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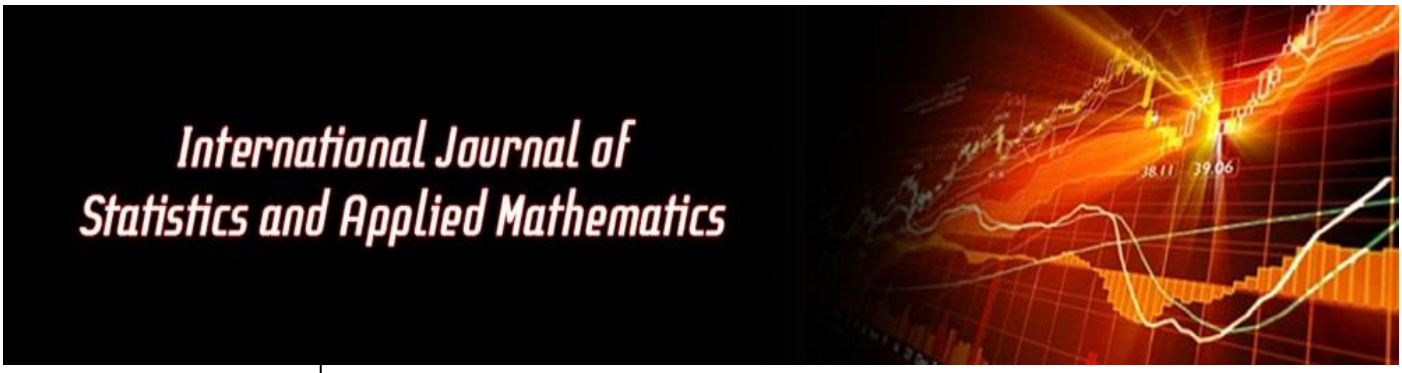

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Periodicities in sunspot numbers using Morlet wavelet function

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Abstract
We present an analysis of various periodicities in sunspot numbers (SSNs) during Solar Cycles 23 and 24. To identify these periodicities, we applied wavelet analysis method using the Morlet wavelet function. Our results reveal short-term periodicities corresponding to solar rotation, primarily in the 25 to 36-day range, with prominent periods of 25, 27, and 28 days. Additionally, Rieger-type periodicities of 112, 129, 131, and 192 days were detected during both cycles. We also identified intermediate-term periodicities of 263, 290, and 313 days; quasi-biennial oscillations of 528 and 798 days; and longer-term periods of 3.15 and 3.4 years. Our findings suggest that most of these periodicities occur either during solar maxima or during periods when the respective solar activity features were at their peak frequency.

Keywords: Sunspot number, periodicity, morlet wavelet function, short term period, rieger type periodicity

Introduction
The periodic phenomena in solar activity features are correlated with periodic variations in the solar magnetic field generated by the solar dynamo (Pesnell, 2015) [49-50]. The polarity of the Sun's magnetic field undergoes a periodic reversal every 22 years, forming what is known as the solar magnetic cycle. However, the most widely recognized cycle is the 11-year solar cycle, also referred to as the Schwabe cycle (Schwabe, 1843) [53]. These periodic variations influence all aspects of solar activity across timescales ranging from days to years (Nayar, 2006; Kilcik *et al*., 2010; Mendoza & Velasco-Herrera, 2011; Du, 2012; Zou & Li, 2014; Li *et al*., 2016, 2017) [39, 27, 36, 21, 65, 32, 33]. Short-term periodicity is generally 27-days periodicity obtained for short term data, which correspond to the Sun's rotation period. In contrast, midrange periodicities refer to cycles with durations longer than 27 days but shorter than 11 years (Bai, 2003) [4].

Numerous studies have previously investigated the periodicities of various solar activity features. For example, Rieger *et al*. (1984) [51] identified a 154-day periodicity in solar Soft X-Ray (SXR) flares. Various midrange periodicities such as 64, 78, 83, 84, 127, 129, 230, 295, 330, and 392 days have been identified across different solar activity features and solar cycles by several researchers (Bai & Sturrock, 1991, 1993; Ozguc & Atac, 1994; Lou *et al*., 2003; Atac *et al*., 2006; Chowdhury & Ray, 2006; Chowdhury *et al*., 2009; Mendoza & Velasco Herrera, 2011; Oloketuyi *et al*., 2019) [6, 7, 44, 35, 2, 15, 12, 36, 43].

