Bull. Astr. Soc. India (2013) **41**, 237–246

The relationship between grouped solar flares and sunspot activity

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Received 2013 July 28; accepted 2013 December 27

Abstract. We investigate the phase relationship between grouped solar flares (GSFs) and sunspot numbers (SNs) during the time interval from 1965 January to 2008 June. It is found that, (1) from a global point of view, GSFs lead SNs in phase during solar cycles 20, 22 & 23, while the former lags behind the latter in solar cycle 21; (2) the phase relationship between them is not only time-dependent but also frequency-dependent. This implies that their relationship is a complex nonlinear relationship, although they are highly correlated with each other.

Keywords : Sun: flares – Sun: sunspots – Sun: magnetic fields – methods: data analysis – methods: statistical

1. Introduction

Since the first observation of solar flare from white-light observations was reported by Carrington (1859) and Hodgson (1859), the physical mechanisms of solar flares, and the relationship between flare activity and sunspot activity have become two of the hottest and biggest problems in the field of solar physics (Hathaway 2010; Hudson 2011). Sunspot numbers (SNs) are taken as the most famous and typical index in the lower atmosphere of the Sun, and the upper atmospheric activity (e.g. solar flare activity, 10.7-cm radio flux and coronal Fe XIV line) is significantly delayed with respect to photospheric-activity indicator (such as SNs), with a time lag from several

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months in a hierarchical manner (Wheatland & Litvinenko 2001; Temmer et al. 2003; Deng et al. 2012, 2013a) to a few years (Wagner 1988; Aschwanden 1994; Bromund et al. 1995). The data used in their studies are based on soft X-ray flare occurrence, soft X-ray background flux, hard X-ray flare, Hα flare occurrences and flare index. However, another important index called grouped solar flares (GSFs), which can be also used to describe flare activity, is neglected. Usoskin (2008) pointed out that most of solar indices are highly correlated with each other due to 11-year Schwabe cycle, but differ in fine details or long-term trend. Therefore, it is important to investigate the phase relationship between GSFs and SNs, and to study whether their leading or lagging phenomenon is in agreement with the previous findings reported by above authors.

To better understand the origin and evolution of active regions on the Sun, synchronization of dynamical processes is utilized by Zolotova & Ponyavin (2006, 2007). Traditional linear approaches, such as auto-correlation analysis and Fourier transform, are inappropriate for analyzing the phase relationship of different solar activities and recognizing complex nonlinear coupling (Deng et al. 2011, 2013b). Nowadays, many advanced nonlinear analysis technologies, such as continuous wavelet transform (CWT) and cross-wavelet transform (XWT), are widely applied to examine the synchronization or phase differences between two time series and to reveal hidden physical meanings in scientific fields (Grinsted et al. 2004; Marwan et al. 2002; Donner & Thiel 2007; Deng et al. 2013c, d).

The layout of this paper is as follows. The data are shown in Section 2.1, phase difference analysis of GSFs and SNs is given in Section 2.2, and further in Section 2.3 the CWT and the XWT analyses are utilized to investigate their phase relationship. Finally, the main conclusions and discussions are given in Section 3.

2. Observations, methods and results

2.1 Observational data

The data used in this paper to investigate the phase relationship between GSFs and SNs are as follows:

(1). The monthly counts of GSFs are obtained from National Geophysical Data Center (NGDC) and can be downloaded from the Website (`ftp://ftp.ngdc.noaa.gov/STP/SGD/sgdpdf/Number_of_Solar_Flares.pdf`). The data set covers the period from 1965 January to 2008 June.

Solar flares are the result of complex magnetic phenomena, seen as a sudden and intense brightening on the solar disk. They are the result of the rapid conversion of a large amount of magnetic energy, stored for a while in the solar corona, and dissipated through magnetic reconnections. The numbers of Grouped solar flares were selected from the reports of Solar Geophysical Data (Coffey 1989). The term "grouped" means all observations of the same flare event by different solar observatories (sites) were lumped together and counted as one (Xanthakis et al.

