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What does the Sun tell and hint now? *

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Abstract Some historical records, which have held since the beginning of modern solar activity cycles, are being broken by the present Sun: cycle 23 records the longest cycle length and fall time; latitudes of high – latitude sunspots belonging to a new cycle around the minimum time of the cycle are statistically the lowest at present, compared with those of other cycles; there are only one or no sunspots in a month appearing at high latitudes for 58 months, which is the first time that such a long duration has been observed. The solar dynamo is believed to be slowing down due to: (1) the minimum smoothed monthly mean sunspot number is the smallest since cycle 16 onwards, and even probably among all modern solar cycles; and (2) once the time interval between the first observations of two neighboring sunspot groups is larger than 14 d, it should be approximately regarded as an observation of no sunspots on the visible solar disk, called a spotless event. Spotless events occur with the highest frequency around the minimum time of cycle 24, and the longest spotless event also appears around the minimum time for observations of the Sun since cycle 16. Cycle 24 is expected to have the lowest level of sunspot activity from cycle 16 onwards and even probably for all of the modern solar cycles.

Key words: Sun: activity — Sun: general — sunspots

1 INTRODUCTION

Of all the kinds of phenomena associated with solar activity, sunspots are the most marked photospherical events that can be easily observed. The earliest sunspot record in the world is believed to have appeared in China on May 10 of the year 28 B.C., as recorded in a historical book from the Han Dynasty (Zhang & Li 1989). Sunspots were intermittently observed by telescopes just from 1610 on. The continuous routine daily observations of sunspots began in 1818, and from then on, observations of sunspots are relatively reliable (Hoyt & Schatten 1998; Li et al. 2004). In 1848, Wolf proposed a new concept, relative sunspot number (or sunspot number or Wolf number) to represent the amount of sunspots on the visible solar disk (Hoyt & Schatten 1998). The amount of sunspots has a close relationship with all other solar active phenomena. With the increasing number of sunspots, other solar active phenomena, such as faculae, plages, prominences, filaments, flares, burst frequencies and so on. The Wolf sunspot number can be used to represent the level of solar activity, thus becoming the most fundamental index, and it has been widely applied in solar physics and solar-terrestrial physics. Through the hard work of many solar physical scientists and geophysical scientists, the monthly mean sunspot number in the time

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interval of year 1749 to the present and the yearly mean sunspot number during the period of year 1610 up to now are available. However, the reliable time series of sunspot number is generally thought to start from solar cycle 10 and this is called the start of modern solar activity cycles (Wilson et al. 1996). The first measurement of sunspot area began at Greenwich Observatory in 1874, which appeared later than the observations of sunspot number. A reliable and continuous record of sunspot area is available since cycle 12. These observations are important for understanding the present Sun.

Solar activity impacts us in many ways. High levels of solar activity can produce solar energetic particle events and strong geomagnetic storms. These events and storms have the potential to cause satellite failure, power blackouts, and so on (Hathaway & Wilson 2004; Watari 2008), thus, it is necessary to know the present status of the Sun and compare it with historical observations of the Sun (Du et al. 2006a; Li et al. 2005). In this paper, we report what the present Sun tells and hints, and we find that the present Sun is breaking some historical records kept since the start of modern solar activity cycles, and so the "solar dynamo" is decreasing.

2 WHAT THE PRESENT SUN TELLS AND HINTS

The different sunspot activity time series analyzed in our study are:

– The first one: the observational data of sunspot groups, which come from the augmented Royal Greenwich Observatory (RGO) data set (the RGO data set extends from 1874 to 1976; thereafter, the observations are from NOAA) and are available at NASA's Web site[1]. The data set comprises sunspot groups during the period of 1874 May to the present (2009 June) and will be updated monthly. In the following, we use the data to count the monthly number of sunspot groups, and then they are smoothed with a 13-point running-average method.

– The second: the monthly mean sunspot number from 1874 June to 2009 June, which can be downloaded from NOAA's web site[2]. It is smoothed with a 13-point running-average method.

– The third: the monthly mean sunspot area (in the sunspot area unit, namely, ppm of the solar hemisphere) from 1874 June to 2009 June, compiled by D. Hathaway, which can be downloaded from NASA's web site. It is smoothed with a 13-point running-average method.

