Signature of the 27-day Variation in Hemispheric Sunspot Activity and Asymmetry during 2010-2015

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Abstract In the present work, we study the time evolution, the significance of the N-S asymmetry excesses presented as a function of the solar cycle and the prominent rotational periods (~27 days) separately for the northern and southern hemisphere. We have investigated short-term variations of the hemispheric solar activity (sunspot numbers and sunspot areas) during the time period of 2010-2015, which covers the ascending and the maximum phase of solar cycle 24. We have implemented the Lomb-Scargle periodogram and continuous wavelet transforms power spectrum techniques to study the time evolution and dominant rotational periods separately for the northern, southern hemisphere, and whole solar disk. Our results showed that the northern hemisphere exhibited longer solar synodic periods than the southern hemisphere, indicating that; northern hemisphere has a lower rotation rate. Moreover, the northern hemisphere was found to be dominant before transferring to the southern hemisphere during mid-2013. Also, the sunspot areas have much apparently demonstrated the two-peak structure of the solar activity in northern and southern hemispheres respectively during 2012 and 2014. The statistical significance of the southern hemisphere showed enhanced excess during the maximum phase of solar cycle 24.

Key words: Sunspots, Sunspot Area, Asymmetry, Solar cycle

1 INTRODUCTION

Numbers of sunspots observed on solar disk are the longest observational solar data set used to explore the solar activity and its temporal variations. Such variability is represented by various indices such as sunspot numbers, the 10.7 cm solar radio flux, sunspot areas, X-Ray Emission from the Solar Corona, and solar flare indices, etc. All these indices show periodic variations over days to years (Chowdhury et al., 2013; Hathaway, 2015; Kilcik et al., 2018; Singh et al., 2019a, 2019b and references therein). The most significant periods are 11-year solar cycle variation and Bartels rotation (Bartels, 1934) of 27 days. The significant periodicity (27-day) of solar activity represents the solar rotational period, which is related to the dynamo effect on the
The periodic behaviours of the hemispheric data of solar activity (sunspot number and sunspot area) are manifestations of the processes governing the solar rotational phenomena. The 27-day solar rotational period and its subharmonics is also detected in galactic cosmic ray and geomagnetic index time series with high amplitude (Poblet, and Azpilicueta, 2018; Chowdhury and Kudela, 2018; El-Borie et al., 2019). This ~27 day period is known to be related primarily to the large-scale solar magnetic fields (Balthasar and Schüssler, 1984). The solar activity has been investigated for a long time, considering the Sun as a single object. This approach allowed solar physicists to attain the basic features of the solar cycle. Gradually, however, it became evident that the northern and southern solar hemispheres are not identical as they do not exhibit similar behavior all the time. These hemispheric differences are usually known as the north-south (N-S) asymmetry.

Several manifestations of solar activity have been previously investigated to study the north-south (N-S) asymmetries revealing that it is a fundamental characteristic of solar activity. Various solar activity indices such as sunspot number, solar flares, filaments, prominences, radio, and gamma-ray bursts, coronal emission, solar magnetic fields, and others are utilized to analyze the asymmetry phenomena (Waldmeier, 1971; Howard, 1974; Rušin, 1980; Swinson et al., 1986; Carbonell et al., (1993); Knaack et al., 2004; Gigolashvili et al., 2005; Oliver and Ballester, 1994; Ataç and Özgüç, 1996; Li et al., 2009, 2010; Temmer et al., 2006; Chowdhury et al., 2013; Javaraiah, 2016, 2019; Leussu et al., 2017; Chowdhury et al., 2019; Singh et al., 2019b).

