bad Space Weather conditions. This usually happens in the course of solar cycle maximum. Highly variable conditions in the geospace environment and those on the sun persist throughout the maximum phase of solar activity. Expressing aspects of that activity in terms of single indices is useful in investigating its role as a driver for various space and terrestrial phenomena. Many studies in the solar-terrestrial field classified solar flares as one of the most important solar events affecting the Earth. To describe that aspect of activity for the Sun as a whole, the authors continue to compile the daily flare index for solar cycle 23 using the tables of solar flares from the National Geophysical Data Center (NGDC). A brief description and final results of the flare index of solar activity for cycle 23 up to 31 December 2002 are given. The patterns of similar activity indices that arise under different physical conditions during cycle 23 were compared with the flare index. The intermediate-term periodicities in the daily flare index data for the northern and southern hemisphere were calculated using the Fourier transform, and it was found that 64, 83, 125 day periodicities are in operation during the maximum phase of solar cycle 23. The wavelet transform results show that the occurrence of flare index power is highly intermittent in time.

1. Introduction

Solar activity variations demonstrate themselves not only in electromagnetic radiation from radio frequencies of a few kHz to powerful gamma rays but also in particle flux. In broad physical terms, solar activity may be understood in terms of the properties and the behavior of the magnetized solar plasma. Magnetic fields undergo some instability at the base of the convection zone. As the fields extend into the convection zone, they become buoyant and rise and determine the behavior of the outer layers of the Sun (Zwaan, 1985; Pecker, 1996). Eventually solar activity is driven by the temporally and spatially varying distribution of magnetic flux in the photosphere, chromosphere and corona. It covers a range of phenomena at all levels in the solar atmosphere and time-scales ranging from seconds and minutes (solar flares and solar coronal mass ejections), through months (the evolution of active regions and solar activity complexes), to the 11 or 22-year solar activity cycle. Some powerful and explosive events on the Sun, such as coronal mass ejections (CMEs) and solar flares, can lead to a worldwide disturbance of the geomagnetic field and associated ionospheric and thermospheric disturbances. These events can, and do, have an impact on the performance and reliability of space and ground-based operational systems (Lambour et al., 2003). Solar physicists have tried to quantify the variation of solar activity with time, beginning with Wolf’s classical formula for the relative numbers of sunspots. An index of solar activity is a
quantity intended to describe some aspect of activity for the sun as a whole. Being able to express aspects of that activity by many indices, such as the Wolf number, the 2800 MHz radio flux, X-ray and EUV indices, cosmic-ray flux, etc. is useful for studying the Sun’s long-term behaviour and its interaction with our near Earth space environment. The longest continuous record of solar activity is regular sunspot observations, which were started by Galileo in 1610 soon after the invention of the telescope. As well as in many studies in the solar-terrestrial field, solar flares are classified as one of the most important solar events affecting the Earth. Kleczek (1952) introduced the quantity \( FI = it \) to quantify the daily flare activity over a 24-hour period. He assumed that this relationship roughly gave the total energy emitted by the flare and named it ‘flare index’ (\( FI \)). In this relation, \( i \) represent the intensity scale of importance of a flare in \( H_a \), and \( t \) the duration of the flare in minutes. Catalogues of flare activity using Kleczek’s method are given for each day from 1936 to 2004 by Kleczek (1952), Knoška and Petrásek (1984), Ataç and Ozguc (2004, http://www.koeri.boun.edu.tr/astronomy/findex.html). The flare index is an interesting parameter and is of value as a measure of the short-lived activity on the Sun. Therefore the authors will continue to compile this index in the future. In this paper the results of the determination of the flare index for solar cycle 23 are presented. The amplitude of the 23. solar cycle for similar activity indices with the amplitude of the previous cycle was compared in Section 2. Midrange periodicities in solar flare occurrence during the maximum phase of the cycle 23 are calculated in section 3 and 4 using Fourier and wavelet transforms respectively, and concluding remarks are presented in Section 5.

2. The Amplitude of the Solar Cycle 23

We compared the amplitudes of the cycles 22 and 23 by using similar activity indices which are produced at different layers in the solar atmosphere and by different processes. Each of them reflects different physical conditions in the solar atmosphere. The indices to be selected are as follows:

1. Stanford University, Wilcox Solar Observatory’s measurement of the net magnetic field intensity in microteslas summed over the disk. Such integrated light measurements of the mean solar magnetic field (MMF) have been made daily since May 1975 [Scherrer et al., 1977] (http://quake.stanford.edu/~wso/wso.html).