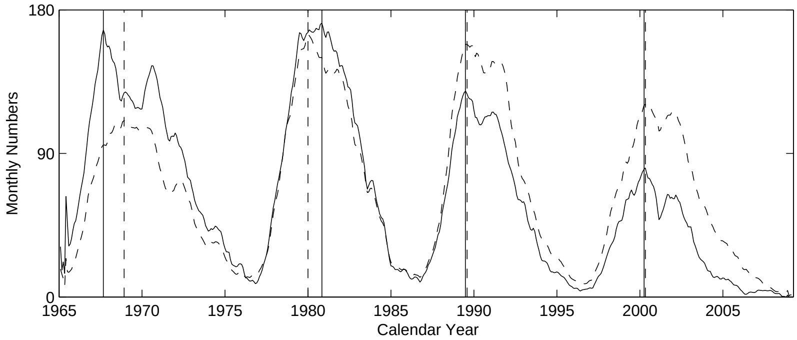

Figure 1. Monthly counts of GSFs (solid line) and SNs (dashed line) from 1965 January to 2008 June. The first maximum of these are indicated by solid and dashed lines respectively.

Table 1. Dates of cycle maxima for GSFs and SNs, and the difference between the two in cycles 20 to 23.

Solar Cycle	Maximum time of GSFs	Maximum time of SNs	Difference of Maximum time
20	1967 August	1968 November	15 months
21	1983 October	1979 December	-10 months
22	1989 June	1989 July	1 month
23	2000 March	2000 April	1 month

1992; Feminella & Storini 1997; Gupta et al. 2007). The solar flare parameters, including its heliographic coordinates, the start, maximum and end time, duration, apparent and corrected areas, optical importance, are deduced using the data of all observations. This procedure is used for any important flares including subflares. This index is different from flare index and hard X-ray flare.

(2). The monthly counts of SNs can be also downloaded from NGDC's Website (`ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/MONTHLY/MONTHLY.PLT`). The data series is from 1749 January to 2013 May and is updated every month. We extract SNs from 1965 January to 2008 June, the common period to the GSFs.

2.2 Phase difference of GSFs and SNs

Fig. 1 shows the monthly count of GSFs and SNs during the time interval from 1965 January to 2008 June. To eliminate the impact that large, active flare-productive regions exert simultaneously to sunspot and flare numbers, both of them are smoothed with a 13-point smooth method. From the figure, one can see that GSFs hold an approximately 11-year Schwabe cycle, as SNs do. However, the two time series do not have coinciding maxima and minima, implying that they should be asynchronous.

Table 2. Centre time for GSFs and SNs, and the difference between the two in cycles 20 to 23.

Solar cycle	Centre time of GSFs	Centre time of SNs	Difference of Centre time
20	1969 August	1969 October	2 months
21	1980 November	1970 October	-1 months
22	1990 June	1990 August	2 month
23	2000 September	2001 April	7 month

The date for the cycle maxima is an important parameter to characterize the solar activity. Table 1 gives the maximum times of the smoothed GSFs and SNs during solar cycles 20 to 23, and the difference between the maximum times of the two in each cycle is listed in Table 1. As shown in the table, GSFs reach their maximum earlier than SNs in solar cycles 20, 22 & 23, and later in solar cycle 21.

Systematic differences between different sources may distort the results, which is a common problem of all long-term analyses. To better determine phase relation between different solar-activity indicators, the temporal position should be reliably established. But irregular shapes of cycle profiles, such as ambiguous maximum values and different ascending/descending slope, make this determination difficult. Moreover, smoothing procedures with arbitrary windows (e.g. 13-point smooth method) may input subjective factors into the analysis, which should be avoided. For this reason, Murak*ö*zy & Ludm*á*ny (2012) presented a new approach called "*centre-of-weight*" to represent the cycle profile by its center of mass (temporal position). In such way, the bulk of the cycle profile is considered regardless of its irregular shape. In a word, it disregards the occasional differences in phase within the individual cycles which is not necessarily the result of the same mechanisms as the possible secular variations of solar time series. Using this approach we calculate the center time (the date when the areas of the preceding and following half-profiles of a cycle are equal) of GSFs and SNs in each of the cycles 20 to 23 and the results are shown in Table 2. Here, the original data are used and the dates of the cycle minima of each cycle are taken from the paper of Tlatov (2009). The phase difference of the center time between GSFs and SNs differs from that of the maximum time between them in each cycle. Maybe the results obtained by "*centre-of-weight*" method are more accurate. It is interesting that the two methods clearly indicate that GSFs leads SNs in cycles 20, 22 & 23, while lags in cycle 21.

2.3 CWT analysis of GSFs and SNs

Wavelet transform is a powerful tool for analyzing the non-stationary signals and the evolution in time of each frequency (Torrence & Compo 1998). CWT is good technique for detecting the quasi-periodic fluctuations, and XWT can be used to analyze the relative phase difference between two systems (for details, see Grinsted et al. 2004).