White and Trotter (1977), observed the asymmetry of the solar magnetic field cycle in the sunspot area in northern and southern hemispheres of the Sun. Vizoso and Ballester (1990), reported some common features in the behavior of N-S asymmetry in various forms of solar activity such as sunspots, flares, and sunspot area. Carbonell et al. (1993), examined north-south (N-S) asymmetry and found it was statistically highly significant in sunspot number and area. The hemispheric asymmetry of the solar activity phenomenon is considered as an essential aspect of the solar dynamo action, which in turn is a subject matter of research as it holds the key to understand the very origin of the solar cycle and activity. Several models to understand solar dynamo have been developed (Antonucci et al., 1990; Pulkkinen et al., 1999; Temmer et al., 2002; Charbonneau, 2020). Chowdhury et al. (2013), investigated the solar dynamo process using a non-linear dynamo model in view of north-south asymmetry observed in different solar indices.

The objective of the present work is to study temporal variation in the sunspot activity of the Sun at the time scale of the solar rotation period. Daily data on sunspot numbers and areas during the ascending phase (including maximum phase) of solar cycle 24 (2010-2015) for northern, southern, and the full solar disk have been examined. Spectral and statistical analysis is employed for this investigation.

2 METHODS AND DATA ANALYSIS:

In the present study, we have used the time series data of daily sunspot numbers and areas separately for northern, southern, and for the whole solar disk, from January 1, 2010, to December 31, 2015, that includes ascending and maximum phases of solar cycle 24. The time series of sunspot number is provided by http://sidc.oma.be/silso/newdataset while the data of the sunspot area is downloaded from https://solarscience.msfc.nasa.gov/greenwch/daily_area.txt.

The daily sunspot number and sunspot area for northern, southern, and the entire solar disk separately are used to investigate the asymmetry and the periodicities present therein. The periods are inferred through the Lomb-Scargle periodograms and continuous wavelet transformation analysis method. Also, the periodic variations of the north-south (N-S) asymmetry of the sunspot numbers and areas are studied. Periodic variations of solar activity evolve in a complex wave-like function and it exhibit asymmetry in both the hemispheres. In this study,
the periodicities around and below ∼27-day period are defined as the short-term periodicities, and only those detected periods that are above the 95% confidence level are taken into account.

As has been found that the asymmetry based on the absolute asymmetry (N-S) is enhanced near the cycle maximum (Temmer et al., 2006) and the solar activity would dominate typically in the hemisphere where the maximum sunspot group number is the largest (Li et al., 2002), we have used in this study the daily value of sunspot number and area of N-S hemispheres for calculating absolute asymmetry for each year during maximum phase of solar cycle 24. The absolute asymmetry index (A), chosen to prevent the presence of spurious periods in the spectrum (Ballester et al., 2005), is determined as:

Absolute Asymmetry (A) = N – S \hspace{2cm} (1)

where N and S, are representing either the sunspot number or the sunspot area, as the case may be, in the northern and southern hemisphere of the Sun. If absolute asymmetry A>0, northern hemisphere dominates, and if A<0, southern hemisphere dominates. In this study, we used the periodic behavior of absolute asymmetry, instead of the normalized asymmetry. As mentioned in Ballester et al. (2005), the periodicities obtained by normalized asymmetry are misleading as they change the general shape of the power spectrum due to the presence of (N+S) in the denominator.

Here, we apply paired Student’s t-test and the significance of the asymmetry. The test statistics t is given as:

\begin{equation}
    t = \frac{\overline{D}}{S_{\overline{D}}} = \frac{\left(\frac{\sum D_i}{n}\right)}{\sqrt{\left(\frac{\sum D_i^2}{n(n-1)}\right)}}
\end{equation} \hspace{2cm} (2)

where Di is the difference between a northern and southern hemisphere of sunspot area and number, \(\overline{D}\) mean of n differences and \(S_{\overline{D}}\) is the standard deviation for n-1 degree of freedom, n is the number of pairs in northern and southern hemispheres of the Sun. We consider preselected error probability (\(\alpha\)) = 0.05, i.e. the difference between northern and southern hemispheres of sunspot area and number is statistically significant with a 95% level (Temmer et al., 2002 and 2006; Chowdhury et al., 2013). We used a 95% significance monthly value which is plotted to northern and southern hemispheres (Fig. 9a and 9b).

