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Activity Cycle of Solar Filaments

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Abstract. Long-term variation in the distribution of the solar filaments observed at the Observatorie de Paris, Section de Meudon from March 1919 to December 1989 is presented to compare with sunspot cycle and to study the periodicity in the filament activity, namely the periods of the coronal activity with the Morlet wavelet used. It is inferred that the activity cycle of solar filaments should have the same cycle length as sunspot cycle, but the cycle behavior of solar filaments is globally similar in profile with, but different in detail from, that of sunspot cycles. The amplitude of solar magnetic activity should not keep in phase with the complexity of solar magnetic activity. The possible periods in the filament activity are about 10.44 and 19.20 years. The wavelet local power spectrum of the period 10.44 years is statistically significant during the whole consideration time. The wavelet local power spectrum of the period 19.20 years is under the 95% confidence spectrum during the whole consideration time, but over the mean red-noise spectrum of $\alpha = 0.72$ before approximate Carrington rotation number 1500, and after that the filament activity does not statistically show the period. Wavelet reconstruction indicates that the early data of the filament archive (in and before cycle 16) are more noiseful than the later (in and after cycle 17).

Key words. Sun: activity—filaments—active cycle.

1. Introduction

Solar filaments are prominences observed against the solar surface, and they are cool and dense clouds in the hot and diluted solar corona. The shape, dynamics and physical properties of filaments vary in the wide range of values (Tandberg-hanssen 1995). Solar filaments are distributed around the whole solar disk, from the solar equator to the poles, and during the whole period of the cycle. Such a distribution is not random due to filaments that are closely connected with sites of magnetic fields on the solar surface (Martin 1990). Filaments can provide the possibility for investigation of global properties of large-scale magnetic fields, especially when magnetographic observations are not available. Their property to appear in all heliospheric latitudes and to outline the border between magnetic fields with different polarities makes them suitable tracers for the large-scale pattern of the weak background magnetic field

(McIntosh 1972; Minarovjech *et al.* 1998a, 1998b). On the other hand, study of the occurrence of filaments can help us to better understand distribution of these fields on the solar surface, their development with a cycle activity, and especially, provide useful insights into the nature of the sun's magnetic field (Rusin *et al.* 1998, 2000; Mouradian & Soru-Escaut 1994). Study on filaments through both individual events and statistical analyses are of importance. In the present study, the long-term cyclic variation in the distribution of the solar filaments observed at the Observatorie de Paris, Section de Meudon from March 1919 to December 1989 is presented to compare with the sunspot cycle.

The so-called periods of solar activity, such as the well-known 11-year Schwabe period and the 80–100-year Gleissberg period, are generally referred mainly to those of solar activity in the photosphere and have been widely studied (Ogurtsov *et al.* 2002; Polygiannakis *et al.* 2003; Prabhakaran *et al.* 2002). However, up to now we have known much less about the periods of the solar chromosphere and corona activities. The wavelet transform is a very powerful tool to analyze non-stationary signals. It permits identification of the main periodicities in a time series and the evolution in time of each frequency (De Moortel *et al.* 2004; Torrence & Compo 1998; Faria *et al.* 2004). In the present study, the complex Morlet wavelet transform (Torrence & Compo 1998) is utilized to study the periodicity in the solar filaments, showing the periods of the coronal activity.

