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The north-south asymmetry of solar filaments separately at low and high latitudes in solar cycle 23 *

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Abstract We present the results of a study on the north-south asymmetry of solar filaments at low (<50°) and high (>60°) latitudes using daily filament numbers from January 1998 to November 2008 (solar cycle 23). It is found that the northern hemisphere is dominant at low latitudes for cycle 23. However, a similar asymmetry does not occur for solar filaments at high latitudes. The present study indicates that the hemispheric asymmetry of solar filaments at high latitudes in a cycle appears to have little connection with that at low latitudes. Our results support that the observed magnetic fields at high latitudes include two components: one comes from the emergence of the magnetic fields from the solar interior and the other comes from the drift of the magnetic activity at low latitudes.

Key words: Sun: activity — Sun: filaments, prominences — methods: data analysis

1 INTRODUCTION

Solar activity indices vary over the solar disk, and various activity parameters are found to be not symmetric between the northern and southern hemispheres of the Sun, with more events occurring in one or the other hemisphere during certain periods (Newton & Milsom 1955; Du & Wang 2012; Vizoso & Ballester 1990; Zharkov et al. 2005). The north-south (N-S) asymmetry in solar activity has been investigated in terms of several solar activity indicators, such as sunspot numbers, sunspot areas, sunspot group numbers, flares, filaments, coronal mass ejections (CMEs), faculae, photospheric magnetic flux, differential rotation, etc. (Ballester et al. 2005; Carbonell et al. 1993, 2007; Ataç & Özgüç 1996, 2001, 2006; Joshi & Pant 2005; Joshi et al. 2006; Duchlev 2001; Verma 1993; Deng et al. 2012, 2013; Temmer et al. 2002, 2006; Badalyan & Obridko 2011; Knaack et al. 2005; Song et al. 2005; Gigolashvili et al. 2003, 2005; Yan et al. 2008; Li et al. 2002, 2003, 2009a,b, 2010). These studies indicate that the N-S asymmetry of solar activity is a real physical phenomenon and not a random fluctuation (Vizoso & Ballester 1990). The N-S asymmetry of activity in the solar atmosphere may yield important information regarding the nature of solar dynamo action, which

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is a phenomenon that attracts great interest in modern nonlinear dynamo models. Thus, it is very important to analyze the N-S asymmetry of solar activity (Brandenburg & Tuominen 1991; Duchlev 2001).

Filaments (or prominences) are relatively cool and dense plasmas suspended in the hot solar corona. They can be well observed in Hα, either in absorption against the disk or in emission at the limb. Observations indicate that filaments are often formed in the filament channel along the polarity inversion line between opposite magnetic polarities (Martin 1998). As filaments can appear at all heliospheric latitudes and outline the border between magnetic fields with different polarities, they can be used as markers to trace the large-scale pattern of the weak background magnetic field (McIntosh 1972; Minarovjech et al. 1998), especially when magnetographic observations are not available. On the other hand, studies on the occurrence of filaments can help us to better understand the distribution of large-scale fields on the solar surface, their development within a cycle, and provide useful insights into the nature of the Sun's magnetic field (Howard & Labonte 1981; Makarov & Makarova 1996; Makarov & Tlatov 1999; Rusin et al. 2000; Yan et al. 2011; Kong et al. 2014).