These midrange periodicities are also observed in other solar phenomena, such as radio emissions (Das & Chatterjee, 1996; Zieba *et al*., 2001; De *et al*., 2014) [17, 64]. The periodic behavior of solar radio emissions at various frequencies, along with sunspot numbers, plays a crucial role in understanding solar magnetic activity. It also aids in analyzing periodicities in solar indices across different atmospheric layers and phases of the solar cycle (Zięba *et al*., 2001) [64]. According to Zięba *et al*. (2001) [64], in addition to the short-term 27-day rotation period, multiple other periodicities are linked to the Sun's rotation and the long-term 11-year magnetic activity cycle, which is associated with the emergence of strong magnetic fields in the photosphere.

(Lobzin, Cairns, & Robinson, 2012) [34]. Aroori *et al*. (2021) [1] conducted a time-series analysis of solar radio emissions and compared the results with daily sunspot number (SSN) data during Solar Cycle 23. Their study revealed solar rotational modulation periods ranging from 26 to 31 days across all observed radio frequencies as well as in the SSN data. The periodogram for SSN also showed the presence of Rieger-type periodicities (130-180 days), mid-term periods (300-400 days), and long-term periodicities ranging from 430 to 850 days.

From above discussion, it is evident that examining the sunspot number periodicities is crucial in understanding the magnetic behavior of the Sun. we therefore present here a study of periodicity in sunspot numbers during the solar cycles 23 and 24. Section 2 presents the Observations and methodology. In section 3, analysis and results are described. Section 4 contains the discussion and conclusion.

Observations and Methodology

In this study, we utilized time series data of daily International Sunspot Numbers (ISSN) spanning solar cycles 23 and 24. The dataset, covering the period from 1996 to 2019, was obtained from the Brussels World Data Center for Sunspot Numbers (SIDC), available at http://www.sidc.be/silso/datafiles. We took the solar cycle 23 and 24 combined for the determination of long periodicities in SSNs and hemispheric periodicity is determined for solar cycle 24.

We employed the wavelet analysis method to compare power distribution and identify periodicities within the time series. This technique is particularly effective for examining varying signals in both time and frequency domains. For this analysis, we used the Continuous Wavelet Transform (CWT) to detect localized and quasi-periodic oscillations, following the approaches of Grinsted *et al*. (2004) [22] and Singh & Badruddin (2014) [54]. The Morlet wavelet function was applied in the present study. The CWT of a signal x (t) is given by (Chui 1992) [16].

$$X\,(b,a) = |a|^{-1/2} \int_{-\infty}^{+\infty} x(\eta)\overline{\varphi}\left(\frac{\eta-b}{a}\right)d\eta \qquad (1)$$

Where, φ is the Morlet wavelet function, which is given by

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

This plane wave has a non-dimensional frequency of ω_0 and is modulated by a Gaussian wave. This indicates how frequently the periodicity inside the wavelet itself occurs. Here, ω_0 is taken as 6 (Oloketuyi *et al*., 2019; Grinsted *et al*., 2004; Torrence and Compo, 1998) [43, 22, 57]. This value of ω_0 provides an appropriate spatial and temporal resolution and significance level η (Fourier time period) as 1.033s, where s is Morlet time scale. Due to the suffering of edge artifacts, the wavelet is not fully localized. Therefore, we consider a cone of influence (COI) that defines the wavelet power for a discontinuity at the edges that drops by a factor of e^{-2} (Grinsted *et al*. 2004) [22]. According to Torrence and Compo (1998) [57] and Auchere *et al*. (2016) [3], the wavelet transform power's confidence levels are determined by the null hypothesis of the existence of global power spectrum. For this investigation, we have used a 95% confidence threshold.

Analysis and Results

We analyzed the total sunspot numbers to identify various periodicities, taking into account Solar Cycles 23 and 24. The following subsections present a detailed examination of the results.

