Study of sunspots and sunspot cycles 1–24

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Sunspots are the most obvious feature on the disturbed surface of the photosphere above the solar atmosphere and appear to play a key role in major solar and terrestrial disturbances. The solar source activity varies with a 11-year sunspot cycle. During solar activity maximum years, maximum transient solar activity (i.e. solar flares, solar proton events and coronal mass ejections) is released from the Sun and enters the earth's magnetosphere which is found to be responsible for producing large geomagnetic storms. In solar activity minimum years, a few geomagnetic storms are observed due to the presence of coronal interaction regions. We have studied the general characteristics of past solar cycles 1–23 and predicted about the present sunspot cycle 24. We conclude that sunspot cycle 24 is similar to sunspot cycle 22, peaking between September 2012 and February 2013. Solar maximum of sunspot cycle 24 may pose a great risk to satellite communication, space weather and result in geomagnetic hazards.

Keywords: Coronal interaction regions, coronal mass ejections, solar cycle, sunspot cycles.

SOLAR cycle prediction is a long-lasting interesting activity in the field of solar physics. Planning for satellite orbits and space missions often requires knowledge of solar activity levels years in advance. Association of solar cycle dependence on geomagnetic disturbance and geomagnetic hazards has been discussed earlier[1–4] on solar cycles 22 and 23. Many predictions for solar cycle 24 have been provided even before it started. Some of them were made during the ascending phase and the maximum period of solar cycle 23. Two basic classes of methods exist for the solar cycle predictions: the empirical methods and methods based on dynamo models[5]. The empirical methods[6] can be further divided into two subgroups, the statistical methods based on extrapolation[7] and precursor methods[8]. The other class of methods is based on various dynamo models[9–12], but can also be combined with some precursor features such as polar magnetic field of the Sun around the solar minimum[13].

Sunspots are magnetized cool spots in the solar photosphere, and are commonly formed in a group and a large group may contain as many as 350 or 400 spots of different size and may extend to a distance of about 3×10^5 km. The most rapid changes in the Sun's magnetic field occur locally in restricted regions of the magnetic field. However, the entire structure of the Sun's global magnetic field changes in a 11-year cycle. During the 11 years, the strongest magnetic fields slowly migrate towards the Sun's equator from locations about midway to the Sun's poles. The 11-year period is not constant, but varies between 9.5 and 12.5 years as discussed by Mursula and Ulich[14]. The position of the sunspots is not random. They first appear in the middle latitudes above and below the Sun's equator. After 11 years, when the next cycle begins, the magnetic field poles are reversed. The sunspot cycle is remarkable in its elegant complexity and regularity. The three major aspects of 11-year sunspot cycle are the 11-year period of sunspot number, the Hale–Nicholson law of sunspot polarity and the reversal of the general magnetic field. Schwabe[15] discovered the sunspot cycle, so it is also known as Schwabe cycle. The 11-year sunspot cycle is related to a 22-year cycle for the reversal of the Sun's magnetic field. Thus, the time required for the Sun to return to the same magnetic configuration of sunspots and polarities is 22 years, known as helio-magnetic cycle or Hale cycle. The Hale cycle is characterized by an opposite sign of the helio-magnetic north (south) pole. A longer 88-year cycle has been suggested. After 88 years, the same position of maximum sunspot number returns, known as 88-year Glienberg cycle. A recent theory claims that there are magnetic instabilities in the core of the Sun, which cause fluctuations with periods of either 41,000 or 100,000 years. These could provide a better explanation for the ice ages than the Milankovitch cycles[16]. The counting of the 11-year sunspot cycle was started in 1755 and the 23rd solar cycle has been completed. Recently the 24th solar cycle has started. In the 17th century, the solar cycle appears to have stopped entirely for several decades; very few sunspots were observed during this period. During this era, which is known as the Maunder minimum or Little Ice Age, Europe experienced very cold temperatures[17].

For solar observers and those who are concerned with forecasting of the solar-terrestrial environment, the end of a solar cycle and the anticipation of a new one brings a feeling of excitement along with some regret at the end of the era. We have studied the general characteristics of solar cycles 1–23. The International Sunspot Number data are taken from the National Geophysical Data Centre (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html). Table 1 gives a catalogue of sunspot cycles 1–23.

