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N-S ASYMMETRY AND PERIODICITY OF DAILY SUNSPOT NUMBER DURING SOLAR CYCLES 22-24

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In this paper, a broad examination of the N-S asymmetry of daily sunspot numbers during the period January 1992 to March 2020 has been performed, examining its statistical significance and looking for the short term periodicity of daily sunspot numbers using the Fast Fourier Transform (FFT) during solar cycle 22 (1 January 1986 to 27 August 1996), cycle 23 (28 August 1996 to 10 December 2008) and cycle 24 (11 December 2008 to 31 March 2020). The present study indicates that sunspot number activity dominates in the southern hemisphere during the solar cycles 22 and 23, while during the solar cycle 24, the sunspot number becomes dominant in the northern hemisphere. It is also revealed that the magnitude of sunspot number activity for solar cycle 23 is more prominent in both the northern and southern hemispheres than in solar cycles 22 and 24. The power spectrum of daily sunspot numbers shows several significant periodicities in a wide range between 26 days and 83 days. We discuss the possible explanations of the observed periodicities and north-south asymmetry of the daily sunspot number in light of previous results and existing techniques.

Keywords: *N-S asymmetry: periodicity: daily sunspot number*

1. Introduction

The non-uniform distribution of solar activity over the northern and southern hemispheres of the Sun, which is apparent in long-term observations, is attributed to N-S asymmetry.

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The north-south asymmetry is one of the significant characteristics of solar activity. Thus N-S asymmetry is an intensively studied phenomenon. Many solar activity indices are investigated over a period of time to know the proper behavior of N-S asymmetry. Some of the essential features considered have been: the sunspot number and sunspot area [1-13], the solar flares and flare index [14-18], and the solar active prominences [19,20].

The most important aspect before analyzing the action of N-S asymmetry is to determine the statistical significance of N-S asymmetry of the time series data under consideration. The best way of evaluating the statistical significance of north-south asymmetry (SSNSA) is binomial distribution [6,8,13,21-24]. However, Vizoso and Ballester [1], Carbonell et al. [2], and Carbonell et al. [8] have utilized excess test to acquire the SSNSA of sunspot area.

Visoco and Ballester [1] examined the N-S asymmetry of the sunspot area from 1874 to 1976, concluding that it is a real phenomenon rather than random fluctuations, and the statistical significance and statistical independence of the sunspot area to other asymmetry signals. Carbonell et al. [8] used various statistical methods to determine the statistical significance of N-S asymmetry in various solar activity time series data (SN, SA, SAP, X-ray flares, flare index and magnetic flux density). They discovered that there is a real and significant asymmetry between the hemispheres.

Temmer et al. [7] identified significant N-S asymmetry using a data catalog of hemisphere sunspot numbers spanning the entire six solar cycles (1945-2004). They examined the hemispheric asymmetry in the context of rotational behaviors in the northern and southern hemispheres and presumed that the magnetic field systems in the two hemispheres are weakly coupled. Ahluwalia and Ygbuhay [12] analyzed the hemisphere SSNs throughout five solar cycles (19-23) and discovered that SH becomes increasingly active during solar cycles 22 and 23.

Periodic fluctuations in sunspot activity indices can last from a few days to several years; the best-known oscillations are the 27-day (short term) and 11-year (long term). The modulation of solar activity features caused by solar rotation and solar magnetic activity is responsible for these periods. Various investigations have been performed to examine the presence of intermediate or mid-range periodicities in different characteristics of the active Sun that lie between 27 days and 11 years [25-29]. A significant area of research is the quest for the other feasible midrange periodicities in solar activity indicators, as any periodicity detection may provide some insight into understanding the dynamics of solar plasma.

Many authors have additionally searched for midrange periodicities during solar cycle 19-23 and observed various variations, such as 78, 84, 127, 83, 64, 129, 230, 295, 330, 392 days in different phases of different solar cycles with different solar parameters [30-32]. A systematic analysis of the N-S asymmetry of daily SN during the period 1992-2020 in the current study examines its statistical significance and searches for short-term and midrange periodicities using the Fast Fourier Technique. The periodic variation of the daily SN for the entire disk of the Sun is studied separately for solar cycles 22, 23 and 24.

2. Data and analysis

2.1. The sunspot numbers. For the current study, we have used daily sunspot numbers (SSNs) data for three consecutive solar cycles 22, 23 and 24. The data for the period of 01 January 1986 to 31 March 2020 has been downloaded from http://www.sidc.be/silso/datafiles.