2.1 Lomb–Scargle Periodogram:

We have used the Lomb–Scargle periodogram technique which is an appropriate algorithm for the analysis of unequally spaced data. The Lomb–Scargle periodogram is an important time–frequency analysis to be obtainable by the statistical analysis of a time series (Lomb, 1976; Scargle, 1982). This periodogram technique is useful to assess the statistical confidence by computing the false alarm probability (FAP). For a time series \(X_i = X(t_i), i=1,2, ..., N\), this periodogram can be defined as a function of frequency \(\omega\) as (Lomb, 1976, Scargle, 1982):

\begin{equation}
    P_N(\omega) = \left(\frac{1}{2\sigma^2}\right) \cdot \left\{ \frac{\left[\sum_{i=1}^{N}(X_i\overline{X}) \cos \omega(t_i\tau)\right]^2}{\sum_{i=1}^{N} \cos^2 \omega(t_i\tau)} + \frac{\left[\sum_{i=1}^{N}(X_i\overline{X}) \sin \omega(t_i\tau)\right]^2}{\sum_{i=1}^{N} \sin^2 \omega(t_i\tau)} \right\}
\end{equation} \hspace{2cm} (3)

where \(\overline{X} = \frac{1}{N} \sum_{i=1}^{N} (X_i)\) and \(\sigma^2 = \frac{1}{N} \sum_{i=1}^{N}(X_i-\overline{X})^2\) are respectively the mean and the total variance of the time series and the time shift interval \(\tau\) is defined by the relation:

\begin{equation}
    \tan(2\omega\tau) = \frac{\sum_{i=1}^{N} \sin 2\omega t_i}{\sum_{i=1}^{N} \cos 2\omega t_i}
\end{equation} \hspace{2cm} (4)
2.2 Continuous wavelet transformation:

The temporal evolution of the detected periods is estimated by using continuous wavelet transforms technique. The continuous complex Morlet wavelet transformation function is used with $\omega_0 = 6$. In this technique the thin black contours within a cone of influence (COI) show the periods above 95% confidence level (Torrence and Compo, 1998):

$$\psi_\eta(\eta) = \pi^{1/4} e^{i\omega_0 \eta} e^{\eta^2/2}$$

where $\omega_0$ is a non–dimensional frequency and $\eta$ is the Fourier time period.

3 RESULTS:

Presented in figures 1 to 8 are the short-term variations around the solar rotational cycle (27-day) of sunspot numbers and areas for northern, southern, and whole solar disk, and their absolute asymmetry. It is easily seen that each figure comprises of 4 panels. The upper panel (a) displays the time profile of the daily time series (in red) under investigation for the time span of 2010-2015. As the daily data are highly fluctuated, the 30-day moving average data are also plotted (in black) in the same panel to highlight the trend and the general behavior of the data. It enables us to easily associate the data with the phase of solar activity. The 30-day moving average shows a double-peak structure during ascending phase of solar cycle 24. In the middle row, the wavelet power spectrum (WPS) and the global wavelet spectrum (GWS) are shown in the two panels (b) and (c), respectively. The lowermost panel of each figure represents the normalized Lomb-Scargle periodogram (LSP). Both spectral methods are displayed in the period range 16-36 days only, as the present study concerns primarily with period at $\sim 27$ day. The subharmonics (not shown here) of this period were found to be not significant. The red-dashed lines in panels (c) and (d) indicate the 95% significance level estimated respectively by the red noise and the false alarm probability.

The detected periodicities that are above the 95% confidence level are taken into account and inserted in each figure by both methods i.e., WPS and LSP. In WPS, periodicities with a 95% confidence level are the dark region areas surrounded by solid curves. The GWS is the wavelet power at each period-scale averaged over time and similar to the Fourier spectra. The advantage of combining these two methods, where the LSP gives a precise estimate for each spectral peak, the wavelet analysis specifies where this peak takes place. Both spectral methods reveal periods close to the synodic period as described below.