Several characteristics of sunspot cycles 1–23 are presented in Table 1. We find that the length of solar cycle, position of solar maxima of sunspot cycle from the beginning of sunspot cycle and maximum sunspot number differ from cycle to cycle. Some similarities are observed in particular sunspot cycles which is a good base for

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Table 1. Some properties of solar cycle 1–23

Solar cycle number	Starting of solar cycle (mm/yyyy)	Solar maximum (mm/yyyy)	Ending of solar cycle (mm/yyyy)	Maximum number of sunspots	Position of solar maxima (years)	Length of solar cycle (years)
1	3/1755	6/1761	5/1766	85.9	6.33	11.25
2	6/1766	9/1769	5/1775	106.1	3.33	9.00
3	6/1775	5/1778	8/1784	154.4	3.0	9.25
4	9/1784	2/1788	4/1798	132	3.5	13.67
5	5/1798	2/1805	7/1810	47.5	6.83	12.25
6	8/1810	4/1816	4/1823	45.8	5.75	12.75
7	5/1823	11/1829	10/1833	67	6.58	10.5
8	11/1833	3/1837	6/1843	138.3	3.41	9.67
9	7/1843	2/1848	11/1855	124.7	4.66	12.42
10	12/1855	2/1860	2/1867	95.8	4.25	11.25
11	3/1867	8/1870	11/1878	139	3.5	11.75
12	12/1878	12/1883	2/1890	63.7	5.0	11.25
13	3/1890	1/1893	12/1901	85.1	2.91	11.83
14	1/1902	2/1906	7/1913	63.5	4.16	11.58
15	8/1913	8/1917	7/1923	103.9	4.0	10.0
16	8/1923	4/1928	8/1933	77.8	4.75	10.08
17	9/1933	4/1937	1/1944	114.4	3.66	10.42
18	2/1944	5/1947	3/1954	151.6	3.66	10.17
19	4/1954	3/1957	9/1964	190.2	3.0	10.5
20	10/1964	11/1968	5/1976	195.9	4.16	11.67
21	6/1976	12/1979	8/1986	155.4	3.25	10.25
22	9/1986	7/1989	5/1996	157.6	2.91	10.0
23	6/1996	7/2000	9/2007	119.6	4.16	11.33

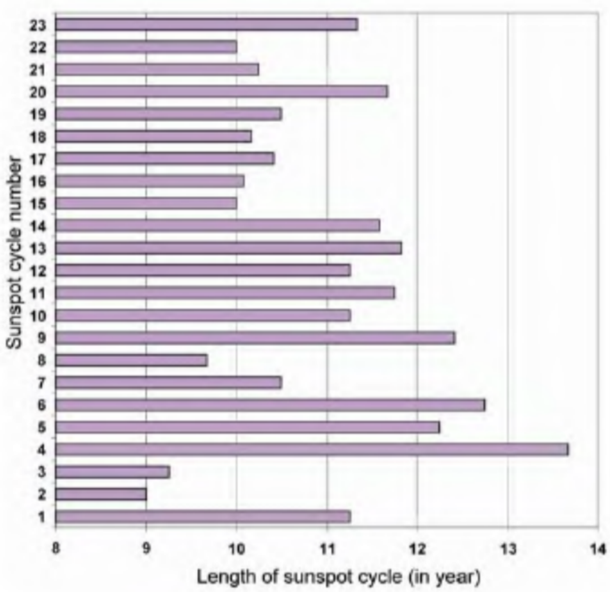

Figure 1. Length of sunspot cycles 1–23.

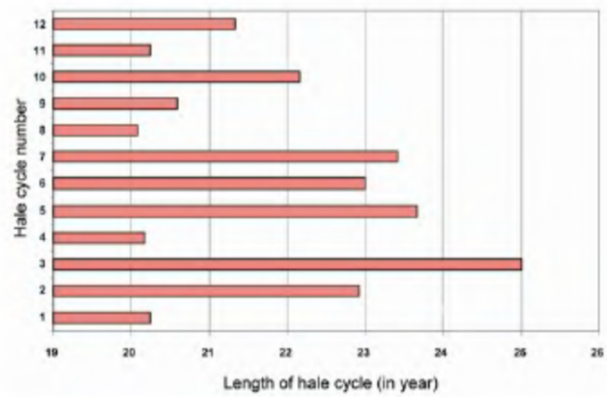

Figure 2. Length of Hale cycles 1–12.