Periodicities in Sunspot Numbers

We have plotted the wavelet power distribution spectrum in the left panel of Figure 1, where we have taken the daily time series data. We find that significant periodicities of 313 and 131 days are reflected. In the right panel of the Figure 1, the Fourier power spectrum is fitted to represent the mean power, which is then incorporated into the wavelet code to evaluate both local and global wavelet spectra, aiming to identify statistically significant values typically at the 95% confidence level (Auchère *et al*., 2016) [3]. In the wavelet power spectrum, prominent periodicities meeting the 95% confidence level are highlighted with circles. The cone of influence (COI), depicted as a black conical boundary in the figure, indicates the region where edge effects become significant and helps distinguish reliable contours from less prominent ones. We found a significant 27 day short term periodicity from the wavelet power spectrum. The contour areas expand at longer periods, indicating presence of longer periodicities and more intense contours represent greater physical significance in these regions. We found three prominent periods for SSNs taking solar cycles 23 and 24 together into account. Most significant period was found as 313 days. Rieger type periodicity of 131 days was also detected. We also observed the periodicity of 28 days which is corresponding to solar rotation period.

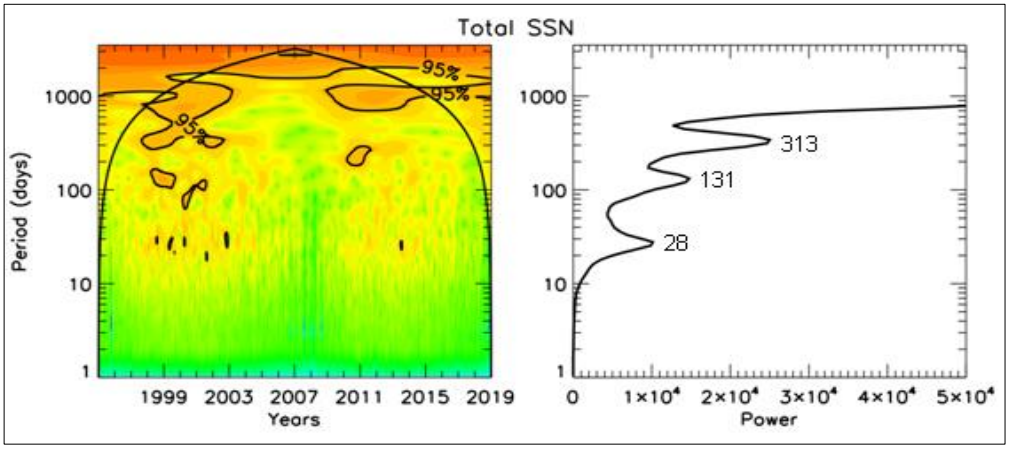

Fig 1: Wavelet power distribution is shown in the left panel for the SSN time series during cycle 23 & 24. Black curved line is showing the cone of influence to separate the edge effects. 95% confidence level is used to detect prominent contours in the spectrum showing significant periodicities. In the right panel, global wavelet power spectrum is plotted to show the significant periods.