Shown in Figure 1 are the monthly number of sunspot groups, the monthly mean sunspot number, and the monthly mean sunspot area from 2008 January to 2009 June. Also shown in the figure are their corresponding smoothed values. As the figure shows, all of the three non-smoothed time series reach their minima in 2008 August, and all of the three smoothed time series continue to decline from 2008 June to 2008 December. So, the minimum time between cycles 23 and 24 should occur in 2008 December (indicated by a vertical dashed line in Figs. 2 to 4) or later (indicated by an interrogation mark in these figures). As this figure shows, the minimum smoothed monthly mean sunspot number is about 1.7 (or lower perhaps in the future) for cycle 24, which is the second smallest among the minimum number of smoothed monthly mean sunspot number of a cycle during the modern solar activity cycles (the lowest is 1.5 which occurred in cycle 15). There is a significant positive correlation between the minimum ($R_{\rm m}$) and maximum ($R_{\rm M}$) amplitudes of solar activity (Hathaway et al. 2002): $R_{\rm M} = 48.8 + 5.39 \times R_{\rm m} \pm 26.6$. We know at present that $R_{\rm m} \approx 1.7$, thus $R_{\rm M}$ for cycle 24 should be 58.0 ± 26.6 at the confidence level of 68%. Therefore, a rather low level of solar activity should be expected for cycle 24.

Cycle 23 began in 1996 May and reached its maximum in 2000 April, and now it is inferred to end in 2008 December (or probably later). Therefore, its length should be 12.6 yr (or longer), and its fall time, 8.7 yr (or longer). Such a cycle length is the longest cycle length, and such a fall time is the longest fall time for observations of the Sun since the start of modern solar activity cycles. The length of a cycle ($L(n)$ for cycle n) is a good indicator of the amplitude of solar activity in the next cycle ($R_{\rm M}(n+1)$), and there is a significant negative correlation between the two (Hathaway et al. 2002; Du et al. 2006b; Watari 2008): $R_{\rm M}(n+1) = -22.91 \times L(n) + 366.58$. Thus, $R_{\rm M}$ for cycle 24 should be 77.9 ± 23.7 at the confidence level of 95%, and a rather low level of solar activity should be expected for cycle 24.

[1] *http://solarscience.msfc.nasa.gov/greenwch.shtml*
[2] *http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html*

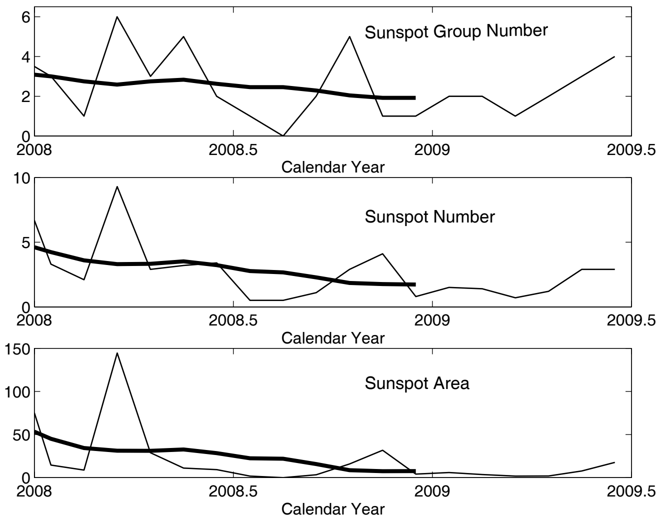

Fig. 1 Monthly number of sunspot groups (*thin solid line in the top panel*), the monthly mean sunspot numbers (*thin solid line in the middle panel*), and the monthly mean sunspot areas (*thin solid line in the bottom panel*) from 2008 January to 2009 June . Their corresponding smoothed values (*thick lines*) are also shown in their corresponding panels.

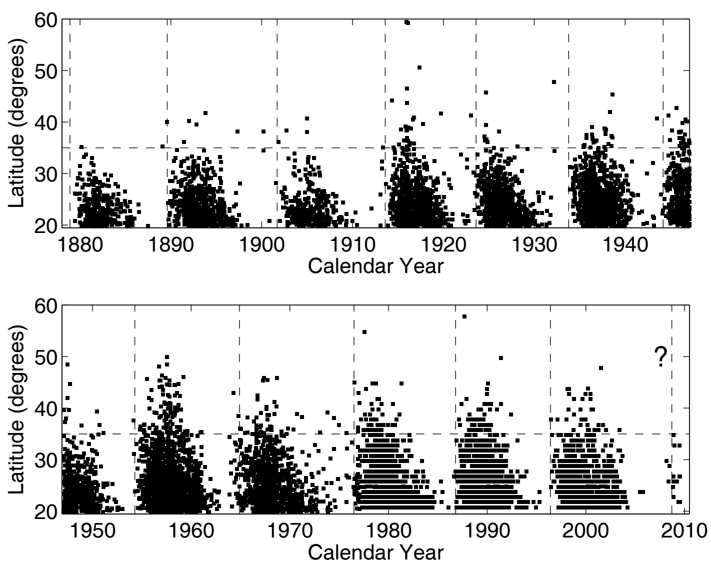

Fig. 2 Butterfly diagram of sunspot groups whose latitudes are higher than 20°. The hemispheric labeling of sunspot groups is ignored. In Figs. 2 to 4, the vertical dashed lines mark the minimum times of cycles, and the question mark indicates that the minimum time between cycles 23 and 24 should occur later than 2008 December.