The N-S asymmetry of solar filaments has been studied by some authors (Waldmeier 1971; Hansen & Hansen 1975; Vizoso & Ballester 1987; Verma 2000; Duchlev & Dermendjiev 1996; Duchlev 2001; Pojoga & Huang 2002; Gigolashvili et al. 2003; Li et al. 2003, 2009a,b, 2010). Vizoso & Ballester (1987) investigated the N-S asymmetry in sudden disappearances of solar prominences during solar cycles 18–21 and found that the N-S asymmetry curve is not in phase with the solar cycle, peaking around the solar minimum and reversing in sign from positive to negative during the solar maximum at the time of the reversal in the Sun's magnetic dipole. Verma (2000) studied the distribution and asymmetry of solar active prominences (SAP) for the period 1957–1998. The N-S latitudinal distribution shows that the SAP events are most prolific in the $11°$–$20°$ slice in the northern and southern hemispheres. The N-S asymmetry of SAP events is significant and has no relation with the solar maximum year or solar minimum year during solar cycles. Pojoga & Huang (2002) analyzed the sudden disappearances of filaments from 2000 January 1 to 2001 June 30, whose distribution shows an asymmetry between the northern and southern hemispheres. On average, a greater number of disappearances were recorded in the northern hemisphere. Gigolashvili et al. (2003) investigated the peculiarities in the characteristics of the solar differential rotation using hydrogen filaments as tracers and statistically confirmed the existence of the N-S asymmetry in rotation by using hydrogen filaments. The connection of the asymmetry with the solar activity cycles is established. Li et al. (2003) studied the asymmetry of solar active prominences, separately at low and high latitudes (1957–1998, solar cycles 19–22) and found that the annual hemispheric asymmetry indeed exists at low latitudes, but a similar asymmetry does not seem to occur at high latitudes. The hemispheric asymmetry of the solar active prominences at high latitudes in a cycle appears to have little connection with the asymmetry of the solar activity at low latitudes. The N-S asymmetry of solar activity is also investigated by Li et al. (2009b), using the high-latitude filament record in cycles 16–21, polar faculae in cycles 19–23, the solar polar field strength in cycles 21–23 and the high-latitude flare record in cycles 21–23. The N-S asymmetry of solar activity at high latitudes is also found to have little or no relation with that at low latitudes. Li et al. (2010) investigated the N-S asymmetry of solar filaments in cycles 16–21, and demonstrated that the same dominant hemisphere of solar activity exists in each of the cycles 16–21, indicating there is a large-scale pattern in the weak background magnetic field. However, the N-S asymmetry of filament activity shows a different asymmetrical behavior at different latitudinal bands.

In this paper, we will analyze the spatial distribution and the N-S asymmetry of solar filaments separately at low and high latitudes in solar cycle 23, using daily numbers of solar filaments from January 1998 to November 2008.

The layout of this paper is as follows. Section 2 gives the data used in this paper. Section 3 provides the asymmetry of filament activity at low and high latitudes. Finally, the conclusions and discussions are given in Section 4.

2 DATA

The original data of solar filaments from January 1998 to December 2009 come from Hα full-disk images obtained by the Mauna Loa Solar Observatory (MLSO)[1]. Hao et al. (2013) developed an advanced method to automatically detect and trace solar filaments in Hα full-disk images and successfully applied it to process and analyze 3470 images obtained by the MLSO from January 1998 to December 2009. The statistical results of the temporal evolution of the latitudinal distribution of filaments are obtained, mainly covering cycle 23. Based on the statistical results of the temporal evolution of the latitudinal distribution of filaments obtained by Hao et al. (2013), we count the daily numbers of solar filaments at low (lower than 50°) latitudes separately in the northern and southern hemispheres from January 1998 to November 2008, shown in the upper panel of Figure 1. The daily numbers of solar filaments at high (higher than 60°) latitudes, in the northern and southern hemispheres from January 1998 to November 2008, are shown in the lower panel of Figure 1. Sakurai (1998) suggested that the activities observed at band $50° - 60°$ should be made up of two parts: one belonging to the low-latitude activity cycle, and the other to the high-latitude activity cycle. Thus, the solar filaments at band $50° - 60°$ are omitted here.

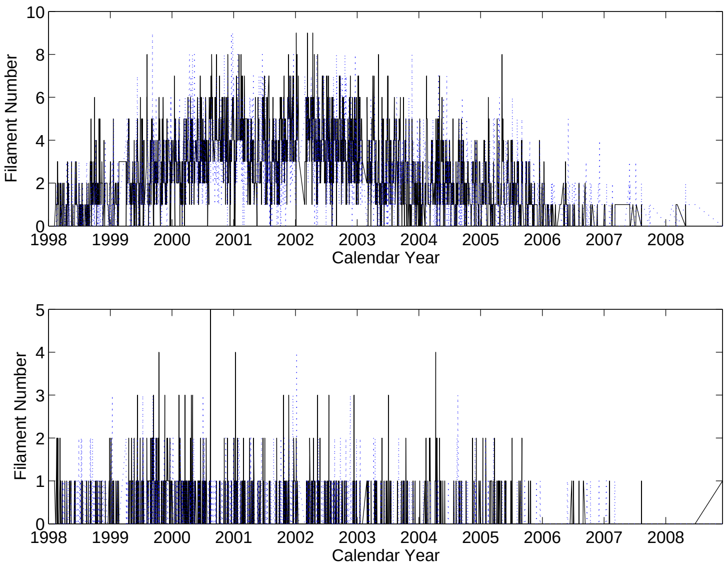

Fig. 1 *Upper panel*: daily number of filaments at low latitudes in the northern hemisphere (*solid line*) and that in the southern hemisphere (*dotted line*). *Lower panel*: daily number of filaments at high latitudes in the northern hemisphere (*solid line*) and that in the southern hemisphere (*dotted line*).