2. Activity cycle of solar filaments

2.1 *Data*

Lucien d'Azambuja investigated solar filament and prominence behaviour over many years, and maintained a synoptic program of this phenomena similar to the Zurich sunspot program (d'Azambuja 1923; Coffey & Hanchett 1998b). He published the first "Cartes Synoptiques de la Chromosphere Solaire et Catalogue des Filaments de la Couche Superieure", a compendium of reduced solar observations covering the time period March 1919–January 1920 (d'Azambuja 1928). The compiled database gave both visual and quantitative measures of solar activity beginning with Carrington rotation 876. Since then, data through 1989 have been published in succeeding Carte Synoptiques issues (Coffey & Hanchett 1998b). The World Data Center A (WDC-A) for Solar-Terrestrial Physics has digitized the Carte Synoptiques (Coffey and Hanchett 1998b). The data can be accessed via the World Wide Web at *ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FILAMENTS*. Utilized here is the Carte Synoptique solar filaments archive (Mouradian 1998), namely the catalogue of solar filaments from March 1919 to December 1989, corresponding Carrington solar rotation numbers 876 to 1823, including 41044 filament regions in total (Coffey & Hanchett 1998b). In fact, in the database, the total 41042 filament regions are recorded with the filaments no 16479 and 17299 were repeatedly recorded, and the filaments No 14678, 16283, 16382, 16383, 18536, 19612, 19622, 30161-30188, and 20655 should be the filaments no 14687, 16282, 16381, 16382, 18546, 19622, 19621, 20161–20188, and 20665, respectively. Each data point represents the central meridian passage data of a filament region that was observed crossing the solar disk (Coffey & Hanchett 1998a).

2.2 *Cycle variation of solar filaments*

The normal solar activity is usually applied to solar active events whose latitudes are less than 50° (Sakurai 1998), and which are found to be anti-correlated with high-latitude solar activity (Li *et al.* 2002). We count the number of the low-latitude solar filaments whose latitudes are less than 50° in each of Carrington solar rotation numbers 876 to 1823, which is shown in Fig. 1. Also given in the figure is the 13-point smoothing values of the filament numbers. The figure shows that the number of the solar filaments waxes and wanes with an approximate 11-year Schwabe cycle, as the sunspot number does, showing a very nice cycle behaviour, called here as activity cycle of solar filaments. But the cycle maxima vary only in a small range (the ratio of the maximum value to the minimum one among the 6 maximum cycle amplitudes is about 2.0 for filaments, but about 2.6 for sunspot relative numbers), this is unlike the behaviour of sunspot numbers, areas or 10.7 cm flux. As we know, there is a good correlation among sunspot numbers, areas or 10.7 cm flux. However, there is a weak positive linear correlation between the maximum smoothed filament number and the maximum smoothed sunspot number, which is given in Fig. 2. The correlation coefficient is 0.578, which is even less than the critical correlation coefficient (0.729) at the 90% confident level. The minimum and maximum times of sunspot cycles are indicated in Fig. 1. The figure shows that the minimum times of activity cycle of solar filaments are very close to those of sunspot cycles, but the maximum times of activity cycle of solar filaments are later than those of sunspot cycles for 4 cycles of the total 6 cycles. And further, filament cycles show some delay on the downward curve of the filament data after sunspot maximum, as noted by d'Azambuja and d'Azambuja (1948). Here, in summary, we infer that activity cycle of solar filaments should have the same cycle length as sunspot cycle, but the cycle behaviour of solar filaments is globally similar in profile with sunspot cycles, but different in detail from sunspot cycles, especially, their corresponding maximum values are not linearly correlated with a statistical significance, and their corresponding maximum times are different from each other (the maximum times are generally later for filaments).

As we know, sunspots are related to magnetic flux, thus, sunspot numbers somewhat represent the "amplitude" of solar magnetic activity. Filaments are usually located at the neutral line of a solar magnetic field with different polarities and related to magnetic non-potentiality or electric currents, therefore, filament numbers are inferred to represent the "complexity" of solar magnetic activity. The magnetic field is observed to be very weak around the minimum of a normal cycle, appearing as simple sunspots, and even almost as single-polarity sunspots, so, it is plausibly expected that both filament activity and sunspot activity should have the same minimum time. Generally, the magnetic field of sunspots is observed to appear more and more complicated with the increase of their magnetic flux, thus, filament numbers seem positively correlated with sunspot relative numbers in general, however, increase of the number of sunspots or sunspot groups does not completely mean increase of pairs of magnetic polarity. The maximum times that filament activity cycles are found to be later than those of sunspot cycles, means that the complexity of sunspots peaks later than the magnetic flux of sunspots do during a normal active cycle. The amplitude of solar magnetic activity should not keep in phase with the complexity of solar magnetic activity.