Figures 1 and 2 represent the sunspot number and area respectively for the northern hemisphere. In Figure 1b, we observed contours for periods between 16-32 days extending first from Feb 2011-October 2011 and then from April 2012-May 2013. However, periods between 25-30 days are sporadically found between September 2013 and late 2016. The corresponding GWS of SSN shows a prominent peak at 26.6 days (Fig. 1c). In figure 2b, periods between 16-36 days persist from Feb 2011-March 2012, and periods between 16-32 days during Jan-April 2013. However, periods between 20-30 days prevail periods during Oct 2013-Jan 2014, between 19-35 days during May-June 2014, and between 16-34 days during April-July 2015. The corresponding GWS of SSA shows the dominant period at 26 days (Fig. 2c). Both figures 1d and 2d indicate a significant period at 28.2 days for sunspot numbers and areas for northern hemisphere as indicated by LSP method.

Similarly, figures 3 and 4 depict, in turn, the sunspot number and area for southern hemisphere. In Figure 3b, periods between 22-34 days show prominence during April-July 2012, while those between 16-35 days during June-Dec 2014. The corresponding GWS shows the dominant period at 26.5 days (Fig. 3c). In figure 4b, periods between 16-34 days show prominence during July 2012 and Dec 2013-Jan 2014. Also, periods between 16-36 days are observed during May 2014-Dec 2014. The corresponding GWS shows the dominant period at 27 days (Fig. 4c). The
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Fig. 1 (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily SSN (northern hemisphere) during 2010-2015.

Fig. 2 (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily SSA (northern hemisphere) during 2010-2015.

LSP method (Fig. 3d and 4d) detected the significant periods at 27.2 and 27.1 days for SSN and SSA, respectively.

Likewise, figures 5 and 6 display the SSN and SSA for the full solar disk. The activity of whole disk (SSN and SSA) provided information different than that for the northern or southern hemispheres. In figure 5b, we see a period contour between 18-33 days becoming prominent during 2012. Similarly, periods between 20-35 days attain significance during April-Nov 2014, whereas another group of periods between 22-34 days during May-July 2015. The corresponding GWS shows the dominant period at 26 days (Fig. 5c). In figure 6b, periods between 22-32 days are significant during June 2012 and those between 16-32 days during Dec 2013-Jan 2014. Two
periods between 16-32 days are found during April-July 2014 and those periods between 16-36 days during Sept-Dec 2014. The corresponding GWS shows the dominant period at 26.6 days (Fig 6c). Figures 5d and 6d reveal close significant periods at 26.1 days and 26.2 days for SSN and SSA, respectively by LSP method.

The spectral analysis of the absolute asymmetry for SSN and SSA is shown in Figures 7 and 8. The absolute asymmetry as estimated by equation (1) displays the daily variation of sunspot numbers and area in the time interval 2010-2015 in Fig 7a and 8a. The variation of northern hemisphere is dominant up to 2012, while southern hemisphere during 2013-2015. Also, the periodic variations of the absolute north-south (N-S) asymmetry of the sunspot numbers and
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Fig. 5  (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily SSN (full solar disk) during 2010-2015.

Fig. 6  (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily SSA (full solar disk) during 2010-2015.

areas are studied. Several contours between 16-35 days are dominant during the years 2011, 2012, 2013, and 2014 (Fig. 7b). The corresponding GWS shows significant periods at 27.6 days (Fig. 7c). In Fig. 8b, periods between 16-33 days are significant during mid-2012 and between 16-32 days during Nov 2013-Jan 2014. Two periods between 16-32 days are observed during April-June 2014 and those during 16-36 days during August to Dec 2014. The corresponding GWS shows the dominant period at 29.4 days (Fig 8c). The LSP method of absolute asymmetry for SSN and SSA exhibits periodicity at 26.1 days and 26.2 days, respectively (Fig. 7d and 8d).
Fig. 7 (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily absolute asymmetry of SSN during 2010-2015.