2. Daily corrected total areas of sunspot groups (TSA). These are observed, measured and compiled by USAF/ NOAA (http://science.msfc.nasa.gov/ssl/pad/solar/greenwch.htm).

3. The relative sunspot number (RSN ). This is an index of the activity of the entire visible disk of the Sun calculated by the Sunspot Index Data Center (SIDC), (http://sidc.oma.be/index.php3).

4. IR, a composite record of the Sun’s total irradiance, is compiled from measurements made by five independent space-based radiometers since 1978. We used Version 26 of that data set. More information about the determination of this composite can be found in the paper of Fröhlich and Lean [1998] (ftp://ftp.pmodwrc.ch/data/irradiance/composite/).

5. Coronal index (CI) introduced by Rybanský (1975) represents the total irradiance of the green corona emitted from the Sun’s visible hemisphere (http://www.ngdc.noaa.gov/stp).

In all activity indices the amplitude of the current cycle in the same time interval is distinguishably weaker than the last one except the total solar irradiance as it can be seen from Figure 1. Cycle 23 violates the well known rule that odd cycles are more active than the preceding even ones. The Even–Odd (or Gnevyshev, G-O) effect (Gnevyshev and Ohl, 1948) is seen in the monthly averaged or smoothed Wolf sunspot numbers (1749-2003) where the odd-numbered cycle amplitudes are compared with the amplitudes of the preceding even-numbered cycles. Odd-numbered cycles are seen to be larger than their even-numbered
precursors (Javaraiah, 2003). The amplitude of the current cycle (Cycle 23) deviates
significantly from this relationship. Recently, Komitov and Bonev (2001) showed that
violation of the Gnevyshev-Ohl rule could not be random phenomena but occurring under
special conditions, the main factor being the very high maximum of the even-numbered cycle.
Hence they conclude that the strong G-O rule violation in cycle 23 suggests the onset of a
solar activity minimum caused by the declining phases of both the 100 and 200 yr solar
cycles. In fact a weaker present 11-year cycle is not completely unexpected. The methods for
predicting the cycle's amplitude are widely reviewed in a recent paper by Schatten (2003).
One of these new prediction techniques was the one proposed by Ahluwalia (1998) which is
based on the annual mean value of Ap observed 1 year into the new cycle onset. It seems to
work for the last six cycles (17 to 22). This technique also predicted successfully that cycle 23
would be lower than cycles 17 and 20, even lower than that of cycle 19. Very recently
Hathaway et al. (2003) have reported strong observational evidence that a deep meridional
flow toward the equator is driving the sunspot cycle. This flow sets the cycle period and
influences the amplitude of the current and, more importantly, the following cycle. During
times of increased amplitude we would expect short-period cycles and during times of
decreased amplitude we would expect long period cycles like in solar cycle 23 (Hathaway et
al., 2002). Another proposal to explain the weakness of the solar cycle 23 was given by
Schatten (2003). He draws our attention to the new interpretation of the Babcock solar
dynamo. In this model the Sun’s polar fields near solar minimum are wrapped up by
differential rotation to form the toroidal fields, which later float to the Sun’s surface and erupt
to form active regions where active flares are formed. Hence, over an 11-year solar cycle, the
amplification sometimes regenerates more polar field and sometimes less. By monitoring the
observed magnetic fields on the Sun one can use these observations for predicting future
amplitude of the solar cycles. Based on this, they have created a new solar index called the
“Solar Dynamo Amplitude” (SODA index) which represents the strength of the Sun’s buried
magnetic flux. In his paper Schatten showed that the time variations of the SODA index has
been gradually decreasing in cycle 22 which would later explain the decreased in the
amplitude in cycle 23.