Fig. 2 shows the continuous wavelet power spectra of GSFs and SNs, and there evidently are common features in the wavelet power of the two time series. Both of them have a large-

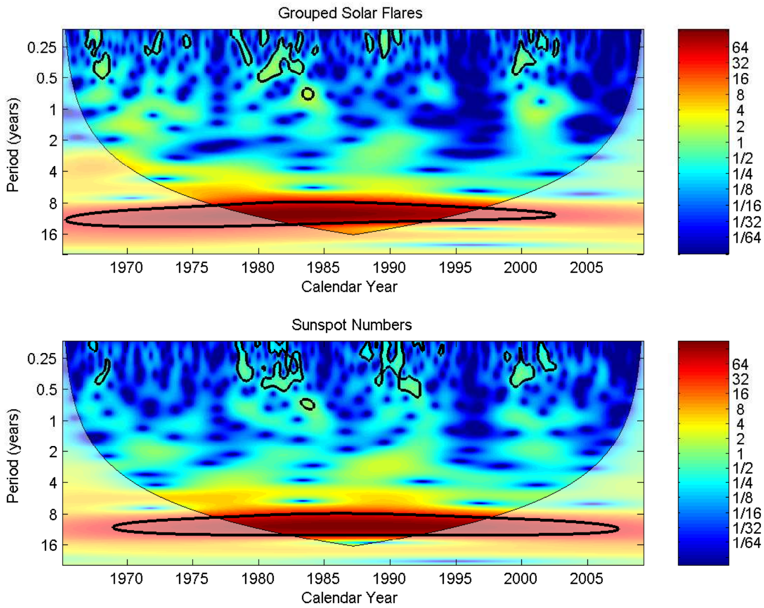

Figure 2. Continuous wavelet power spectra of GSFs (top) and SNs (bottom).

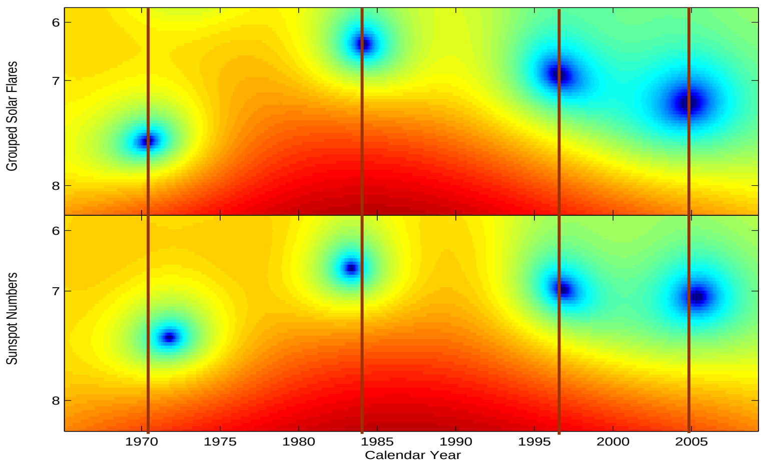

Figure 3. Local wavelet amplitude spectra of GSFs and SNs for the time-scales from 6 to 8.5 years.

scale periodicity (around the 11-year Schwabe cycle) of high power, which is above the 95% confidence level. The local wavelet amplitude spectra of GSFs and SNs are plotted in Fig. 3, the wavelet time-scales are chosen from 6 to 8.5 years. In Fig. 3, the spectra are outlines with contours where the blue regions correspond to the peak of the cycles. The color depth represents the energy density, which is proportional to the amplitude of the oscillation. In the figure the

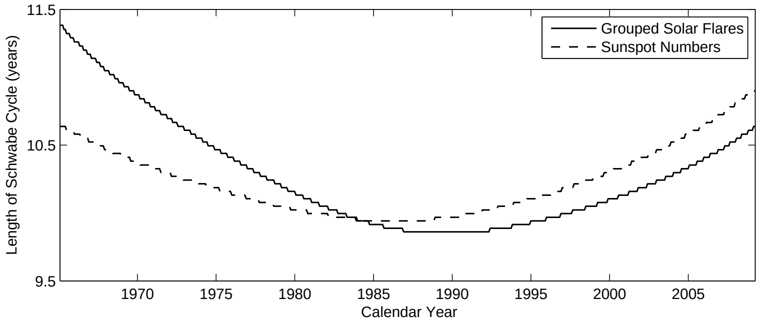

Figure 4. Length of the Schwabe cycle varying with time of GSFs and SNs.

remarkable temporal variations in the wavelet spectra and the changes with time of the periodic amplitudes in GSFs and SNs can be clearly seen. From the wavelet analysis, we can clearly determine that GSFs lead SNs in solar cycles 20, 22 & 23 and lag behind SNs in solar cycle 21.