Time-latitude distribution of the solar filaments was once shown by Coffey & Hanchett (1998b) in their Fig. 2, it is the butterfly plot of the entire Cartes Synoptiques

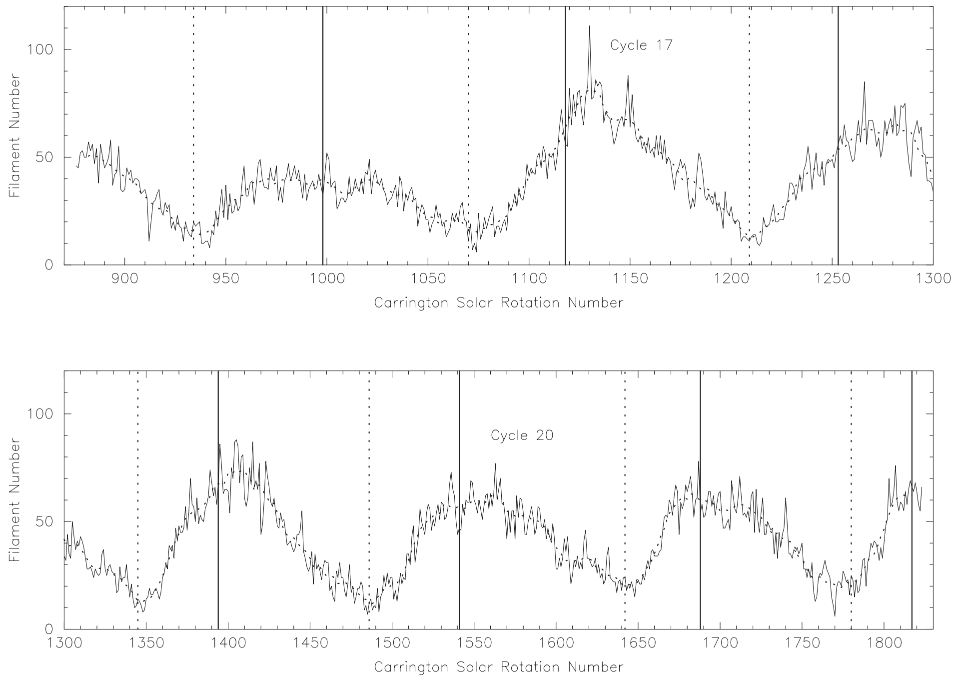

Figure 1. The numbers of the low-latitude solar filaments in Carrington solar rotation numbers 876 to 1823 (the solid thin curve) and their 13-point smoothed values (the dotted curve). The vertical solid and dotted lines are drawn to mark the minimum and maximum times of sunspot cycles, respectively.

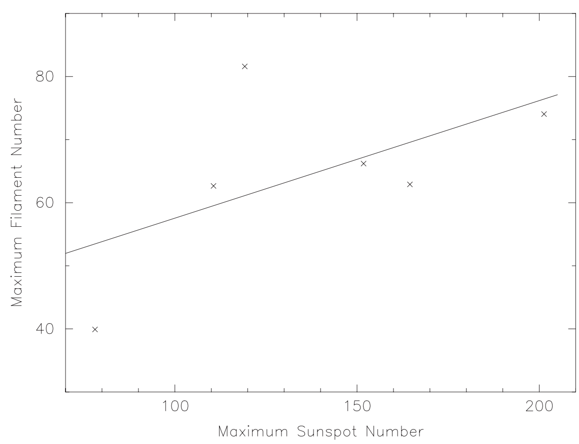

Figure 2. A weak linear correlation between the maximum smoothed filament number and the maximum smoothed sunspot number.

filament data archive. At the mid- and low-heliographic latitudes, filament activity shifts equatorward starting from the beginning of the cycle. But at high latitudes, it migrates polarward. Note the "rush to the pole" close to solar maximum when the