Fig. 8 (a) daily time profile (in red) and 30-day moving average data (in black), (b) wavelet power spectrum, (c) global wavelet spectrum, and (d) Lomb periodogram for daily absolute asymmetry of SSA during 2010-2015.

In Figures 9a and 9b, the cumulative values before the transition phase between northern to southern hemisphere show maximum spacing present in both solar activity parameters SSN and SSA. The cumulative analysis of sunspot number and area during the maximum phase of solar cycle 24 confirm that northern hemisphere dominance at the rising phase of the cycle, after transition phase southern hemispheric dominance. The cumulative analysis of northern and southern hemispheres of sunspot number and area shows that the transition phase occurs in mid of 2013 which is clearly visible in Figures 9a and 9b. Thus, the Gnevyshev gap provides physical information about the solar activity is a superposition of northern and southern hemispheres.
The paired Student’s t-test is applied to determine the significance of the difference between the northern and southern hemispheres of sunspot numbers and areas. In Tables 1 and 2, the result of the Student’s t-test is given as the percentages of significant months concerning
the total number of months during the period 2010-2015. The percentage of total months with significant asymmetry for sunspot area to be 66% and for sunspot number is 50%. The northern and southern hemispheres of sunspot number and sunspot area is monthly significant value is similar for the period 2011 and 2014 by the method of Student’s t-test. The monthly significant value of southern hemisphere is three times the northern hemisphere in the period 2013, (see Table 1 and 2).

Table 1: The 95% significant monthly value of N-S asymmetry (sunspot number) with subdivided into the northern (N) and southern (S) hemisphere is representing as a percentage for the maximum phase of solar cycle 24 (2010-2015) is given for sunspot number by paired Student’s $t$-test.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Months (%)</th>
<th>Months–N(%)</th>
<th>Months–S(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>50</td>
<td>50</td>
<td>Nil</td>
</tr>
<tr>
<td>2011</td>
<td>91.67</td>
<td>91.67</td>
<td>Nil</td>
</tr>
<tr>
<td>2012</td>
<td>50</td>
<td>33.33</td>
<td>16.67</td>
</tr>
<tr>
<td>2013</td>
<td>66.67</td>
<td>16.67</td>
<td>50</td>
</tr>
<tr>
<td>2014</td>
<td>91.67</td>
<td>Nil</td>
<td>91.67</td>
</tr>
<tr>
<td>2015</td>
<td>50</td>
<td>33.33</td>
<td>16.67</td>
</tr>
</tbody>
</table>

Table 2: The 95% significant monthly value of N-S asymmetry (sunspot area) with subdivided into the northern (N) and southern (S) hemisphere is representing as a percentage for the maximum phase of solar cycle 24 (2010-2015) is given for sunspot area by paired Student’s $t$-test.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Months (%)</th>
<th>Months–N(%)</th>
<th>Months–S(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
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</tr>
<tr>
<td>2011</td>
<td>75</td>
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<tr>
<td>2015</td>
<td>75</td>
<td>41.67</td>
<td>33.33</td>
</tr>
</tbody>
</table>

4 DISCUSSION AND CONCLUSION:

The results of the present study indicate that different features of periods are seen when the activity of the northern and southern hemispheres are considered separately (sunspot numbers and areas), and also across the whole solar disk as one. Figures 1-8 clarify that the southern and northern hemisphere does not exhibit similar rotational period variation during the time under investigation. As can be seen, for the northern hemisphere the power is mostly centered at $\sim$28.2 days, whereas for the southern hemisphere it is mostly centered at $\sim$27 days.