prediction of future sunspot cycles. For predictions about the present sunspot cycle 24, we have performed various analyses. The variation in length of sunspot cycles 1–23 is shown in Figure 1. It is clear from this figure that the 11-year period is not constant, but varies between 9 and 13.67 years. We have also analysed variation of length of solar Hale cycle 1–12 (Figure 2). Figure 2 shows that the 22-year period (Hale cycle) is not constant, but varies between 20 and 25 years. Sunspot cycle 23 is similar to sunspot cycle 20 in the way it rises and falls. Sunspot cycle 20 took about four years to peak and about seven years to descend to its minimum. A major part of the sunspot cycle 23's most intense solar activity occurred 3.5–4.5 years after solar maximum. The sunspot cycles 17 and 20 reveal remarkable and intense solar activity in the late stages of both cycles. Sunspot cycles 17 and 20 are very similar in sunspot amplitude to sunspot cycle 23. Five of the top 20 A_p geomagnetic storms in the historical record occurred during an 18-month period in 1940–41. These occurred 3.0–4.5 years after the cycle 17 sunspot maximum in April 1937. The waning stages of sunspot cycle 20 are noted for the intense proton events of August 1972, and in 1973; there were 28 major flares, including two X9 flares. This high activity occurred approximately 3.5–5.0 years after sunspot cycle 20's sunspot maximum

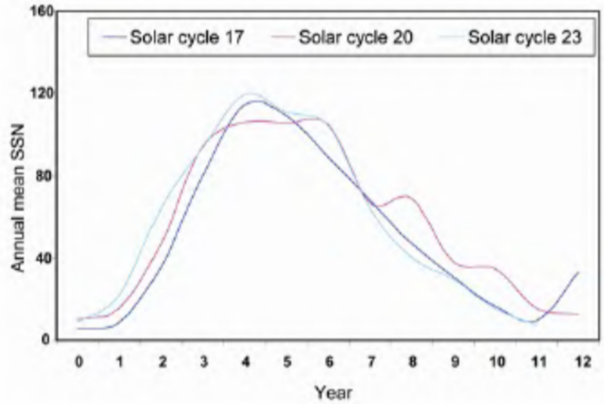

Figure 3. Development of 03 sunspot cycles 17, 20 and 23 during their first 11 years.

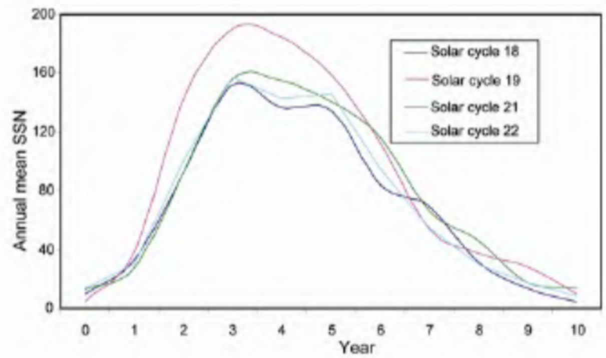

Figure 4. Development of last 04 solar cycles 18, 19, 21 and 22 during their first 10 years.

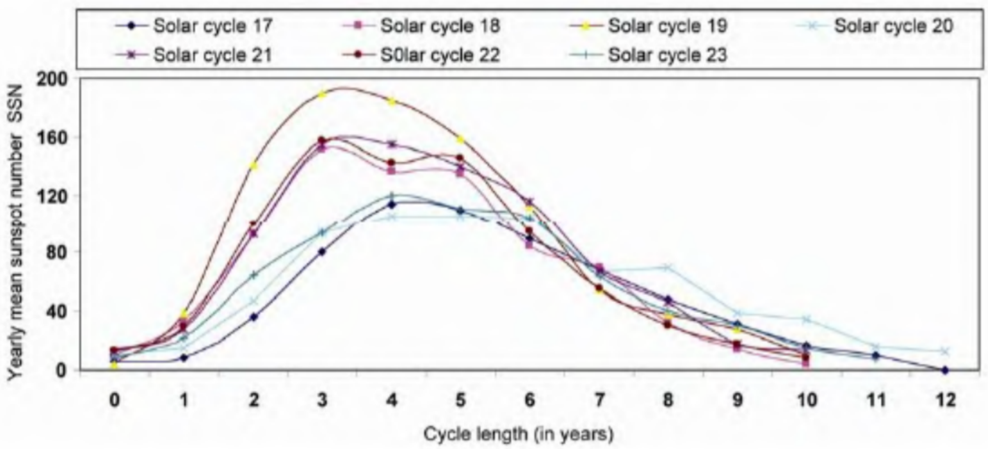

Figure 5. Development of sunspot cycles 17–23.

(November 1968). Figure 3 shows the development of above 03 sunspot cycles 17, 20 and 23 during their first 11 years. Sunspot cycle 23 has been significant even though it has not lived up to its predicted high sunspot number.