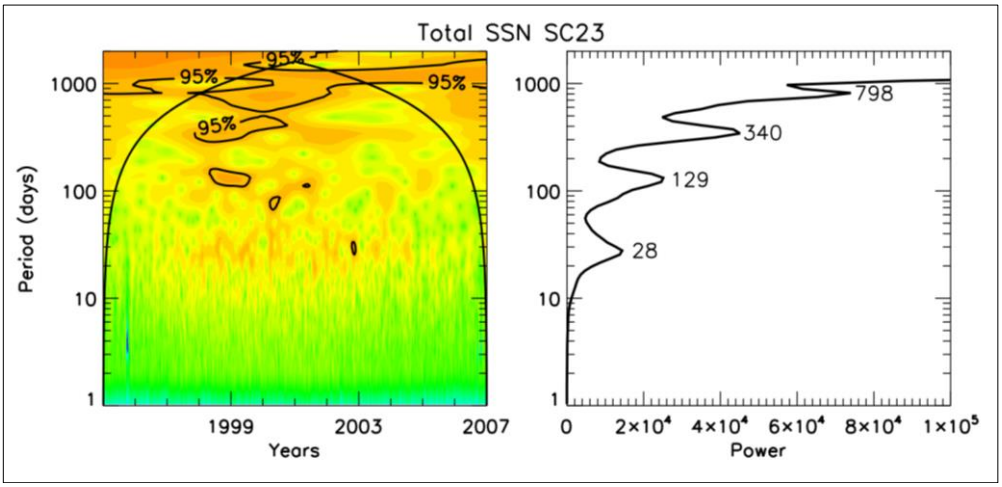

Fig 2: Wavelet power distribution is shown in the left panel for the SSN time series during cycle 23. In the right side of the panel, global wavelet power spectrum is plotted to show the significant periods.

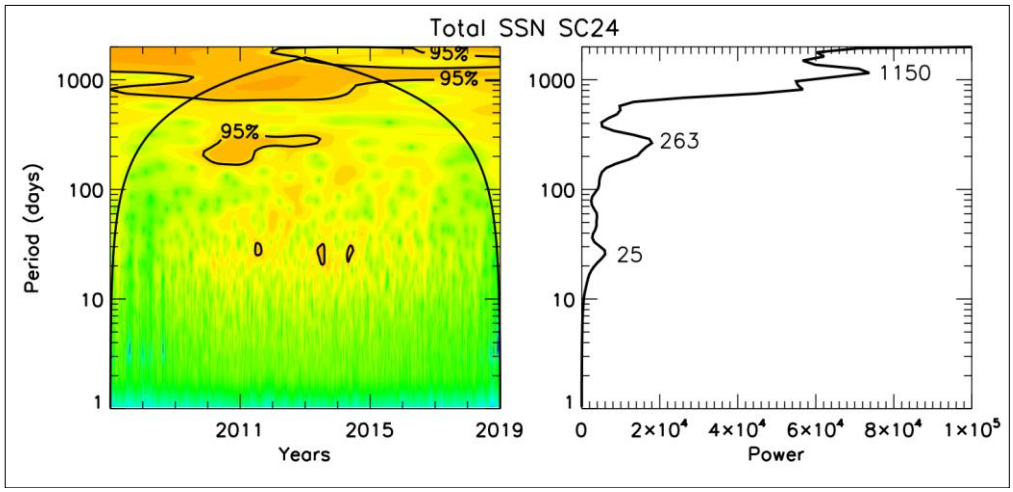

Fig 3: Wavelet power distribution is shown in the left panel for the SSN time series during cycle 24. In the right panel, global wavelet power spectrum is plotted to show the significant periods.

To find the periodicities in sunspot numbers during solar cycle 23 and 24 separately and to compare them with each other, we have plotted a wavelet time series power spectrum with an equivalent smoothed power spectrum showing the prominent periods in Figure 2 and Figure 3 respectively. We found a short term prominent periodicity of 28 days, a mid-term Rieger type periodicity of 129 days with two quasi-periods of 340 and 798 days during solar cycle 23. But in solar cycle 24, we got the 25 day periodicity for the SSNs with a high statistical significance. We got two more periodicities with periods of 263 and 1150 days. We inferred from the power distribution spectrum that 25 day periodicity repeats over the cycle. At first it was detected near mid-2011 then it was reflected back again in 2013 and 2014. The periodicity with 1150 days was highly prominent periodicity, which occurred between 2010 and 2015. Periodicity with a variation of 263 days is also significant frequency showing the occurrence during 2010 to 2012.