3. Periodicities in Solar Flare Index During the Maximum Phase

Many researchers have studied intermediate-term periodicities in different solar activity
indices which were started with the discovery of a 153-day periodicity in γ-ray flare
occurrence (Rieger et al. 1984). The periods between the short-term (13.5 days) and long-term
(11 yr) periodicities are called the “midrange” (Bai., 2003). It is important to detect midrange
solar activity periodicities with different activity indicators and to calculate their statistical
significance, because these periodicities can give information on the periodic occurrence of
various solar phenomena. Many authors using similar solar activity indices have calculated
periodicities of the ongoing current cycle (Caballero and Valdés-Galicia, 2001; Żięba et al,
2001; Oliver and Ballester, 2002; Hady, 2002; Ozguc et al, 2002; Bai, 2003; Lou et al, 2003).
Previous cycle analysis showed that midrange or Rieger type periodicities operated mainly
during maximum phases of solar cycles for only short time intervals. Nearly two years have
passed since the maximum of solar cycle 23 so it is a favorable time to find out which
midrange periodicities have been in operation throughout the maximum years. For this
purpose we used the discrete Fourier transform to estimate which periodicities were in
operation during the years 1999-2002 covering about 1461 days. We examined time series of
the flare index for the northern, southern and total hemisphere separately. We computed the
periodograms after tapering 5% of the data at the ends of the time intervals by applying a split
bell cosine window (Bloomfield, 1976). Figure 4 shows the normalized power spectra of the
time series for the maximum phase of cycle 23. There are three prominent peaks in the plots at 125, 83, 64 days. For this figure power spectra were calculated for the 58–231 nHz (50–200 days) range with 1.12 nHz intervals. The flare index is not independent but is correlated with a characteristic correlation time of a week. Therefore the power distribution follows an exponential distribution [Horne and Baliunas, 1986]; i.e., the probability of the power density at a given frequency being greater than K by chance is given by

\[ P(z>K) = \exp(-K/\sigma^2) \]  

(1)

Even if we use a normalized time series

\[ X_{ni} = (X_i - X_{av}) / \sigma \]

where \( X_i \) is the FI on the \( i \)th day, \( X_{av} \) is the daily mean flare index value, and \( \sigma \) is the variance.

The Fourier periodogram turns out to be not normalized because of the interdependence of occurrence of some big flares. Therefore, whatever analysis method is used, the best way to normalize the power spectrum is to fit the actual power distribution to Equation (1) (Bai and Cliver, 1990). Figure 4 shows the distribution of the Fourier power values corresponding to the normalized spectrum. The vertical axis shows the cumulative number of frequencies for which the power exceeds a certain value.

| TABLE 1 |
|-------------------|-------------------|-------------------|
| **North Hemisphere** | **South Hemisphere** | **Total**         |
| Period (day) | FAP | Period (day) | FAP | Period (day) | FAP |
| 64           | 0.09 | 83           | 0.08 | 64           | 0.34 |
| 125.9        | 0.14 | 125.9        | 0.10 | 125.9        | 0.04 |

For lower values of power, the distribution can be well fitted by the equation \( Y=\exp(-x^B) \), as expected from Equation (1). Thus, we normalize the power spectrum by multiplying the powers of the northern, southern and total hemisphere by “B” to obtain normalized value, which are plotted in Figure 4. The statistical significance of the peaks in the power spectrum was estimated by the ‘false alarm-probability’ (FAP) which is given by the following expression

\[ F = 1 - [1 - \exp(-Z_m)]^N \]  

(2)

where \( Z_m \) is the height of the peak in the normalized power spectrum and \( N \) is the number of independent frequencies [Scargle, 1982; Horne and Baliunas, 1986]. If we have a discrete power spectrum giving the power at each of \( N \) independent frequencies for a set of random data, \( F \) indicates the probability that the power at one or more of these frequencies will exceed \( Z_m \) by chance. Fourier components calculated at frequencies at intervals of the independent Fourier spacing (ifs) (\( \Delta f_{ifs} = \tau^{-1} \), where \( \tau \) is the time span of the data) are totally independent [Scargle, 1982]. By Monte-Carlo simulations, de Jager [1987] has shown that the Fourier powers taken at intervals of one-third of the independent Fourier spacing are still statistically independent (for \( \tau = 1461 \) days \( \Delta f_{ifs} = 7.91 \) nHz). Thus, there are 22 independent frequencies in the 58–231 nHz interval. FAP for the peaks, which appeared in the periodograms of the left panel of Figure 4, are calculated using the formula (2). The results are shown in Table 1 where the peak in 125.9 appeared as the most prominent and statistically significant peak in cycle 23 during the maximum phase.