During this period, 1799 days are spotless, which is discarded from the study. Therefore, the study contains 8519 data points. The temporal evolution of daily SSNs during solar cycles 22, 23, and 24 is plotted in Fig.1. In this figure, variation of solar activity during three solar cycles is clearly shown by the solid smoothed spline curve, which corresponds to a 91-days running average value of SSN. The plot shows that during cycles 22 to 24 level of

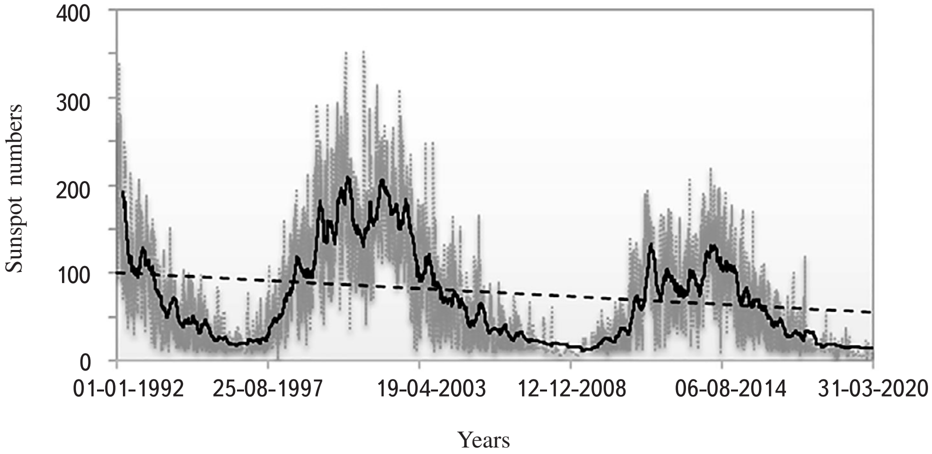

Fig.1. Variation of total SSNs for the daily time series during 1992 to 2020. The solid line shows the smoothed curve of activity. Whereas the dashed trend line shows the nature of activity during three cycles.

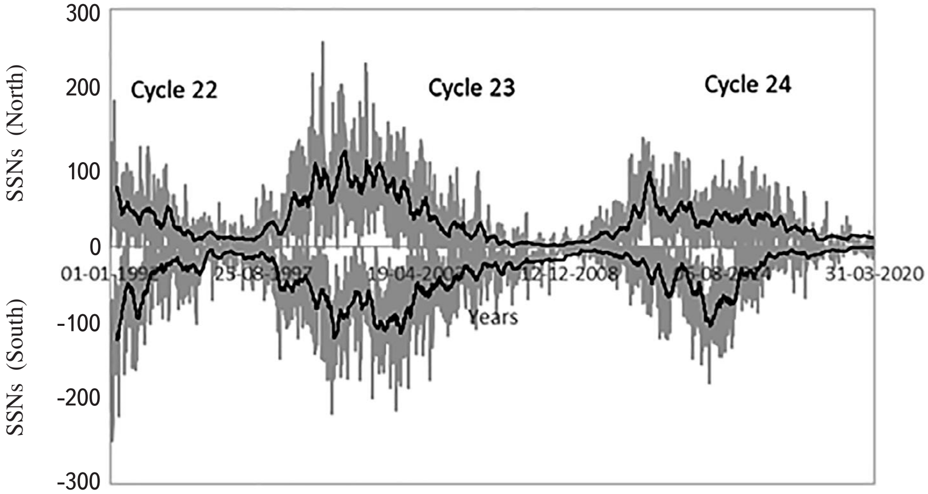

Fig.2. Evolution of northern and southern hemispheric SSNs during solar cycles 22, 23 and 24. The smoothed curve in each hemisphere indicates a 91-days running average of activity.

activity reduces (cf., dashed straight trend line which corresponds to the fit of the first-order polynomial). The plot further clearly indicates that Gnevyshev-Ohl (G-O) rule was violated for the pair of cycles 22/23. The G-O rule states that the sum of sunspot numbers over an odd cycle exceeds that of the preceding even cycle [33]. With the exception of the pair of cycles 4/5, this relationship held until cycle 21 [28]. The evolution of SSNs in the northern and the southern hemispheres during solar cycles 22, 23, and 24 is presented in Fig.2.

Fig.2 shows periodic variation in hemispheric sunspots. This behavior is similar to Fig.1. The northern and the southern hemispheres plots of SSNs clearly indicate the existence of hemispherical asymmetry in the occurrence of sunspots.