The butterfly diagram of sunspots shows that consecutive sunspot cycles overlap by ∼2–3 yr, with the first sunspots of the incoming cycle appearing at high latitudes and the last sunspots of the outgoing cycle appearing near the equator. Sunspot groups of the new cycle, in fact, begin to appear as much as ∼1.6 yr before the statistically defined (conventional) sunspot minimum and continue to emerge up to 1.8 yr after the following minimum (Wilson 1987). Using the first data set, we plot individual sunspot groups whose latitudes are higher than 20° in the latitude – time coordinate system, shown here as Figure 2. In the figure, we ignore the hemispheric labeling of sunspot groups, that is, a sunspot group at north 25° or south 25° would be plotted as a sunspot group at latitude 25° and so forth. As the figure shows, sunspot groups at high latitudes appear at lower latitudes for cycle 24 than those for the other modern solar activity cycles, and the highest latitude of sunspot groups belonging to cycle 24 is just about 35° at present, appearing on 2008 October 30, which is the lowest among the highest latitude of a cycle for the modern solar activity cycles. There exists a significant positive linear relation between the maximum amplitude of sunspot activity and the maximum mean latitude of sunspot groups at high latitudes of $\geq 35^\circ$) (Li et al. 2002), thus, a rather low level of sunspot activity is expected for cycle 24. There exists a significant positive linear relation between the maximum amplitude of sunspot activity and the maximum number of sunspot groups at latitudes over 35° (Li et al. 2003). Up to now, there are no sunspot groups appearing at such high latitudes, thus, a rather low level of sunspot activity is expected for cycle 24.

We use the RGO data set to count the monthly numbers of sunspot groups whose latitudes are over 20°, which are shown in Figure 3. The figure shows that only one or no sunspots appear at high latitudes each month from 2003 December to the present, except for 2008 October. In that month, four sunspot groups appear at latitudes over 20°. During such a long time (58 months from 2003 December to 2008 October), only one or no sunspots at high latitudes appear per month, which has been the first time that such an event was observed since the start of modern solar activity cycles.

Once the time interval between the first observations of two neighboring sunspot groups is larger than 14 d, it should be approximately regarded as an observation of no sunspots on the solar disk, called a spotless event, because it occurs just around the minimum time of a cycle, and the lifetime of a sunspot is very short. We count the time intervals (in days) of spotless events, which are shown in Figure 4. As the figure shows, spotless events occur just within 2 yr around the minimum time of a cycle for cycle 16 and afterwards, but they obviously appear beyond the time limit for cycles 12 to 15. Observational ability of sunspots is believed to improve with elapse of time since cycle 12, and we infer that some small sunspots would not be observed during the minimum times of cycles 12 to 15, which caused spotless events to occur beyond the time limit. Thus, the minimum smoothed monthly mean sunspot number should be the smallest one for cycle 24 among the minimum smoothed sunspot number of cycles since cycle 16 and probably even among those of the modern solar activity cycles. As the figure shows, for observations of the Sun since cycle 16, spotless events appear with the highest frequency around the minimum time of cycle 24, and the longest spotless event lasts 53 d, also occurring around the minimum time of cycle 24. For accurate statistics of spotless days, the reader may refer to the spotless days website[3].

In summary, the aforementioned observations of sunspots around the minimum time of cycle 24 hint that the present Sun should present a rather low level of sunspot activity for cycle 24, and sunspot activity is believed to be lower for cycle 24 than for any of the previous cycles 16 to 23 and even the lowest since the start of the modern solar cycles due to these records being broken.

Figure 5 shows the monthly number of sunspot groups, the monthly mean sunspot numbers, and the monthly mean sunspot areas from 1876 May to 2009 June. Their corresponding smoothed values are also shown in the figure. All of the three indexes indicate the secular trend of sunspot activity obviously seen from cycles 12 to 19, and the level of sunspot activity seems to be reducing from cycle 20 on. The secular trend of sunspot activity is believed to be occurring from an obvious increase in cycles 12 to 19 to a decrease from cycle 20 onwards and even into cycle 24.