The intermediate-term periodicities in the daily flare index data for this cycle have already been studied by the authors (Ozguc et al., 2002) using the Fourier transform, and it was found that the 35-, 62-, 116-, 198-, and 276-day periodicities were in operation during the ascending branch of cycle 23 up to 31 December 2000. Two of the five periods with the most prominent peaks in the power spectrum (35 and 62 days) were also detected by Caballero and Valdés-Galicia (2001). They found these two periods in sunspot number, hard X-ray flux and cosmic ray intensity for the time interval of 1997 and 1999. Zieba et al. (2001) have found the 151-day periodicity by using the solar radio flux, sunspot number and mean magnetic field data...
during the rising phase of solar cycle 23. Many previous researches, which were done with the ascending branch data, have resulted in an extensive range of solar periodicities. This is not easy to explain and indicate that the problem of solar periodicities is still waiting more systematic efforts. Hence Lou et al. (2003) reported mid-term quasi periodicities in CMEs, X-ray flares of class ≥ M5.0 and Ap index using four-year data 1999-2003. Their Fourier power spectral analysis gave significant periods at 358, 272 and 196 day in CMEs; 157, 122, 98 and 34 days in X-ray solar flares of class ≥ M5.0; 273 and 187 day in the data of daily averages of Ap index. Keeping in mind the “dynamic feedback scenario” they explained why Rieger-type periodicities in the emergence of magnetic flux, sunspot areas and high-energy flares are detected within a few years around the solar maxima when solar activity levels are high. They hypothesized their estimation with the following statement: “Specifically, powerful solar flares frequently occurring in magnetically active regions along the two usual belts across the solar equator keep stirring the photosphere and exciting Rossby waves that in turn either trigger or modulate the emergence of subphotospheric magnetic flux.” Finally they concluded that a certain energetic threshold is needed to sustain such dynamic feedback cycle initiations. So every cycle with different physical conditions must produce this threshold energy range differently and that is why during their maxima it is possible to find various prominent peaks in the power spectra of similar solar activity indices. Most recently midrange periodicities in solar flare occurrence (X-ray flares of class ≥ M1.0) have been analyzed by Bai (2003). He found that 129 and 33.5 days periodicities were in operation for the interval from 1999 September 9 to 2001 June 5, during which the five epochs of high activity were identified. He discussed the properties of these periodicities and proposed that the detection of the 129-day periodicity from cycle 23 support the idea (Bai and Sturrock 1991) that 25.5 days is a fundamental period of the Sun. So solar flare activity often exhibits periodicities at its subharmonics periods. Secondly he drew our attention to the fact that the periodicities with periods of integral multiples of 25.5 days operated mainly during maximum phases of solar cycles for only short time intervals. Typically, the numbers of periodic episodes repeated are from 5 to 9. Finally he concluded that 25.5 days is a fundamental period of the Sun, which is well supported by data, where the physics of the clock mechanism is still unknown.

4. Wavelet Analysis

Classical Fourier transform analysis (FT) allows the study of a signal only in the frequency domain whereas wavelet transform (WT) analysis yields information in both time and frequency domains (e.g., Daubechies, 1990; Kumar and Foufoula-Georgiou, 1997). Therefore, we have also applied wavelet analysis to a time series consisting of daily flare index between January 1, 1999 and December 31, 2002 to study the temporal variation with timescales of intermediate-term periods. These three time series (north, south and total) were smoothed with 7-day running means before the WT calculations. The algorithm of the continuous wavelet transform was applied after Torrence and Compo (1998) within the period range 40–200 days. The Morlet wavelet, a plane sine wave with an amplitude windowed in time by a Gaussian function, has been selected to search for variability at different frequencies over the whole length of the time series. The non-dimensional frequency has been set to 6 which fixed the length of all wavelets according to their scales. The calculated wavelet power spectrum is suppressed on the edges of the time domain within the cones of incidence due to the applied WT algorithm. The significance levels of the calculated WT power were derived using the null hypothesis according to Torrence and Compo (1998) assuming that noise was distributed independently on periods. The 99% confidence level, used in this study, implies that 5% of the wavelet power should be above this level for each period. Figures 3, 4 and 5 show the time-period diagram of the WT power spectrum (power in arbitrary units) of the
Results of the WT for southern hemisphere (Figure 5) show that the power around 120 days at 1999.8 reaches a peak value which comes from repetition of the flare index enhancement at 1999.5-1999.9 and 2000.1-2000.4. Power peak around 60 days at 2000.5 comes from repetition of the FI peak located at 2000.6 and two side maxima located at 2000.4 and 2000.7. The peak around 80 days which appeared strongly in FT plot was less prominent in WT power spectrum at 2001.6. Figure 4 show northern hemisphere periods found by WT in which all are centred around the FI power burst at 2000.3-2000.5. Merging these two peaks of FI with other FI enhancements before and after them produced a lot of power almost in the whole period range under study. On the other hand in the northern plot of FT (Figure 2) two peaks can be identified separately around 120 and 160 days. The statistical significance test pointed out that the peak near 120 day is more significant. This complex situation for the northern hemisphere gave rise to different period power output in the WT analysis. Finally for the whole hemisphere as it can be seen from Figure 3 a mess of different waves of the two hemispheres with different phases could produce the other peak in the WT power spectrum. The broad peak around 120 day which is related to the single peaks located between 1999.4-1999.7 and FI enhancement between 2000.1-2000.4, riches in periods. The most significant peak comes from the nearly rotation repetition of FI around 2000.5 in 3 rotations. Wavelet analysis results showed that the flare activity of the opposite hemispheres were not well time-synchronized during the maximum phase. The flare activity of the southern hemisphere was observed to be more dominant in determining the characteristics of the flare activity in solar cycle 23.