Fig. 4 displays the length of the Schwabe cycle (LSC) varying with time for GSFs and SNs, respectively. At a certain time point, the LSC has the highest spectral power among all the time-scales in its local wavelet power spectral. For example, considering 2000 January as a time point, we compare all of the local wavelet power spectral from the beginning to the ending of all periodic scales. When the local wavelet power spectral reaches a maximum, the corresponding periodic scale is the LSC at this time point. Thus, the LSC is 10.1044 for GSFs and 10.2977 for SNs at 2000 January. As the figure shows, (1) the LSC varies continuously and slightly from 9.86-11.38 years during the considered time interval; (2) the LSC for GSFs obviously differs from that for SNs. Moreover, the LSC for GSFs is slightly larger than that for SNs before 1983 and smaller after 1984. The two time series are asynchronous if their main periods or frequencies differ from each other (Zolotova & Ponyavin 2006).

2.4 XWT analysis of GSFs and SNs

We employ the codes provided by Grinsted et al. (2004) to show the XWT between GSFs and SNs to investigate the phase relationship, and the result is displayed in Fig. 5. The relative phase relationship is shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight down. As the figure shows, (1) GSFs and SNs become asynchronous in the high-frequency (correspond to the time-scales less than 4 years) components because almost all the arrows are randomly distributed demonstrating strong phase mixing; (2) for the low-frequency components, the arrows have a small angle with the right direction, pointing down around the time-scales of 4-11 years and pointing up around the time-scales of 11-16 years. It should be pointed out that phase differences are easily affected by edge shown by the cone of influence (COI) at periodic scales. The regions below the black thick line indicate the COI where edge effects might distort the picture. For example, the XWT for the 11-years Schwabe cycle is confident only for the interval from 1980 to 1995. Thus, we should be

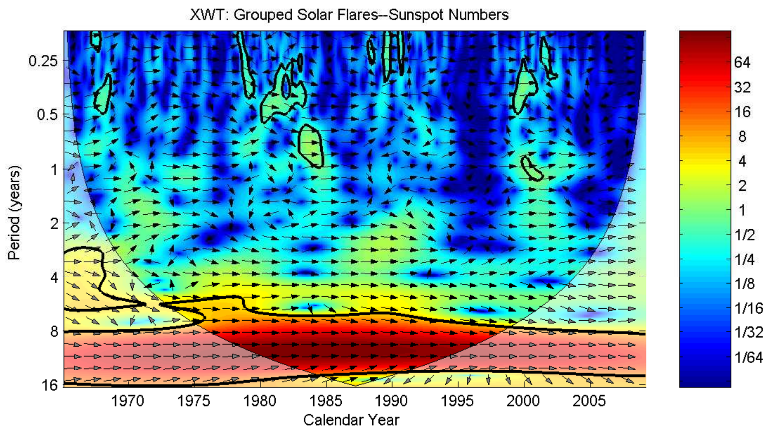

Figure 5. XWT of GSFs and SNs. The relative phase differences are shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight down.

careful in choosing the reference periodic scales when we study the phase relationship between the two time series.

Based on Fig. 5, we calculate the relative phase differences and their corresponding standard deviations varying with periodic scales between GSFs and SNs, which is shown in Fig. 6. Here, such a phase difference at a certain time-scale is calculated as the average value of all phase differences at this time-scale from the beginning to the ending of the considered time interval. The dashed lines in Fig. 6 indicate ±5 percent (about ±7 months) of the average value of the LSC. From this figure, one can see that, (1) the phase difference is positive for periodic scales less than 11 years (except for periodic scales of 0-1.14 years and 2.54-3.29 years), while it is negative for periodic scales of 11-12.5 years; (2) the phase differences for periodic scales larger than 12.5 is uncertain because XWT suffers from edge artifacts. Thus, the phase difference between GSFs and SNs is frequency-dependent.

2.5 Discussions and conclusions

Using the data of GSFs and SNs during the time interval from 1965 January to 2008 June, we investigate their phase relationship by means of two different methods. The analysis results clearly show that GSFs should lead SNs in solar cycles 20, 22 & 23 and lag behind SNs in solar cycle 21. Moreover, their phase relation is not only time-dependent but also frequency-dependent. The phase difference is positive for period-scales of 0-11 years, but negative for period-scales of 11-12.5 years. Thus, the availability of a physically meaning phase definition depends crucially on the appropriate choice of reference period-scales, as pointed out by Donner & Thiel (2007).