Chowdhury et al. (2015) observed quasi-periodic variations in the frequency range 10 to 100 days during the ascending phase of the solar cycle 24. Their analysis revealed that the synodic solar rotation was present in almost all important parameters like the sunspot number/area, solar radio flux (F10.7), geomagnetic activity index $A_p$, interplanetary magnetic field ($B_z$), and Average Photospheric Magnetic Flux. In fact, they ascribed the significant periods in the range of 20–31 days mainly to solar rotational period and its harmonics. In another study by Singh and Badruddin (2019), the presence of sub harmonics of fundamental period (solar rotation period $\approx$27 days) in the interplanetary electric field ($E_y$), southward component of a magnetic field.
field \((B_z)\), and geomagnetic index \((AE)\) was shown. It was reported that the sub harmonics might appear simultaneously with the primary period of \(\sim 27\) days depending upon the strength of the source that contributed to these subharmonics. In a recent study, Xiang et al. (2020), reported the presence of a dominant rotational period of 27.4 days in interplanetary magnetic field as inferred from the analysis of the daily values of \(B_x\), \(B_y\), and \(B_z\) components for the period 1967 January 1 to 2018 December 31. Interestingly, all the periods observed in \(B_y\) were not seen in \(B_x\), revealing a complex relationship between the two.

Consequently, these rotational periods are evidence of a strong asymmetry in both sides of the solar equator. It is the highest power that appears around the rotational period of the Sun, and it is clearly around the maximum phase of the solar cycle 24. This rotational property manifests a strong asymmetry concerning the solar equator, whereas the peak is very strong. The study reveals that the periodic variations of northern and southern hemispheres of the Sun show a kind of asymmetrical behavior.

Furthermore, these figures demonstrated that solar cycle 24 shows pronounced double peaks connected with solar activity maximum in the photosphere. It is evidence for the generation of a non-symmetric magnetic field in solar hemispheres. The first maximum exists due to the activity peak in the northern hemisphere, and second is in the southern hemisphere. The second maximum was observed to be higher than the first and occurred after a change in sign of the polar magnetic field and the mean time interval between these two peaks is about 2.5 years. This interval between two-peak structures is called the Gnevyshev gap which provides physical information about the solar activity is a superposition of northern and southern hemispheres (Gnevyshev, 1967).

Fig.7a and 8a show, the variation of northern hemisphere is dominant up to December 2012, but southern hemisphere over 2013-2015. Swinson et al. (1986b), observed the N-S asymmetry of sunspot area and sunspot number, and they reported that the northern hemisphere activity peaks about two years after the sunspot minimum. Dominance of northern hemisphere activity at the beginning of the cycle and southern hemisphere dominance after the maximum phase of the cycle has been seen and reported earlier (Singh et al., 2019a). This asymmetry flips its direction every solar cycle, which directly revealing a connection to the Hale (22-year) solar magnetic cycle (Zieger and Mursula, 1998; Mursula and Zieger, 2001).

From Fig. 9a and 9b, the circle part shows the change of phase from northern to southern hemisphere in terms of SSN and SSA, in turn representing excess of magnetic flux in the later part of the solar cycle. The magnetic activity of the Sun is generally known to be originating from the magnetic dynamo in the base of the solar convective zone (Pulkkinen et al., 1999). Solar magnetic activity manifests itself differently in each hemisphere and is controlled by differential rotation and meridional circulation in each hemisphere. The temporal asymmetry of meridional flow will also play a key role in the hemispheric asymmetry (Chowdhury et al., 2013).

From Tables 1 and 2, we have found that above \(\sim 66\%\) and \(\sim 50\%\) of the monthly N-S asymmetry value with a 95% significant level, of sunspot area and sunspot number respectively during the period 2010-2015. According to this result, solar activity during the period 2010-2015 is non-symmetric for northern and southern hemispheres. The existence of N-S asymmetry has been established in solar activity phenomena. Our results support the study of Li et al. (2009), and Chowdhury et al. (2013), where the southern hemisphere dominance was observed after the transition phase.