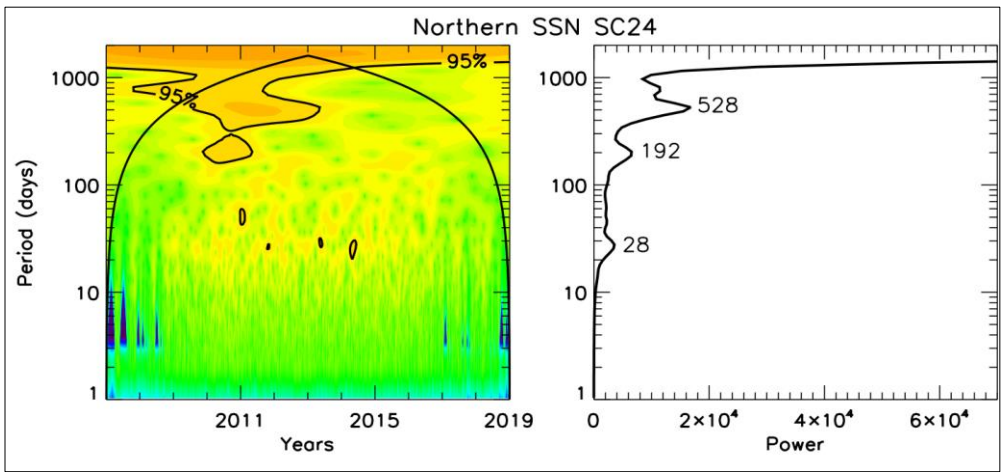

Fig 4: Wavelet power distribution time series is shown in the left panel for the SSNs located in northern hemisphere during cycle 24. In the right panel, global wavelet power spectrum is plotted to show the significant periodicities.

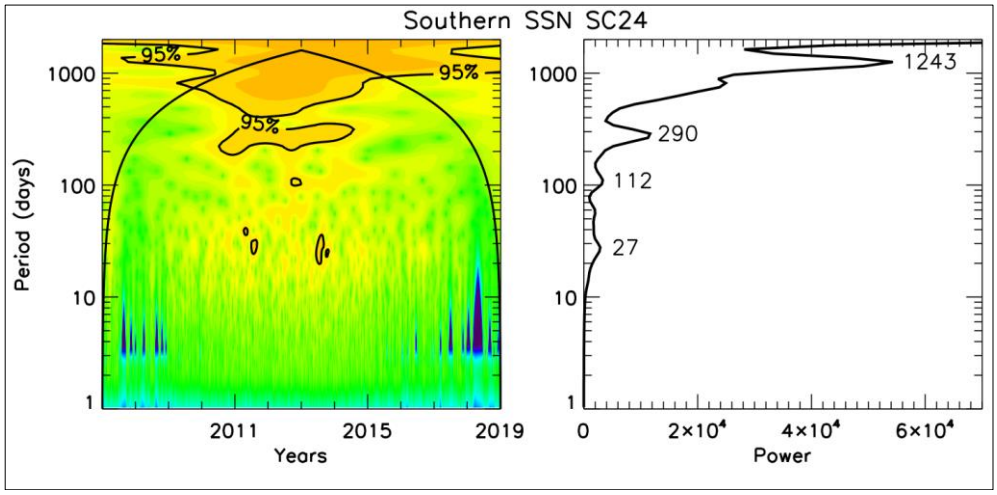

Fig 5: Wavelet power distribution time series is shown in the left side of this panel for the SSNs located in southern hemisphere during cycle 24. In the right side of the panel, global wavelet power spectrum is plotted to show the significant periodicities.

Periodicities in Northern and Southern hemispheres of sunspot numbers

Several solar activity features exhibit hemispheric asymmetry between the northern and southern hemispheres, and sunspot numbers are no exception. Variations in the periodicities of these solar parameters across the two hemispheres contribute to the observed north-south asymmetry (Carbonell *et al*., 1993; Oliver & Ballester, 1994; Ballester *et al*., 2005; Temmer *et al*., 2006; McIntosh *et al*., 2015; Chowdhury *et al*., 2019) [10, 41, 8, 56, 37]. Therefore, we aim to investigate the periodicities of SXR flares and sunspot numbers separately in each hemisphere.

In Figure 4, wavelet power spectrum of sunspot numbers (located in northern hemisphere) is plotted for solar cycle 24, where two plots are representing power distribution (left panel) and significant periods corresponding to peaks (right panel).

We observed that 28 day periodicity is reflected in the wavelet power spectrum periodogram. Another peak was obtained at 528 days in the global wavelet power spectrum, which shows the most intense peak compared to others in that periodogram, a Rieger type periodicity of 192 days was also found for the northern hemisphere located SSNs.