Sunspot cycle 22 has provided us with many highlights. Early in the cycle, the smoothed sunspot number climbed rapidly; in fact more rapidly than in any previously recorded cycle. This caused many to predict that it would eclipse sunspot cycle 19 (peak sunspot number of 201) as the highest peak on record. This was not to be as the sunspot number ceased climbing in early 1989 and reached a maximum in July of that year. Though it did not have high amplitude, sunspot cycle 22 is rated as the 4th best of cycle and continued the run of recent large sunspot cycles. Figure 4 shows the development of above 04 sunspot cycles 18, 19, 21 and 22 during their first 10 years. An important feature of solar cycle 22 was that it had the shortest rise from minimum to maximum.

Wang *et al.*[18] reported that the solar cycle 24 started between March and April 2008 and its maxima should occur during May–October 2012. We do not agree with these results. From the correlative study of solar cycles 17–23 (as shown in Figures 1–5 and from Table 1), sunspot cycle 24 is similar to sunspot cycle 22. From the calculation of the asymmetry of the ascending and descending phases of previous solar cycles, we can assess that the length of sunspot cycle 24 lies between 10 and 10.5 years and its maxima should come after 3 to 3.5 years of its starting. According to NASA scientists, a reversed-polarity sunspot appeared on 4 January 2008, signalling the start of sunspot cycle 24. But the data of monthly mean sunspot number have shown inverse results, during January 2008 to August 2009. During this 1.67 year interval, there were no fluctuations in monthly mean sunspot number and during August 2009, its value was zero. The occurrence of high solar activities during the decline phase of solar cycle 23 was the main reason for this phenomenon. On the basis of monthly mean sunspot data, solar cycle 24 starts from September 2009. The maxima of solar cycle 24 should be between September 2012 and February 2013. The predicted sunspot cycle 24 is shown in Figure 6. Solar maximum of sunspot cycle

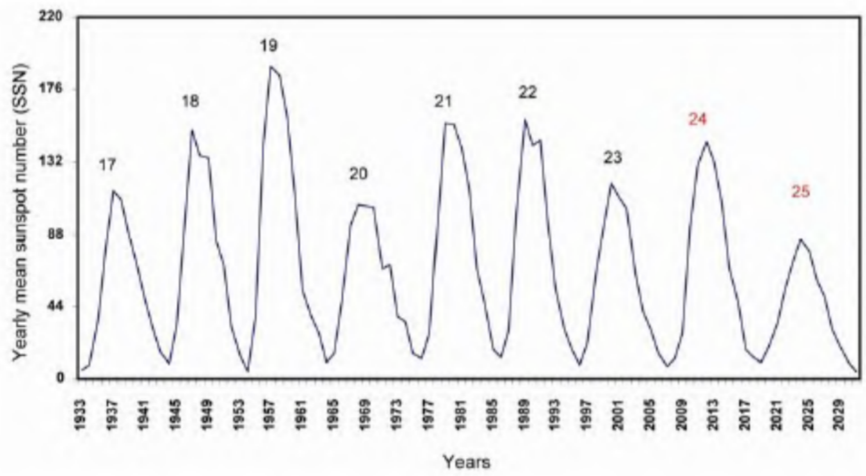

Figure 6. Development of sunspot cycles 17–23. Prediction of sunspot cycles 24 and 25 is also shown.

24 may pose great risk to GPS signals, power grids, cell phones, civilian and airline and military communications. Severe geomagnetic storms may occur in its maximum phase due to the late starting of solar cycle 24.

The Sun's great conveyor belt has slowed down to a record-low crawl, according to Hathaway[19]. This will have important repercussions on future solar activity. This belt is a massive circulating hot plasma within the Sun. It has two branches, north and south, each taking about 40 years to complete one circuit. Researchers believe that the turning of the belt controls the sunspot cycle. The conveyor belt moves about $1 \mathrm{~m~s^{-1}}$. In recent years, the belt has decelerated to $0.75 \mathrm{~m~s^{-1}}$ in the north and $0.35 \mathrm{~m~s^{-1}}$ in the south. According to theory and observation, the speed of the belt foretells the intensity of sunspot activity ~20 years in the future; Hathaway predicted that the sunspot cycle 25 peaking around the year 2022 could be one of the weakest in centuries. We agree with the above prediction and plot the sunspot cycle 25 on basis of different variation trends, as shown in Figure 6. NASA is gearing up to study the active Sun during the sunspot cycle 24 with the launch of a new spacecraft, the Solar Dynamics Observatory (SDO). SDO will join Solar and Heterospheric Observatory (SOHO), the Solar Terrestrial Relations Observatory (STEREO), Hinode and other missions already in orbit to improve our understanding of solar storms and lay the groundwork for better space weather forecasts.

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