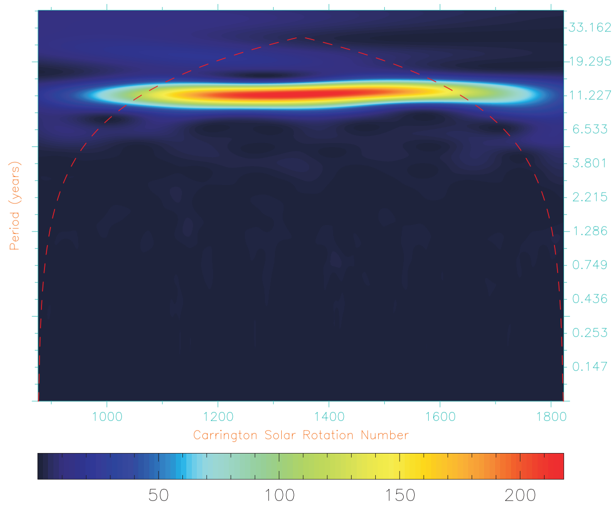

Figure 3. The local wavelet power spectral map of the filament number. The region upwards of the red dashed line indicates the COI.

solar polar magnetic field reversal occurs, and after then, very few filaments appear at high latitudes.

2.3 *Periodicity of activity cycle of solar filaments*

The wavelet analysis is a very powerful tool to analyze non-stationary signals, and it is rapidly gaining popularity as a means of extracting periodicities from observed signals (De Moortel *et al.* 2004a, 2004b; Faria *et al.* 2004). Among the wavelet analyses of solar activity, the Morlet wavelet is usually used, which has a reasonably large number of oscillation and may ensure a good frequency resolution. The complex Morlet wavelet analysis (Torrence & Compo 1998; De Moortel *et al.* 2004a, b) is utilized to study the periodicity of the filament number. Its local wavelet power spectrum is shown in Fig. 3. Through the figure, it can be found that the period belt of the highest power is located around the Schwabe period, as the photospheric sunspot activity does (Ogurtsov *et al.* 2002; Faria *et al.* 2004). It is the Schwabe period of the solar corona activity.

Great care is needed when using a wavelet: the Fourier transform is usually used to speed up the computation in wavelet analysis programme (Torrence & Compo 1998). However, as the Fourier transform assumes that data are cyclic, and most time series are of finite length, this introduces errors at the edges of the transform (De Moortel *et al.* 2004a). The region in which the transform suffers from these edge effects is known as the cone of influence (COI). As in Torrence & Compo (1998), the COI is defined so that the wavelet power for a discontinuity at the edge decreased by a factor e^{-2}. Portions of the transform that are outside the area formed by the 'time' axis and the COI are subject to these edge effects and are, therefore, unreliable (Moortel *et al.* 2004a; Torrence & Compo 1998). In Fig. 3, such an area is marked as the area upwards of the red dashed line. Shown in Fig. 4 is the global wavelet power spectrum of the number of the solar filaments. The period values of the power peaks in the global power spectrum are about 0.36, 1.04, 5.44, 10.44, 19.20, and 35.12 years, which can