We applied Morlet wavelet function to get the periodicity in sunspot numbers located in southern hemisphere for the same cycle (Figure 5), and found that periodicity of 28 days in northern hemisphere is shifted to 27 days. In the northern hemisphere this period of 28 days was found in 2012, 2014 and 2015, while the period of 27 days is reflected in 2012 and 2014 in southern hemisphere. A periodicity of 290 days was found in southern hemisphere while it was not reflected in northern hemisphere. This periodicity was found between 2011 and 2015. A statistically significant period of 1243 days was exhibited by SSNs located in southern hemisphere, which was observed from early 2011 to 2015. A marginally significant period of 112 days was also found which was appeared in 2013.

Discussion and Conclusion

We had taken two solar cycles 23 and 24 for the study of periodicity exhibited by sunspot numbers. We obtained the periods of 25, 27 and 28 days in our results. Periodicities in the range of 27 days (25 to 36-days) are typically associated with the solar rotation period. Numerous studies have confirmed this periodicity across various solar features (Özgüc *et al*., 2004; Yin *et al*., 2007; Kilcik *et al*., 2010; Chowdhury *et al*., 2009, 2011) [12, 61, 27, 14, 11]. For instance, Bai (2003) [4] identified a 33.5-day periodicity during Solar Cycle 23.

A mid-range periodicity ranging from100 to 200 days is also detected in our study and these periods coincide with previous studies done. This falls in the category of famous Rieger type periodicity (Rieger *et al*., 1984) [51]. We observed the periods of 112, 129, 131 and 192 days for southern hemisphere located SSNs in solar cycle 24, total SSNs in cycle 23, total SSNs in cycles 23-24 and for northern hemisphere located SSNs in cycle 24 respectively. These Rieger type periodicities are found in other studies also during different solar cycles (Bogart and Bai, 1985; Bai and Cliver, 1990; Droge *et al*., 1990; Kile and Cliver, 1991; Joshi and Joshi, 2004; Kilcik *et al*., 2010) [9, 5, 20, 26, 24, 27]. Joshi and Joshi (2004) [24] found the periodicity of 161 days during their study of SXR flare indices for cycle 23. Bai and Sturrock (1991) [6] found the period of 129 days during their study in periodicity. Oloketuyi, *et al*. (2019) [43] also found the periodicity of 128 days while doing a study on SXR flares. Similarly Aroori *et al*. (2020) [1] found the several periodicities in this range (like 112, 131, 148, 164, 192 etc) during the study of SSNs and solar radio emissions for cycle 23.

We also found the periodicities of 263, 290 and 313 days, which are generally called intermediate periods. These periods are in well agreement with other studies done earlier (Lean and Brueckner, 1989; Pap *et al*., 1990; Oliver *et al*., 1992; Lou *et al*., 2003) [31, 48, 42, 35]. Aroori *et al*. (2020) [1] found the periodicities having periods of 239, 263, 269, 281, 316 and 317 etc, while investigating the same for SSNs and solar radio emissions. The category of annual period is also detected in our study for SSNs. The periodicity of 340 days was obtained in the study of SSNs during solar cycle 23 (daily time series). These periods are found by several authors during different cycles for different solar parameters (Pap *et al*., 1990; Oliver *et al*., 1992; Howe *et al*., 2000; Lou *et al*., 2003; Knaack and Stenflo, 2005; Aroori *et al*., 2020) [48, 38, 42, 23, 35, 29, 1].

The oscillations having periodicity of 28 or 29 months are called Biennial oscillations. The periodicities found near these periods are termed as quasi-biennial oscillations (QBO). We have taken the range of 1.5 to 2.5 years (~ 500 to 900 days) as QBOs. We found the periods of 528 and 798 days in northern hemisphere located SSNs for solar cycle 24 and total SSNs for cycle 23 respectively. We also found other long term periodicities of 3.15 (1150 days), 3.4 (1243 days) years for

sunspot numbers. All these are supported by previous studies (Nayar *et al*., 2002; Özgüc *et al*., 2002; Knaack *et al*., 2004; Lara *et al*., 2008; Katsavrias *et al*., 2012; Aroori *et al*., 2020) [40, 12, 28, 30, 25, 1].