3 ASYMMETRY OF FILAMENT ACTIVITY AT LOW AND HIGH LATITUDES

The N-S asymmetry of solar activity is characterized as: Asymmetry=$(\mathrm{NO_N}-\mathrm{NO_S})/(\mathrm{NO_N}+\mathrm{NO_S})$, where $\mathrm{NO_N}$ and $\mathrm{NO_S}$ stand for the values of the considered solar activity indicators in the northern and southern hemispheres, respectively (Ballester et al. 2005). If Asymmetry > 0, the activity in

[1] *http://mlso.hao.ucar.edu*

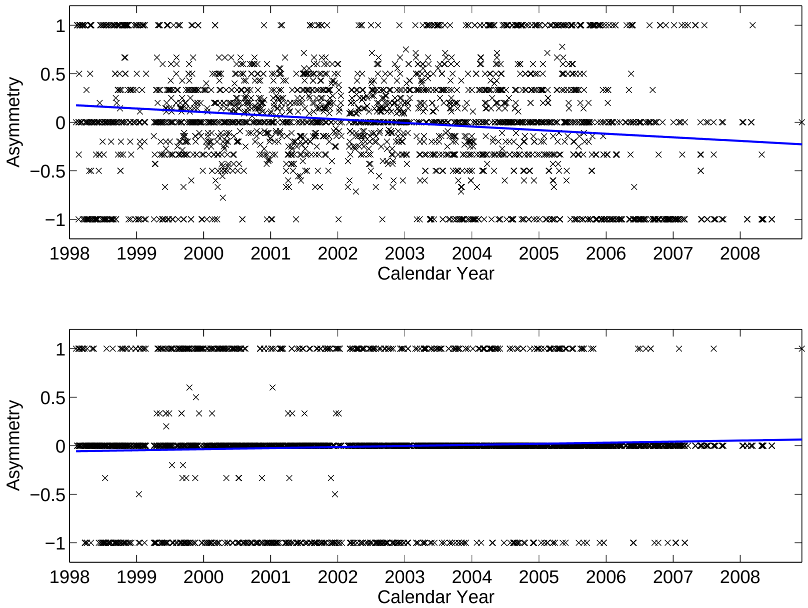

Fig. 2 *Upper panel*: fit of a linear regression line to the N-S asymmetry values of the daily filament numbers at low latitudes for cycle 23. *Lower panel*: fit of a linear regression line to the N-S asymmetry values of the daily filament numbers at high latitudes for cycle 23.

the northern hemisphere dominates. If Asymmetry < 0, the activity in the southern hemisphere dominates. We calculate the asymmetry values of the daily filament numbers in the northern and southern hemispheres at low latitudes, which are shown in the upper panel of Figure 2. As done by Vizoso & Ballester (1990), Ataç & Özgüç (1996) and Li et al. (2002), we have fitted a linear regression line to them (the blue line) which is also plotted in the figure. The figure shows that the slope of the linear regression line has a negative sign. The N-S asymmetry value shifted from positive to negative in 2002–2003, which is around the maximum of solar cycle 23. This means that the southern hemispheric solar activity becomes stronger and stronger compared to the northern hemispheric solar activity. The asymmetry suggests that the northern hemisphere is dominant at the onset of the cycle. Then, as the cycle progresses, the southern hemisphere becomes dominant. Similarly, we calculate the asymmetry values of the daily filament numbers in the northern and southern hemispheres at high latitudes, which are shown in the lower panel of Figure 2. A linear regression line is fitted to them, and is also plotted in the figure. The figure shows that the regression line has a slight shift in the positive direction. Such a positive sign for a cycle means that the northern hemispheric solar activity becomes stronger and stronger compared to the southern hemispheric solar activity, when solar activity is progressing in solar cycle 23.