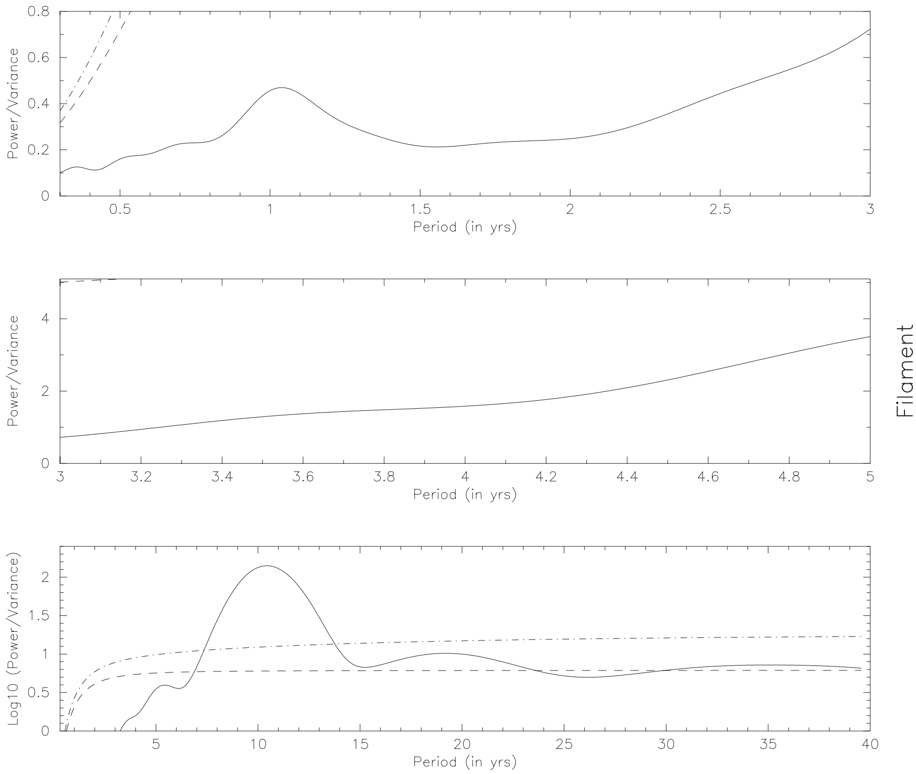

Figure 4. The global Morlet wavelet power spectrum of the filament number (the solid line). The dashed line is the mean red-noise spectrum of $\alpha = 0.72$, while the dotted and dashed line is the 95% confidence level for the global wavelet spectrum.

be all found in the periods of the photospheric sunspot activity (Prabhakaran *et al.* 2002; Polygiannakis *et al.* 2003). The most eminent period is shown to be 10.44 years, whose spectral power is over the 95% confidence level line, it is the Schwabe period of the solar corona activity. The power spectra of the periods of 19.20 and 35.12 years are under the 95% confidence level line but over the mean red-noise spectral line (Torrence & Compo 1998), being possible periods of the filament number, and the other rest periods are even under the mean red-noise spectral line, which are statistically insignificant. However, the period of 35.12 years locates in the COI are thus unreliable. Thus, reliable and possible periods in the filament number are 10.44 and 19.20 years.

The periodicity of 2.98 years is the so-called QBO (quasi-biennial 2–3 year oscillation) (Kane 2005), and a QBO was reported earlier in many solar indices and the solar magnetic field (Obridko & Schelting 2001; Kononovich & Shefov 2002; Knaack & Stenflo 2004; Kane 2005, and references therein). The QBO is considered the main feature of the 11-year cycle and it is suggested that the source of the QBO of the solar magnetic field should be situated rather low at the base of the solar convection zone (Bumba 2003; Kane 2005). However, strangely, such a period has not been found in filament activity.

Recent helioseismic probing of the solar interior has shown that the rotation rate of the Sun near the base of its convective zone changes with a period of roughly 1.3 years

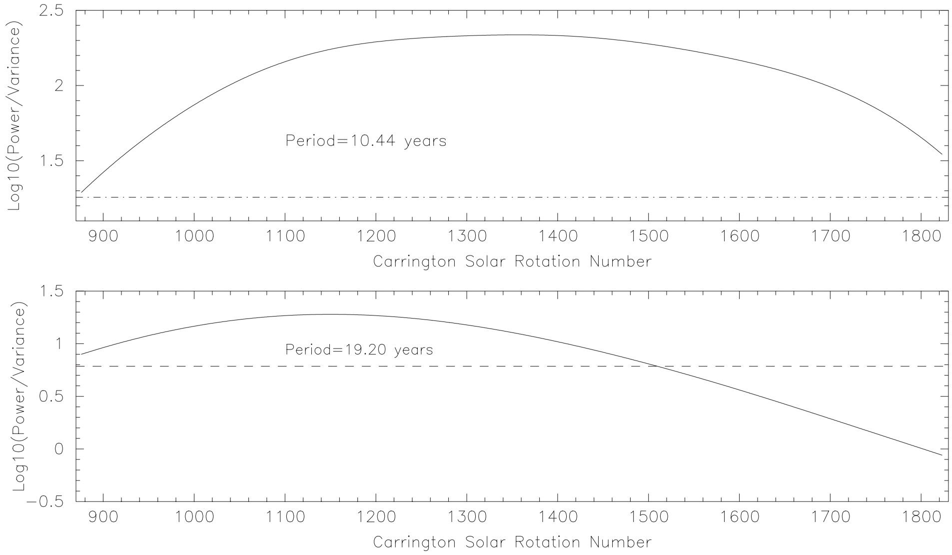

Figure 5. The local power spectra (the solid lines) of the reliable and possible periods in the filament number. The dashed line is the mean red-noise spectrum, while the dotted and dashed line is the 95% confidence level for the local wavelet spectrum.

