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North–South Distribution of Solar Flares during Cycle 23

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Abstract. In this paper, we investigate the spatial distribution of solar flares in the northern and southern hemispheres of the Sun that occurred during the period 1996 to 2003. This period of investigation includes the ascending phase, the maximum and part of the descending phase of solar cycle 23. It is revealed that the flare activity during this cycle is low compared to the previous solar cycle, indicating the violation of Gnevyshev–Ohl rule. The distribution of flares with respect to heliographic latitudes shows a significant asymmetry between northern and southern hemisphere which is maximum during the minimum phase of the solar cycle. The present study indicates that the activity dominates the northern hemisphere in general during the rising phase of the cycle (1997–2000). The dominance of northern hemisphere shifted towards the southern hemisphere after the solar maximum in 2000 and remained there in the successive years. Although the annual variations in the asymmetry time series during cycle 23 are quite different from cycle 22, they are comparable to cycle 21.

Key words. Sun: activity—flares—north–south asymmetry.

1. Introduction

The distribution of various solar activity features with respect to heliographic latitudes as a function of time has been investigated in several studies. These activity features include flares, filaments, magnetic flux, sunspot numbers, sunspot area, etc. These studies indicate that a solar cycle is not symmetric considering the distribution of solar activity separately in northern and southern hemisphere. This intrinsic feature (N–S asymmetry) poses a challenge for dynamo model calculations.

Howard (1974) examined the N–S distribution of solar magnetic flux for the period 1967–1973 and concluded that about 95% of the total magnetic flux of the Sun is confined to latitudes below 40° in both the hemispheres. It was also found that total magnetic flux in the north exceeded to that in the south by 7%. Roy (1977) studied the N–S distribution in the data of major flares, sunspot area and their magnetic configuration during 1955–1974 and found the dominance of northern hemisphere over the southern one in all these categories. Garcia (1990) investigated the N–S distribution of soft X-ray flares (class $\geq$ M1) during solar cycle 20 and 21. It was concluded that the spatial distribution of flares varies within a solar cycle such that the preponderance of flares occurs in the north during the early part of the cycle and then moves south as the cycle progresses. Knoška (1985) investigated the N–S asymmetry of Hα flare index, introduced by Kleczek (1953), for cycles 17–20, which was later extended till cycle 22 by Ataç & Özgüç (2001). Their results show a long-term periodic behaviour in asymmetry time series. Verma (1993) examined the N–S asymmetry of various solar active phenomena and reported cyclic behaviour of asymmetry. Joshi (1995) and Li *et al.* (1998) studied the N–S asymmetry of Hα and soft X-ray flares respectively during solar cycle 22. In both the above investigations, a southern dominance was prevalent. Joshi & Pant (2005) analysed the data of solar Hα flares during solar cycle 23 to investigate their spatial distribution. Recently Knaack *et al.* (2004, 2005) studied the temporal and spatial variations in the photospheric magnetic flux between the northern and southern hemisphere of the Sun from 1975 to 2003 and reported significant periodic variations of magnetic activity between the two hemispheres. They also studied N–S asymmetry using the monthly averaged sunspot areas obtained for the period of 1874–2003.

In the present study, we investigate the latitudinal distribution of Hα flares during the present solar cycle 23. We have studied the yearly variations in N–S asymmetry and discussed the significance of observed asymmetry by using the binomial probability test. These results for solar cycle 23 have been compared with the behaviour of previous cycles 22 and 21 as reported by Temmer *et al.* (2001).

2. Hα flare data

The data used in the present study have been collected from Hα flare lists published in the SGD (Solar Geophysical Data) during the time span of 01 May 1996 to 31 December 2003, covering almost 8 years of solar cycle 23. During this period, the occurrence of 20235 Hα flares is reported. In Hα, flares are classified according to their importance and brightness classes. The important class (S = subflare, or 1, 2, 3, or 4 for successively large flares) denotes the size of the flare and the brightness class (f = faint, n = normal, b = bright) corresponds to a subjective estimate of the intensity of the emission. In the list of Hα flares, classifications are not given for some events. After excluding such events, we get a total of 20223 Hα flares, which provides an extensive database for the present study. Figure 1 shows the plot of monthly flare counts as well as monthly mean sunspot numbers during the period of our investigation.

3. Latitudinal distribution and N–S asymmetry

To study the spatial distribution of flares with respect to heliographic latitudes, we have calculated the number of flares in the interval of 10° latitude for northern and southern hemispheres (see Table 1). In this table those events have been excluded which occurred at 0° latitude. Since the number of flares above 50° latitude is very small in both the hemispheres, the number of flares occurring above 50° latitude is merged in one group. Column 8 of Table 1 gives the total number of flares in the northern and southern hemispheres. It is evident from Table 1 that for all these years one hemisphere produces more flares than the other.