In order to check whether these asymmetrical values are statistically significant or not, we used the following binomial formula to compute the actual probability $P(k)$ of getting k objects in class 1 and $(n-k)$ objects in class 2, considering a distribution of n objects in two classes (Vizoso & Ballester 1990)

$$P(k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} . \tag{1}$$

Table 1 Solar Activity at Different Latitude Bands in the Northern and Southern Hemispheres in Solar Cycle 23

Latitude Band (1)	NO_N (2)	NO_S (3)	Asymmetry (4)	Probability (5)	Dominant Hemisphere (6)
0°–10°	966	906	0.0321	8.633e–02	North
10°–20°	1261	1187	0.0302	7.004e–02	North
20°–30°	1423	1310	0.0413	1.607e–02	North
30°–40°	1168	1117	0.0223	1.478e–01	–
40°–50°	910	793	0.0687	2.463e–03	North
50°–60°	630	544	0.0733	6.538e–03	North
60°–70°	364	366	–0.0027	5.442e–01	–
70°–80°	123	120	0.0123	4.489e–01	–
80°–90°	67	55	0.0984	1.597e–01	–
0°–50°	5728	5313	0.0376	4.066e–05	North
60°–90°	554	541	0.0119	3.584e–01	–
0°–90°	6912	6398	0.0386	4.35e–06	North

The probability of obtaining more than d objects in class 1 is given by

$$P(\geq d) = \sum_{k=d}^{n} P(k)\,. \tag{2}$$

If the probability of obtaining a hemispherical distribution of solar activity in a cycle is less than 10%, the distribution of solar activity for the two hemispheres should be considered statistically important or marginally significant and not due to random fluctuations. If the probability is larger than 10%, the solar activity in the cycle should be regarded as being equivalent for the two hemispheres and not statistically important (Vizoso & Ballester 1990; Oliver & Ballester 1994).

We count the total numbers of daily filaments at different latitude bands in the northern and southern hemispheres as shown in Table 1. The corresponding asymmetry values and the actual probabilities of obtaining such an N-S distribution are all listed in the table. The dominant hemisphere is also obtained and listed in the table, where symbol "–" means that the activity level is even in the two hemispheres. The table shows that the frequency of solar filaments increases from the equator to latitude 30° and decreases from 30° to 90°. The filament numbers are maximum at latitude band $20° - 30°$ for solar cycle 23 on both hemispheres. The dominant hemisphere of solar activity is the northern one in solar cycle 23, at latitude bands $0° - 10°$, $10° - 20°$, $20° - 30°$, $40° - 50°$, $50° - 60°$, $0° - 50°$ and $0° - 90°$. However, there is no dominant hemisphere with solar activity being statistically equivalent in the two hemispheres during solar cycle 23, at latitude bands $30° - 40°$, $60° - 70°$, $70° - 80°$, $80° - 90°$ and $60° - 90°$.

To investigate the exact period during which the excess filament trailed from one hemisphere to the other, we have plotted the cumulative counts of daily filament numbers for the northern (the solid lines) and southern (the dotted lines) hemispheres at low (upper panel of Fig. 3) and high (lower panel of Fig. 3) latitudes for solar cycle 23.

Figure 3 shows that filament activity always dominates in the northern hemisphere at low latitudes. However, the dominant hemisphere changes from one to the other several times at high latitudes.

4 CONCLUSIONS AND DISCUSSIONS

In the present paper, the N-S asymmetry of solar activity at low and high latitudes was examined by statistically analyzing the hemispheric distributions of the daily number of solar filaments in solar cycle 23, occurring from January 1998 to November 2008. We found that solar activity is dominant in

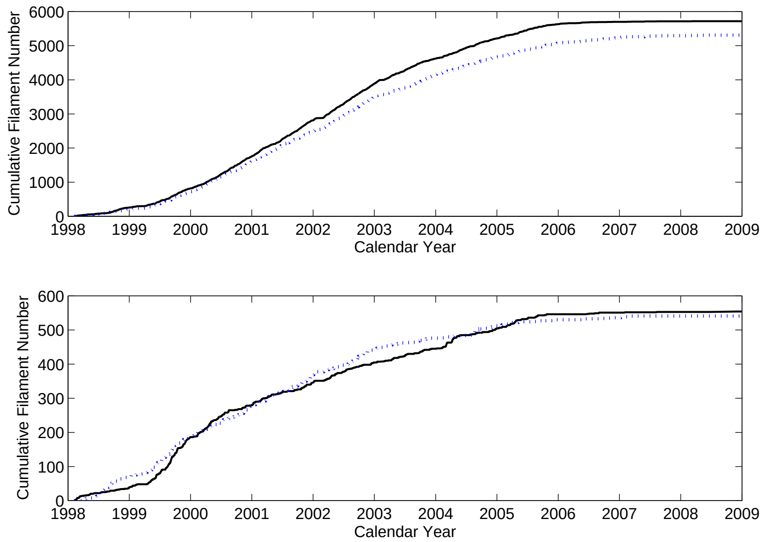

Fig. 3 *Upper panel*: cumulative filament numbers at low latitudes in the northern hemisphere (*solid line*) and the southern hemisphere (*dotted line*) in cycle 23. *Lower panel*: cumulative filament numbers at high latitudes in the northern hemisphere (*solid line*) and the southern hemisphere (*dotted line*) in cycle 23.