5. Discussion and Conclusion

Detailed analyses of the time behavior of the different solar activity indices pointed out that the multi-peaked structure of solar cycle maximum is a real future of solar activity (Bazilevskaya et al. 2000, Storini et al 2003, Sello, 2003). Fourier and wavelet analyses demonstrated that during the maximum phase of current solar cycle the very prominent multi-peaked structures existed in each solar hemisphere. The appearance of the period nearly 120 day in our analysis reminded us the idea that 25.5 day is a fundamental period of the Sun, and solar flare activity often exhibits periodicities at its subharmonic periods (Bai and Sturrock 1991). Recent dynamo model brings a new interpretation to the Babcock dynamo (Schatten, 2003). In this model the Sun’s polar fields near solar minimum are wrapped up by differential rotation to form the toroidal fields, which later float to the Sun’s surface and erupt to form active regions where active flares are formed. Flare production during this cycle was comparatively less than the previous cycle. Hence over an 11-year solar cycle the amplification sometimes regenerates more polar field and sometimes less. At the same time Hathaway et al. (2003) have reported strong observational evidence that a deep meridional flow toward the equator is driving the sunspot cycle. Obviously, other mechanisms, such as fluctuations in the meridional flow (Hathaway, 1996) believed to be a product of turbulent convection and variations in the gradient of the rotation rate which was also contribute to the cycle amplitude variations. The differences on the speed of the meridional circulation during cycles with different amplitude and all the mechanism mentioned above can act as an intrinsic dynamics which would explain the midrange solar activity periodicities. Solar cycle 23 with its weak magnetic activity throughout its progression merits all this detailed studies which was done with different indices. Recent research of the long-term solar variability shows that our epoch is at the onset of an upcoming minimum of the 100-yr Gleissberg cycle (Bonev et al., 2004). So it can be expected that the solar cycle 24 may be magnetically weaker than the ongoing cycle.
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Figure 1. Comparison of the monthly means of the similar activity indices for the previous and the current cycles.
Figure 2. Normalized power spectrum and the power distribution of discrete Fourier transform of the flare index for the time interval from 1 January 1999 to 31 December 2002.
Figure 3. The wavelet power spectra of the daily flare index (7-day running mean) of the total hemisphere for the period range 40-200 days. Grey-scale coding of power from white to black represents the square root of power in a linear scale given on the right side bar. The solid curve shows the 95% confidence levels of the local power above the noise level assuming noise independence on periods. The cone of incidence is marked by the crosshatched regions.
Figure 4. The wavelet power spectra of the daily flare index (7-day running mean) of the northern hemisphere for the period range 40-200 days. Grey-scale coding of power from white to black represents the square root of power in a linear scale given on the right side bar. The solid curve shows the 95% confidence levels of the local power above the noise level assuming noise independence on periods. The cone of incidence is marked by the crosshatched regions.
Figure 5. The wavelet power spectra of the daily flare index (7-day running mean) of the southern hemisphere for the period range 40-200 days. Grey-scale coding of power from white to black represents the square root of power in a linear scale given on the right side bar. The solid curve shows the 95% confidence levels of the local power above the noise level assuming noise independence on periods. The cone of incidence is marked by the crosshatched regions.