According to our analysis results, three reasons are found to cause phase asynchrony between

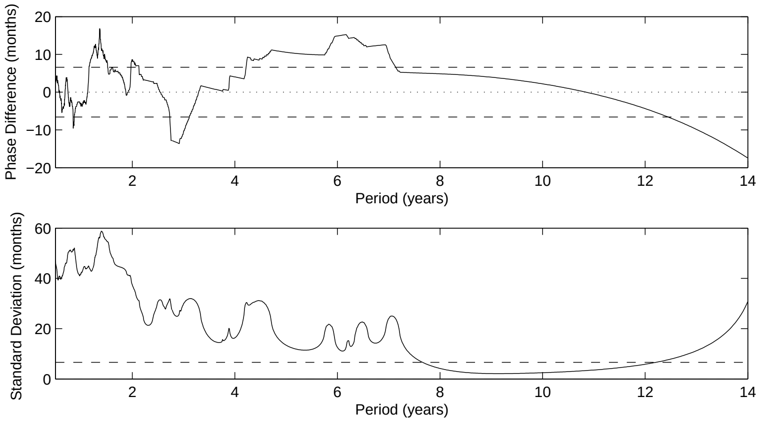

Figure 6. Phase differences of GSFs with respect to SNs as a function of periods (top panel) and their corresponding standard deviations (bottom panel). Positive values should be interpreted as GSFs leading SNs.

GSFs and SNs: (1) there is a phase difference between them in cycle maxima and center time of each solar cycle, which should lead to their phase asynchrony; (2) the length of Schwabe cycle for GSFs actually differs from that for SNs, which should also lead to phase asynchrony between them, and (3) the cross-wavelet power spectra shows that they are asynchronous in both the low- and high-frequency components. We now know several reasons which mathematically cause phase shift between GSFs and SNs, but the physical reasons have been known little.

It is well known that solar flare activity is strongly related with sunspot activity as it generally occurs in active regions which have one or group of sunspots. However, solar flare activity described by GSFs precedes sunspot numbers in solar cycles 20, 22 & 23. Some possible reasons are as follows: (1) their different definitions and physical meanings may be a major reason why there is a phase difference between them. The appearance of sunspots denotes the emergence of a strong magnetic flux, and the energy supplying to the corona comes from the emergence of new magnetic flux, or photospheric stressing of coronal fields. That is to say, SNs are the proxy of the energy supply to the corona. GSFs are not the total energy emitted by solar flares but are relative numbers on a given month; (2) the lifetime of solar flares and sunspots differs from each other. Sunspots have a lifetime longer than one solar rotation, and SNs are one measure of the complexity of magnetic structure of the active regions, while solar flares are the rapid conversion of a large amount of magnetic energy, stored for a while in the corona and dissipated through magnetic reconnections. They are a sudden and intense brightening, and (3) the existence of many solar flares, which comes from non-sunspot regions in a certain time point, maybe a possible reason why they show phase asynchrony.

Actually, the solar flare is a sudden release of energy that was previously stored in the magnetic field, which is a process of rapid transformation of the magnetic energy of the active region into the kinetic energy of particles, radiation, plasma flows and heat. The flares derive their power from the free energy stored in stressed or non-potential magnetic fields in the active regions. The magnetic energy in flaring regions can built up by shear flows in photospheric and chromospheric layers along the magnetic neutral lines. The moving plasma drags the magnetic field lines to form a non-potential magnetic topology, so the shearing motions are a signature of the accumulation of magnetic non-potentiality (Tan et al. 2009). The free magnetic energy will be released and the potential configuration will be restored after the sheared field reaches its critical point. However, Denker et al. (2007) concluded that the photospheric shear flow along the magnetic neutral line was commonly presented in complex sunspot but not related to any change of the local magnetic shear in their case. That is to say, it is still not clear whether the shear flow can be affected by the energy releasing process during solar flare. Therefore, to better understand the physical processes of flare energy storage and dissipation, forthcoming data set and future works are needed.

Acknowledgements

We would like to thank the anonymous referee for valuable comments and suggestions which led to a significant improvement of the paper. We appreciate the support from National Natural Science Foundation of China (11303011, 11163004, 11263004, U1231205), and Open Research Program of Key Laboratory of Solar Activity of Chinese Academy of Sciences (KLSA201309). This work is also supported by the Opening Project of Key Laboratory of Astronomical Optics & Technology, Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences. The authors thank the staff of all the Websites that provide the data and codes for the public to download.

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