(Howe *et al.* 2000), and significant power at this period (1.28 years) is indeed found in sunspots and is observed to vary strongly with time (Krivova & Solanki 2002). As well, the periodicity of the 1.3 year and 1.7 year are reported to be present in interplanetary plasma parameters and cosmic ray intensity as a modulation effect of solar activity (Kudala *et al.* 2002; Kato *et al.* 2003; Kane 2005, and references therein). Kane (2003) reported, however, that whereas such periodicities did exist, these were not all similar for solar indices, interplanetary plasma parameters, cosmic ray neutron monitor intensities during the time of the years 1991 to 2001. Recently, Kane (2005) identified the short-term (few tens of months) periodicities of several solar indices and found that, the periodicities of 1.3 year and 1.7 year often mentioned in the literature were seen neither often nor prominently. Here, the two periodicities are not found in the low-latitude filaments. One needs to check whether these periodicities are consistently in all solar indices and all the time. And, the magnetic field around the low-latitude filaments cannot be seemingly inferred to be related to the deep solar convection zone as well.

Shown in Fig. 5 are the local power spectra of the reliable and possible periods in the filament number. The wavelet local power spectrum of the Schwabe period is over the 95% confidence spectrum at the whole consideration time and highly significant. The wavelet local power spectrum of the period 19.20 years is under the 95% confidence spectrum at the whole consideration time, but over the mean red-noise spectrum of $\alpha = 0.72$ before Carrington rotation number 1501. The period is more eminent before Carrington rotation number 1501, and after that it is statistically insignificant.

Since the wavelet transform is a band-pass filter with a known response function (the wavelet function), it is possible to reconstruct the original time series. Such a reconstruction will denoise any low-amplitude regions of the wavelet transform, which are