It is customary to describe N–S asymmetry by an asymmetry index

$$A = \frac{N - S}{N + S}, \qquad (1)$$

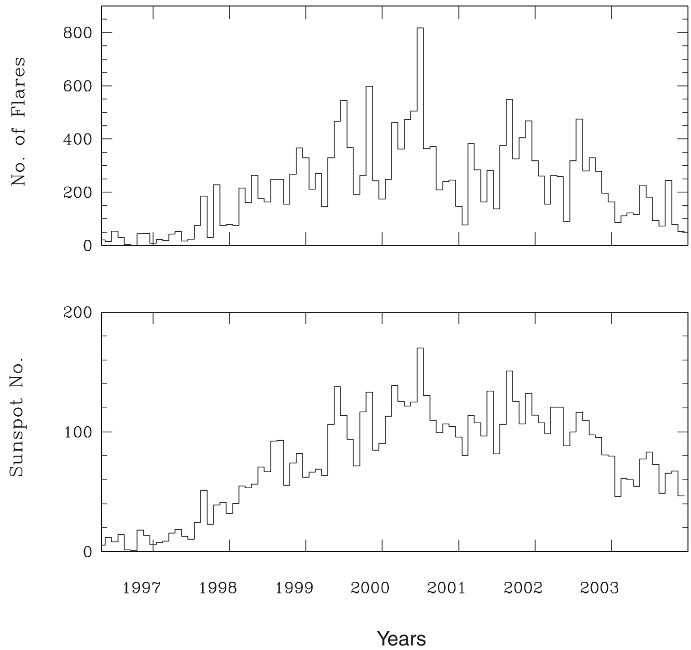

Figure 1. Monthly numbers of Hα flares and monthly mean sunspot numbers from 1996–2003.

where N and S are the yearly number of flares in the northern and southern hemisphere of the Sun respectively. The asymmetry indices, based on annual flare counts from 1996 to 2003, have been plotted in Fig. 2. The statistical significance of the flare dominance in northern and southern hemispheres has been assessed by using the binomial probability distribution. Let us consider a distribution of n objects in 2 classes. The binomial formula gives us the probability $P(k)$ of getting k objects in class 1 and $(n-k)$ objects in class 2, such that

$$P(k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \tag{2}$$

and the probability to get more than d objects in class 1 is given by

$$P(\geq d) = \sum_{k=d}^{n} P(k). \tag{3}$$

In general, when $P(\geq d) > 10\%$, implies a statistically insignificant result (flare activity should be regarded as being equivalent for the two hemispheres), when $5\% < P(\geq d) < 10\%$ it is marginally significant, and when $P(\geq d) < 5\%$ we have a statistically significant result (flare occurrence is not due to random fluctuations). The calculated values of probability are given in Table 1 and based on that the highly significant, marginally significant and insignificant values of asymmetry indices are marked with different symbols in Fig. 2. Figure 2 also shows the yearly N–S asymmetry (given by equation 1) of Hα flare index (dashed line) from 1996 to 2003.

Table 1. Number of Hα flares at different latitude bands in the northern (N) and southern (S) hemispheres are tabulated for each year. The binomial probability (Prob.) and the dominant hemisphere (DH) is given for all the years as well as for all the latitudinal bands. Dash (–) represents that the probability is not significant. Flares occurred exactly at the equator have been excluded.

	Number of flares								
Years	0–10°	10–20°	20–30°	30–40°	40–50°	> 50°	Total	Prob.	DH
1996 N	21	2	0	1	0	0	24	1.107×10^{-33}	S
S	112	53	21	2	0	0	188		
1997 N	39	160	230	20	0	0	449	5.641×10^{-6}	N
S	5	103	199	18	1	1	327		
1998 N	13	635	503	54	1	1	1207	0.428	–
S	3	366	807	31	9	0	1216		
1999 N	169	1240	811	105	11	0	2336	7.017×10^{-30}	N
S	71	874	644	38	0	0	1627		
2000 N	463	1327	633	55	1	2	2481	8.712×10^{-14}	N
S	248	1288	373	79	1	0	1989		
2001 N	503	978	262	5	1	0	1749	0.058	S
S	449	1062	282	42	8	0	1843		
2002 N	250	746	255	6	0	0	1257	1.329×10^{-35}	S
S	675	1006	272	4	0	0	1957		
2003 N	407	315	14	3	0	0	739	0.069	S
S	222	475	83	17	0	0	797		
Total N	1865	5403	2708	249	14	3	10242	0.018	N
S	1785	5227	2681	231	19	1	9944		
Prob.	0.093	0.956	0.356	0.205	0.189	0.125	0.018		
DH	N	–	–	–	–	–	N		