2.2. Scrutiny of asymmetry time series. A prominent index of different solar activity features is SSN and these solar activity features are not symmetrically distributed in the northern and southern hemispheres. To perform the statistical analysis of SSNs, we have calculated the N-S asymmetry index for SSNs, defined as

$$ASY_{SSN} = \frac{SSN_N - SS_S}{SSN_N + SS_S}, \tag{1}$$

where SSN_N and SSN_S stand for the daily SSN in the northern and southern solar hemispheres, respectively. Thus, if $ASY_{SSN} > 0$, activity in the northern hemisphere dominates, and if $ASY_{SSN} < 0$, the reverse is true. The above expression gives us an asymmetry time series composed of 8519 values as spotless days were excluded from our study. The total

TABLE 1. Total Number of SSNS in the Whole Disk, in the Northern and Southern Hemisphere, Asymmetry Index, Dominanat Hemisphere, and Corresponding Percentage Values

Solar cycles	Sunspot numbers (SSNs)			Asymmetry	Dominant
	NH (%)	SH (%)	Total		Hemisphere
Solar cycle 22 (01/01/1992-27/08/1996)	46333 (44.19)	58512 (55.81)	104845	-0.116	SH
Solar cycle 23 (28/08/1997-10/12/2008)	173849 (46.81)	197576 (53.19)	371425	-0.064	SH
Solar cycle 24 (11/12/2008-31/03/2020)	103855 (52.16)	95233 (47.83)	199088	0.043	NH

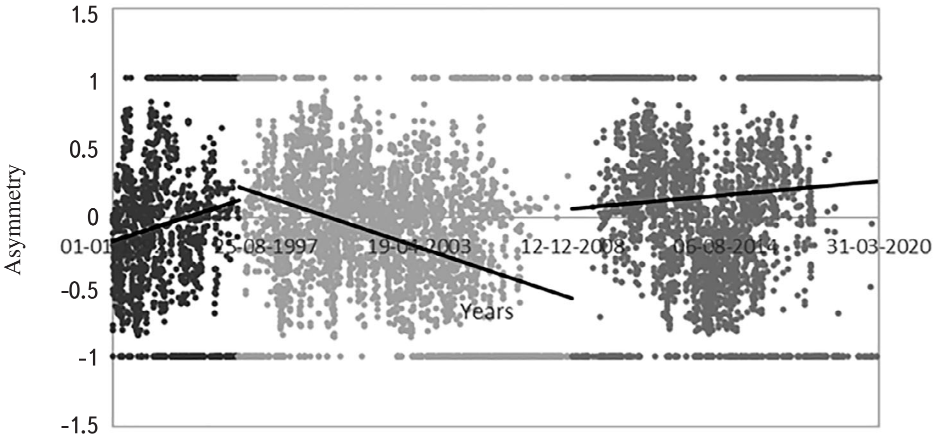

Fig.3. The plot of the daily values of asymmetry time series during solar cycles 22, 23 and 24. The straight line corresponds to the fit of the first-order polynomial.

SSNs, the hemispheric SSNs, N-S asymmetry index, and the dominant hemisphere for the solar cycles 22, 23 and 24 are presented in Table 1.

In Fig.3, the plot of the daily asymmetry time series is presented. To show the reality of the variations of asymmetry time series, we have fitted a straight line to the daily values of ASY_{SSN} for each cycle separately.

To evaluate the statistical significance of our data, two statistical tests (viz., Binomial distribution & Excess) are applied for the daily asymmetry time series data of SSNs. The obtained results are shown in Table 2, and applied statistical tests are described as follows:

1. Binomial distribution: The binomial formula [34] can be utilized to compute the probability of getting any specific distribution of n objects into two classes, when the considered time series data are integers. The two classes correspond to the north and south hemispheres, so the binomial formula is

$$P(r)=\frac{n!}{r!(n-r)!}\,p^{r}(1-p)^{n-r}\ ,$$

TABLE 2. Asymmetry Time Series Analysis of the Number of Data Pointe and their Percentage According to Binomial Distribution and Excess Methods

Methods	Highly significant	Significant	Marginally significant	Insignificant
Binomial distribution	5898 (69.23%)	616 (7.23%)	377 (4.43%)	1628 (19.11%)
Excess	5496 (64.51%)	697 (8.18%)	637 (7.48%)	1689 (19.83%)

where n is the number of objects in both the classes and the probability $P(r)$ of getting r objects in class one and (n-r) objects in other classes. The probability of getting more than d objects in class one is given by

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

In general, when $P(\geq d) > 10\%$, implies a statistically insignificant result, when $5\% < P(\geq d) < 10\%$, it is marginally significant, when $1\% < P(\geq d) < 5\%$, it means a statistically significant result and when $P(\geq d) < 1\%$, a highly significant result. Here, n is the total SSNs, referred to the northern hemispheric SSNs and imposing p equal to 0.5, outcomes show that, for daily asymmetry, $P(\geq d) < 1\%$ in 5898 cases, $1\% < P(\geq d) < 5\%$ in 616 cases, $5\% < P(\geq d) < 10\%$ in 377 cases and $P(\geq d) > 10\%$ in 1628 cases, indicating that 81% of the cases, the asymmetry of daily SSNs has been statistically significant during solar cycle 22 to 24.