the northern solar hemisphere at low latitudes in cycle 23. The activity of solar filaments gradually shifted from the northern hemisphere to the southern one. The transition occurred in 2002–2003, which agrees with the evolution of other solar activity indices (Vizoso & Ballester 1987; Oliver & Ballester 1994; Garcia 1990), i.e. the sign of the asymmetry always changes around the maximum of solar activity. The asymmetry was very weak at high latitudes in cycle 23, which is consistent with the results obtained by Li et al. (2009b) using the polar faculae activity and polar field activity in cycle 23.

Some authors investigated the N-S asymmetry of solar activity during solar cycle 23 using different solar activity features, such as sunspot groups, sunspot areas and CMEs (Chowdhury et al. 2013; Li et al. 2009a; Gao et al. 2007) and their studies showed that solar activity for cycle 23 is dominant in the southern hemisphere. Li et al. (2009b) found that solar activity for cycle 23 is dominant in the northern hemisphere, using solar polar field strength in normal cycles of activity at low latitudes. Deng et al. (2012) studied the N-S asymmetry and found that there is a north-dominant asymmetry in solar cycle 23, using the monthly flare index from 1966 January to 2008 December. In the present investigation, it is found that solar activity is dominant in the northern hemisphere at low latitudes in cycle 23, with the use of filament data. Our result is consistent with that obtained by Li et al. (2009b) and Deng et al. (2012).

Li et al. (2010) used a linear regression line to separately fit the yearly values of the asymmetry of sunspot groups for each of the cycles 8–23, and found that the slopes of the linear regression lines have a positive sign for the first four cycles 16–19, but a negative sign for the last two cycles 20–21. According to the regularity referenced quote “each four cycles the slope of the straight fitting line changes its sign” proposed by Vizoso & Ballester (1990), it can be inferred that the slope of the linear regression line for cycle 23 should have a negative sign. As shown in the upper panel of Figure 2, the slope of the linear regression line has a negative sign at low latitudes for cycle 23, which confirmed the regularity in Vizoso & Ballester (1990) and Li et al. (2010). It can be inferred that the slope of a linear regression line to the asymmetry at low latitudes should have a positive sign as cycle 24 progresses. This should be further investigated using the data of cycle 24.

Li et al. (2003) found that the annual hemisphere asymmetry exists at low latitudes and does not occur at high latitudes, using the solar active prominences in the period 1957–1998. The N-S asymmetry of solar activity is also investigated by Li et al. (2009b), using the high-latitude filament record in cycles 16–21, polar faculae in cycles 19–23, the solar polar field strength in cycles 21–23 and the high-latitude flare record in cycles 21–23. The N-S asymmetry of solar activity at high latitudes is found to have little or no relation with that at low latitudes. Our results confirmed the investigations of Li et al. (2003) and Li et al. (2009b).

According to the Babcock-Leighton mechanism of solar activity cycles, magnetic flux emergence inside the Sun is generated in the form of active regions at low latitudes. The evolution of the large-scale weak magnetic field is thought to be caused by dispersal and surface transport of the magnetic flux of active regions (Makarov & Tlatov 1999). The movement of magnetic fields from sunspot latitudes to the poles forms the polar magnetic fields (Howard & Labonte). In addition, the magnetic fields of sunspots diffuse toward polar regions and polar magnetic fields are reversed. Ruediger & Brandenburg (1995) proposed a dynamo model to produce butterfly diagrams with two branches: one branch propagates toward the equator and the other propagates toward the poles. If high-latitude magnetic fields are formed entirely by the "rush to poles" of low-latitude ones, the N-S asymmetry at high latitudes should be the same as that at low latitudes. However, the N-S asymmetry of solar filaments at high latitudes is found to have little or no relation with that at low latitudes. This indicates that the observed magnetic fields at high latitudes include two components: one comes from the emergence of the magnetic fields from the solar interior and the other comes from the drift of the magnetic activity at low latitudes.

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