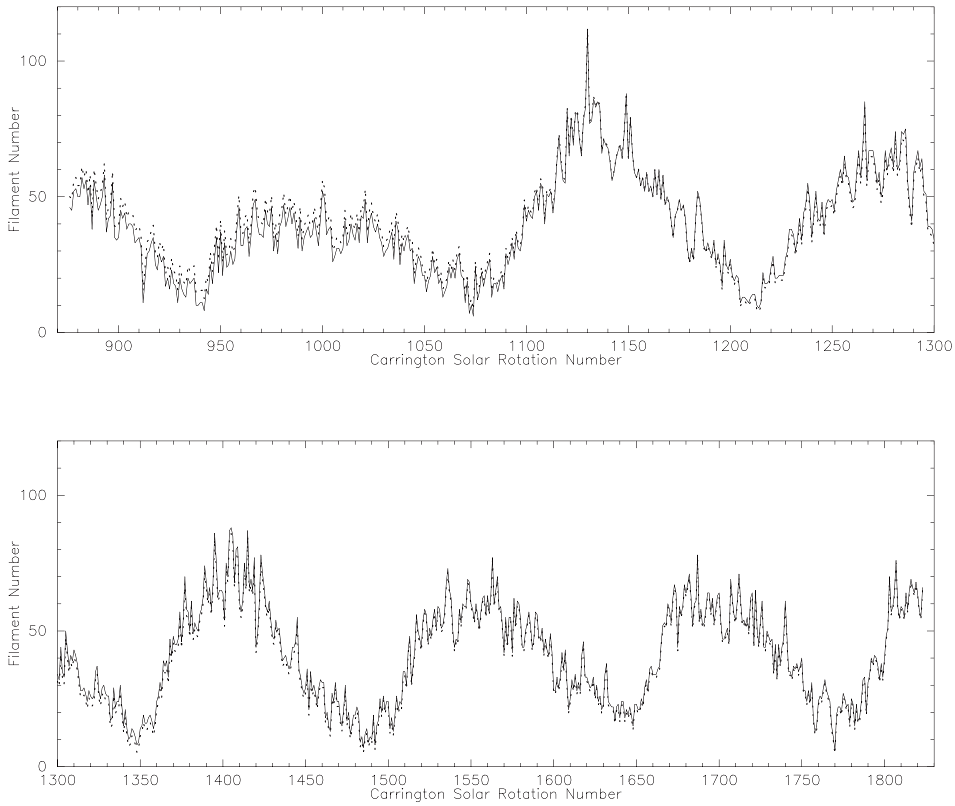

Figure 6. Comparison of the filament number (the solid line) and its reconstruction time series (the dotted line).

presumably due to noise (Torrence & Compo 1998). Shown in Fig. 6 is the comparison of the filament number and its reconstruction time series. The figure shows that the reconstruction time series fits better in and after cycle 17 than before, indicating that the early data of the filament archive are more noiseful.

3. Conclusions and discussions

The Carte Synoptique solar filament archive, namely, the catalogue of solar filaments observed at the Observatorie de Paris, Section de Meudon from March 1919 to December 1989, corresponding Carrington solar rotation numbers 876 to 1823 is used to show the long-term cyclic variation in the space and time distributions of the solar filaments. The number of the low-latitude solar filaments whose latitudes are less than 50° is counted in every Carrington solar rotation number of the consideration time. The time-latitude distribution of the filaments shows the butterfly plot of the coronal activity and the "rush to the pole" close to solar maximum when the solar polar magnetic field reversal occurs. Strangely, very few filaments appear at high latitudes after the solar polar magnetic field reversal.

The temporal distribution of the occurrence of the filaments shows that the filament number waxes and wanes with an approximate 11-year Schwabe cycle, as the sunspot number does. It is the cyclic activity of solar filaments. Comparing with sunspot cycle,

- the minimum times of activity cycle of solar filaments are very close to those of sunspot cycles;
- the amplitudes of the cycle maximum varies only in a small range, obviously less than that for sunspot cycle;
- there is not a statistical positive linear correlation between the maximum smoothed filament number and the maximum smoothed sunspot number;
- the maximum times of activity cycle of solar filaments are later than those of sunspot cycles for 4 cycles of the total 6 cycles, with some delay on the downward curve of the filament data after sunspot maximum;
- the filament number appears to be more sensitive to solar minima than sunspot number (Coffey & Hanchett 1998b). Thus, it is inferred here that activity cycle of solar filaments should have the same cycle length as sunspot cycle, but the cycle behaviour of solar filaments is globally similar in profile with, but different in detail from, that of sunspot cycles. The amplitude of solar magnetic activity should not keep in phase with the complexity of solar magnetic activity.

The complex Morlet wavelet analysis is utilized to study the periodicity in both the filament number and its smoothed number. The possible periods in the filament activity are about 10.44 (the Schwabe period of coronal activity) and 19.20 years. The wavelet local power spectrum of the period 10.44 years is statistically significant at the whole consideration time. The wavelet local power spectrum of the period 19.20 years is under the 95% confidence spectrum at the whole consideration time, but over the mean red-noise spectrum of $\alpha = 0.72$ before approximate Carrington rotation number 1500, and after then the filament activity does not statistically show the period. The periods of 154 days and 1.3 years, appearing in sunspot activity are not detected in the filament activity, but the period of about 5.4 years is detected. The Gleissberg period is not detected yet due to the short length of the filament data. Wavelet reconstruction indicates that the filament data are more noiseful in and before cycle 16 than after.

One thing should be pointed out that one Carrington solar rotation cycle is here regarded approximately as 27 days, or 0.9 months. The data used here show that 948 Carrington solar rotation cycles from Carrington solar rotation numbers 876 to 1823 correspond to 850 months from March 1919 to December 1989, therefore, one Carrington solar rotation cycle is 0.897 months. The two values are very close to each other.

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