2. Excess: The excess [35], which is an approximation to compute $P(\geq d)$ to be proportional to the uncertainty, is measured as $d\,(n/2)^{-1/2}$, where d is the positive difference of SSNs between the two hemispheres and n is the total SSNs corresponding to both hemispheres. In general, when Excess < 2 it implies $P(\geq d) > 10\%$, 2 < Excess < 3 implies $5\% < P(\geq d) < 10\%$, 3 < Excess < 4 implies $1\% < P(\geq d) < 5\%$ and 4 < Excess implies $P(\geq d) < 1\%$. So, for Excess approximation, we found that 5496 cases are highly significant, 697 cases are significant, 637 cases are marginally significant, and 1689 cases are insignificant in all 8519 cases. This indicates that 80% of the cases, the asymmetry of daily SSNs has been statistically significant during solar cycles 22-24.

2.3. Power spectra of asymmetry time series. To perform power spectral analysis, we have split the data into three parts corresponding to the period of solar cycle 22 (01 January 1986 to 27 August 1996), cycle 23 (28 August 1996 to 10 December 2008), and cycle 24 (11 December 2008 to 31 March 2020). For periodic analysis of these data sets, FFT is applied separately for solar cycles 22, 23, and 24. The data sets are analyzed for the period interval of 25-100 days. The power spectra is shown for the solar cycle 22 (Fig.4a), solar cycle 23 (Fig.4b) and solar cycle 24 (Fig.4c). These figures present three short-term periodicities for all three cycles. The periodic fluctuations between power and frequency of daily SSNs have been studied using Fast Fourier Transform (FFT).

3. Discussions and conclusion

In this paper, the daily time series data of sunspot numbers and hemispheric sunspot numbers are used to analyze the asymmetric behavior, and short-term periodicity during solar cycles 22, 23, and 24. To analyze the N-S asymmetry of SSNs, the daily N-S asymmetry index is calculated using equation (1), and then the mean value of the asymmetry index is computed. The mean values of the asymmetry index for solar cycles 22, 23, and 24 are