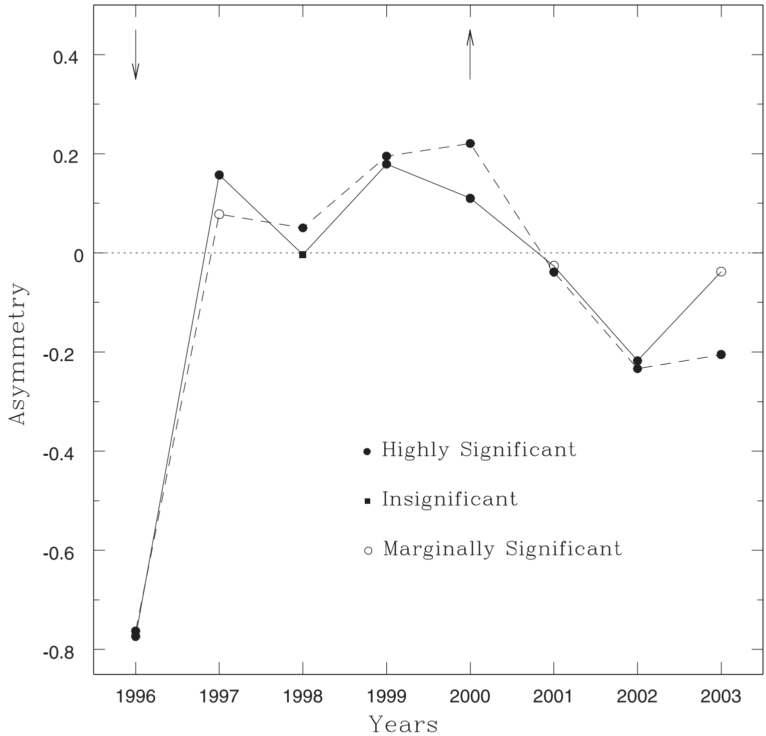

Figure 2. Plot of annual N–S asymmetry index of Hα flare counts (solid line) and Hα flare index (dashed line) from 1996 to 2003. Arrows indicate the maximum and minimum phases, respectively, of solar cycle 23.

4. Discussions and conclusions

Temmer *et al.* (2001) and Temmer (2004) made an extensive statistical analysis of Hα flare data of cycles 21 and 22 to study their temporal behaviour and spatial distribution over the solar cycle. The comparison of monthly flare counts during cycle 23 (Fig. 1) with those reported by Temmer *et al.* (2001) for cycles 22 and 21 shows that the activity level during cycle 23 is significantly lower than two previous cycles. This clearly indicates the violation of the Gnevyshev–Ohl (G–O) rule in terms of the level of flare activity, for the pair of solar cycles 22–23. This empirical rule states that the sum of sunspot numbers over an odd cycle exceeds that of the preceding even cycle (Gnevyshev & Ohl 1948). The sunspot numbers, starting from cycle 0 (i.e., from the year 1750), show that G–O breakdown had also occurred for the Hale cycles consisting of the 11-year pair of cycles 4–5 and 8–9. Komitov & Bonev (2001) examined the conditions for the violation of the G–O rule. They analysed a long data set of 152 solar activity cycles obtained from direct and indirect records and predicted a high probability for violation of the G–O rule for the pair of the cycles 22–23.

Table 1 shows several interesting aspects of flare distribution with the evolution of solar cycle. In the beginning of the cycle 0–10° latitudinal belt in southern hemisphere produced maximum number of flares, which could be a remnant of the preceding cycle. In the year 1997, just after solar minimum, most of the flares were produced in the 20–30° latitudinal belt and with the progress of solar cycle, the flare occurrence increased in lower latitudes also. Table also shows that 10–20° latitudinal belt was the highest flare producing region.

Figure 2 shows the annual variations in N–S asymmetry. There is a strong southern dominance during the solar cycle minima in 1996. This behaviour of asymmetry that it peaks at or around the minimum phase of solar activity has been reported in several studies with different manifestations of solar activity (Swinson *et al.* 1986; Vizoso & Ballester 1990; Joshi & Joshi 2004). In 1997, 1999 and 2000, when the cycle was in the ascending phase, northern hemisphere dominated. The preference for northern hemisphere during the rising and maximum phase of cycle 23 is reported by Ataç & Özgüç (2001) and Joshi & Joshi (2004) in yearly values of Hα and soft X-ray flare index respectively. Gopalswamy *et al.* (2003) compared the latitudinal distribution of prominence eruptions (PEs) and coronal mass ejections (CMEs) as a function of time from 1996 to 2002. Their study revealed that there is a shift in the dominance of PEs and CMEs activity from northern to southern hemisphere after solar maximum in 2000. Similar trend has been found in the present investigation with solar flare count data. The yearly variations in N–S asymmetry for flare counts and flare index (Fig. 2) show a similar trend. In the year 2000 flare index asymmetry is stronger in the northern hemisphere compared to flare count asymmetry, which indicates that most of the major flares occurred in the northern part of the solar disk during solar cycle maxima. Similarly during October and November months of 2003, most of the big flares occurred in the southern hemisphere of the Sun and consequently the asymmetry in flare index values became stronger in the southern part of solar disk. Comparing our results with Temmer *et al.* (2001) we find that the variations in N–S asymmetry index during cycle 23 differ from cycle 22 but are similar to cycle 21. There was mostly a southern dominance during cycle 22 while cycle 21 showed northern dominance during the early phases and southern dominance during the later phases. The present investigation is consistent with the N–S asymmetry analysis performed with soft X-ray flare index data during cycles 21–23 (Joshi & Joshi 2004).

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