The northern hemisphere displays an increased level of solar activity (sunspot numbers and areas), during Jan 2010 to May 2013. From May 2013 to May 2015, the asymmetry becomes negative i.e. southern hemisphere increases in the maximum phase of solar cycle 24. It is very much clear that the northern and southern hemispheres individually do not exhibit the same behavior as described in the north-south (N-S) asymmetry. The N-S asymmetry occurs in the maximum phase of solar cycle 24, before the reversal of the magnetic field. Vernova et al. (2002), reported that the change of dominant activity of northern maximum to southern maximum is connected with each other.
In our results, the asymmetrical distribution of the solar activity phenomenon represents an important clue of the solar dynamic action. Generally, the solar activity proceeds independently in each hemisphere and is governed by the laws of differential rotation as well as the meridional flows in both hemispheres (Balogh et al., 2015). Gigolashvili et al. (2003), proposed that each hemisphere has its rotational rate which is related to the N-S asymmetry of solar activity. Georgieva and Kirov (2003), also indicated that the variations of the rotational traces have different periodicities for each hemisphere. Hazra and Nandy (2019), made an attempt to explain the hemispheric asymmetry as a nonlinear coupling between the dipolar and quadrupolar components of the solar magnetic fields and indicated that parity of the Sun and hemispheric asymmetry is closely related.

The analysis of the rotational behavior for each hemisphere is of particular interest, since it is closely linked to the evolution of magnetic fields and solar dynamo. In this sense, the rotational period of the photospheric magnetic field is investigated during solar cycle 21, where it was found each hemisphere has different periods; hence a weakly coupled magnetic field is suggested between the two hemispheres. Moreover, the rotational behavior and magnetic fields originating in the two hemispheres provide strong evidence for the existence of non-symmetric solar activity (Autonucci et al., 1990). Temmer et al. (2002), revealed the same results when concerning the study of solar flares and sunspot numbers, concluding a strong correlation of the rotation of the sunspots with the large-scale magnetic fields. In this regard, it is to be emphasized that the N-S asymmetry is largely affecting many manifestations of solar activity such as the different rotational behavior of activity proxies in each hemisphere and the preference of one hemisphere over the other.

The reversal of the polar magnetic field during the solar cycle 24 is investigated by many studies which give inconsistent results. For instance, Gopalswamy et al. (2016), reported that the reversal in the southern hemisphere took place during June 2014 and in the northern hemisphere around October 2012. While, multiple reversals are observed in the northern hemisphere completed by Jun 2012, and only a single reversal in the southern hemisphere was found from Jan 2013 to November 2014 (Janarhan et al., 2018). Such unusual delayed and prolonged reversal by more than 2 years is attributed to faster meridional flow speed in the north than the south. Also, Svalgaard and Kamide (2013), suggested that the occurrence of multiple peaks associated with different polar reversal times is considered as an intrinsic property of the solar cycle. Moreover, they attributed the asynchronous reversal of the Sun’s polar field as a consequence of the N-S asymmetry of solar activity.

To conclude, the study shows that the periodic variations of the solar rotational period (~27 days) in the northern and southern hemispheres of the Sun show a kind of asymmetrical behavior. The value of synodic solar rotation is very consistent with the result in (Xiang et al., 2020, and references therein). The rotational nature of northern and southern hemisphere is relevant, and it is interconnected to the solar dynamo and the magnetic fields generation. The peak value (maximum) of northern and southern hemisphere does not reach simultaneously. It is a shift of several months (approximately 30 months). The peak of sunspot number and area (a combination of the northern and southern hemisphere) gives a shift of several months is a well-known Gnevyshev gap. Besides, the study of solar activity asymmetry imposes limitations on the theories of a solar dynamo to be able to explain the presence of severe N-S asymmetry in the observation of solar activity as well as in the rotational behavior and the weak coupling between the two hemispheres.
References