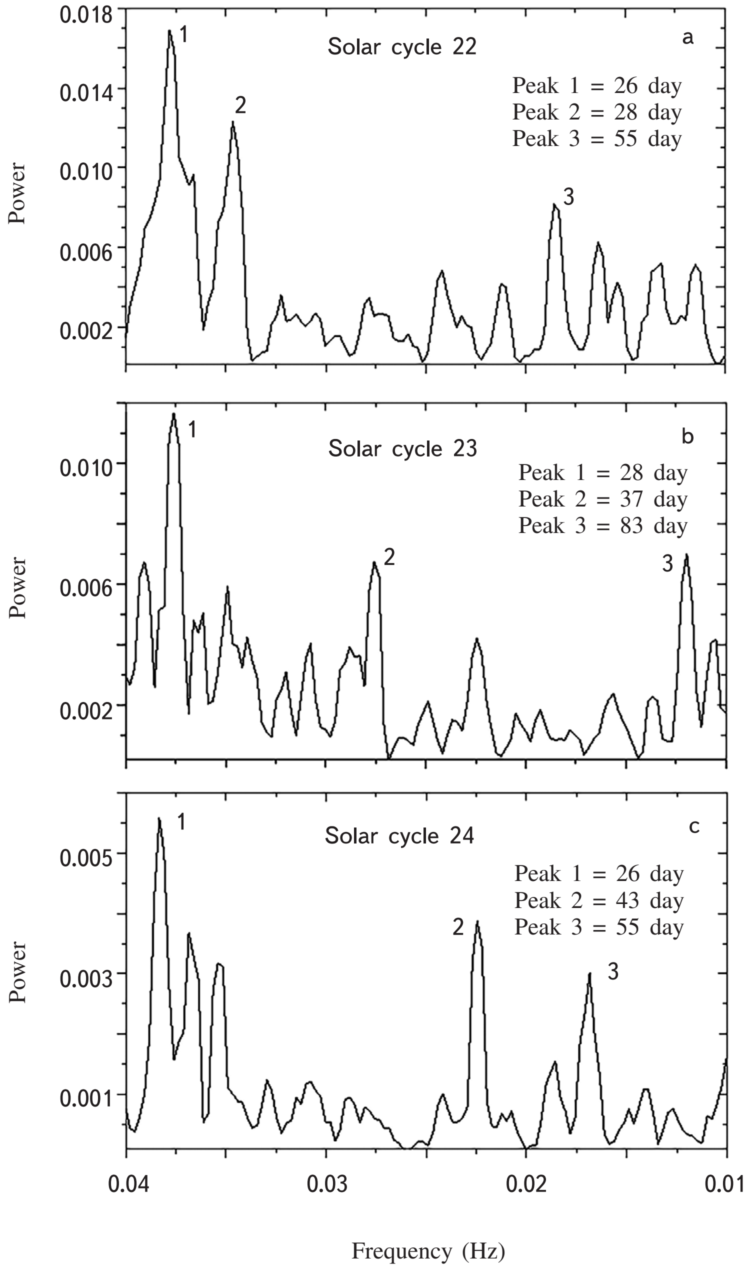

Fig.4. Power spectra of daily sunspot number for a) solar cycle 22, b) solar cycle 23, c) solar cycle 24.

-0.116, -0.064, and 0.043, respectively (Table 1). Based on these mean asymmetry index values, we can conclude that during solar cycles 22 and 23, the sunspot number activity is southern dominated, and during solar cycle 24, it is northern hemisphere dominated. On the other hand, we have shown a plot of the fitted straight line (Fig.3) for the variation of the daily N-S asymmetry index ASY_{SSN} from 01 January 1992 to 31 March 2020. This indicates that daily

Sunspot number activity is found to be asymmetrically distributed in the northern and southern hemispheres during solar cycles 22-24 [4,7,8,13,15]. The present study also concluded that the magnitude of sunspot number activity for solar cycle 23 is larger in both the northern and southern hemispheres compared to the solar cycles 22 and 24 (Fig.2).

The statistical significance of our data has been checked in two ways: The first utilizing computing the actual probability of obtaining the observed results or one having a larger difference due to chance, say $P(\geq d)$, which is based on the binomial formula. The second is by means of the Excess, which measures the significance of d in terms of the uncertainty. These two statistical tests indicate that in more than 80% of the cases, the asymmetry of the daily SSNs has been statistically significant from 1992 to 2020 (Table 2).

In this investigation, the short-term periodicities of daily sunspot numbers are investigated for the total disk of the Sun during solar cycles 22, 23, and 24 separately. For the spectral analysis, the FFT is separately applied to the data sets. The sunspot numbers display several significant periodicities between 26 and 83 days. The power spectra of daily sunspot numbers for the solar cycle 22 (Fig.4a) represents a high power density of 26 days (peak 1), 28 days (peak 2), and 55 days (peak 3). It represents periodicities of daily sunspot numbers for solar cycle 22, and during this period, the sunspot number is highly dominated activity within the period of 25 days to 100 days. It indicates that it is repeated within 25 days to 100 days. Whereas for solar cycle 23 (Fig.4b) three significant periodicities of 28 days (peak 1), 37 days (peak 2), and 83 days (peak 3) are observed. Similarly, three significant periodicities of 26 days (peak 1), 43 days (peak 2), and 55 days (peak 3) are detected for solar cycle 24 (Fig.4c). The periodicity of 26 to 28 days is more stable than other short-term periodicities in all solar cycles. A stable 27-day period with a variation of 21 to 35 days is detected for the daily sunspot numbers covering solar cycles 12 to 23 [36]. A significant short-term period fluctuation of 26 to 36 days is examined in daily sunspot number data for the solar cycle 23 [37]. Joshi et al. [30] found a strong periodicity of 85 days in SSN for solar cycle 23, although changes of length and amplitude in periodicity are exhibited in other solar cycles. Apart from this prominent periodicity, our study also shows other notable short-term periodicities in all data sets.

The above discussion shows that our findings are quite consistent with the previous results of different solar activity indices reported by several researchers. However, none of the researchers worked on the daily time series data of sunspot numbers during solar cycles 22 to 24 separately. Our findings show that it is difficult to provide an exact value or duration of each short-term periodicity due to their time-variable characteristics. This may be the fundamental explanation for why some authors have noticed variations in the indices of solar activity of different periodic lengths at different time intervals. These phenomena demonstrate that solar activity is very complex, and the solar periodicity issue is still open and needs to be studied deeply. For future work, it is essential to combine these complicated phenomena with other indices of solar activity to analyze them.

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