In Figure 6, histogram of sunspot numbers is plotted to know about the occurrence rate. We compared the epoch of occurrence of periodicity with their daily occurrence rate. We found that the sunspot numbers (monthly power spectrum for cycle 23&24) show most significant peak of 313 days from1999 to 2003 and from Figure 6 we note that this is the duration of solar maximum for cycle 23. Maximum sunspot numbers are observed during this period. Another peak of 131 days is again found during this period only. Periodicity of 28 days is found in 2000, 2003 and 2014. It is to be noted that 2014 is the solar maximum period of cycle 24.

We found different type of periodicities like short term periodicity, Rieger type periodicity and quasi-biennial periodicity in our study. No complete physical interpretation is given by physicists till now. Bai and Sturrock (1991) [6], along with Sturrock and Bai (1992) [55], proposed the existence of a solar 'clock' with a fundamental period of 25.8 days, later revised to 25.5 days. They suggested that the well-known 154-day periodicity is a subharmonic of this base period, and that other periodicities such as 51, 78, 104, and 129 days are integer multiples of 25.5 days.

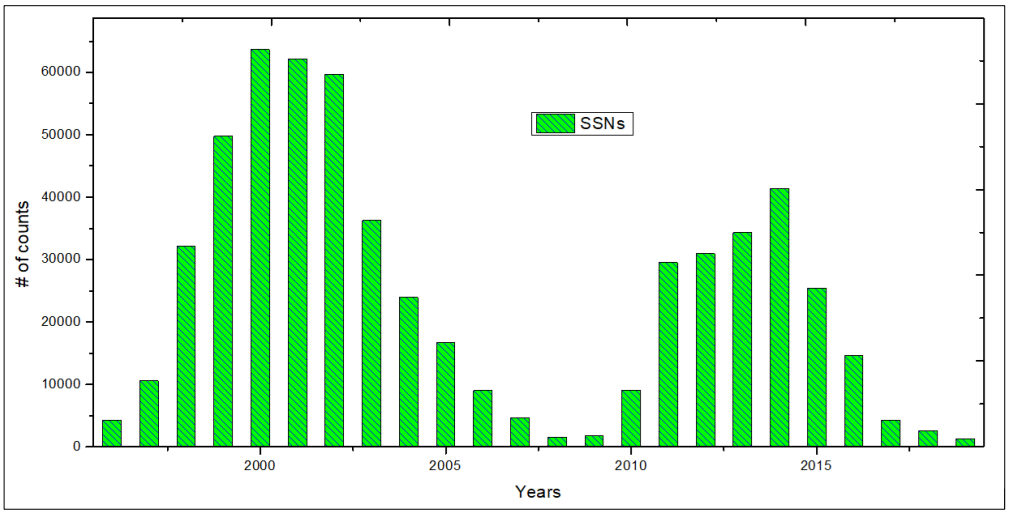

Fig 6: Histogram of SSNs during solar cycles 23 and 24.

Zaqarashvili *et al*. (2010) [62] attributed the origin of certain periodicities to magnetic Rossby-type waves (Rossby, 1939; Pedlosky, 1987) [62, 47]. These waves result from the combined influence of solar differential rotation and the strength of the toroidal magnetic field factors that play a crucial role in the solar interior dynamo and the quasi-periodic emergence of magnetic flux. The existence of such waves was later confirmed through observations of coronal bright points using data from the Solar Terrestrial Relations Observatory (STEREO) and the Solar Dynamics Observatory (SDO) (McIntosh *et al*., 2017) [38]. Now it is known that sunspots are carriers of strong magnetic field density. More sunspots mean more magnetic activity and periodicity in sunspots thus resembles the periodic change in magnetic activity in the Sun.

This study suggests that the periodicities observed in sunspot numbers are inherent solar phenomena driven by fluctuations in solar magnetic activity. These different ranges of periodicities typically appear and are most prominent during solar maxima or during the periods marked by heightened activity of the corresponding solar feature.

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