Figure 6 shows the monthly mean values of the solar radio adjusted flux density at 2800 MHz from February 1947 to 2009 May (in units of 10^{-22} J s^{-1} m^{-2} Hz^{-1}), measured by Ottawa/Pentiction. They are smoothed with a 13-point running-average method. As the figure shows, the smoothed monthly values continue to decline from January to 2008 November. Thus, the minimum time between cycles 23 and 24 should occur in 2008 November or later. The minimum smoothed monthly value is about 68.2 (or lower perhaps in the future) for cycle 24, which is the smallest since the beginning of the radio flux

[3] *http://users.telenet.be/j.janssens/Spotless/Spotless.html*

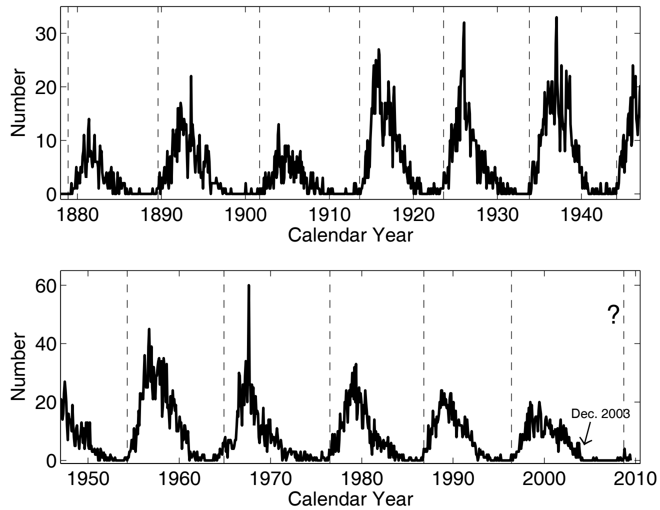

Fig. 3 Monthly numbers of sunspot groups whose latitudes are over 20°.

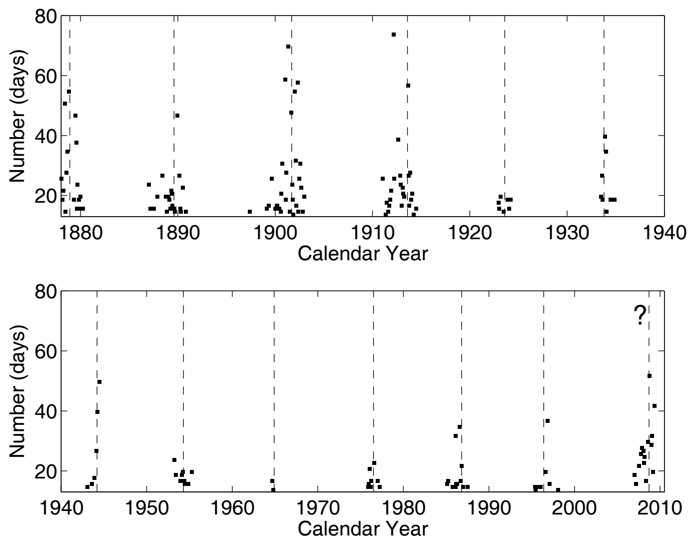

Fig. 4 Time interval (in days) between the first observations of two neighboring sunspot groups on the visible disk. Just those which are larger than 14 d are shown in the figure.

density measurement. Radio flux density measurements seem to agree with the above results inferred from sunspot observations.

3 CONCLUSIONS

The Sun is setting some new records. (1) Cycle 23, which is going into its ending stage now or just now ended, has the longest cycle length and the longest fall time for observations of the Sun since the modern solar activity cycles began. Based on the cycle length, the maximum smoothed monthly mean sunspot number is inferred to be 77.9 ± 23.7 for cycle 24. The importance of a solar cycle length, for

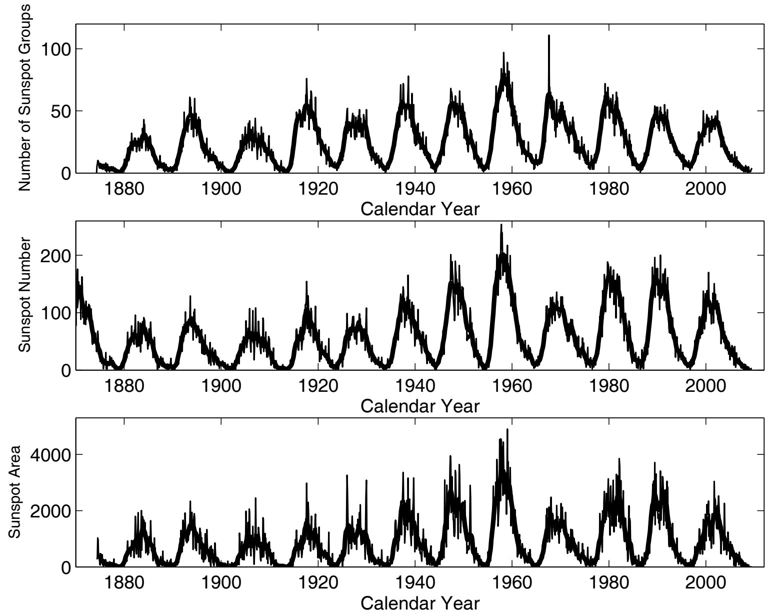

Fig. 5 Monthly number of sunspot groups (*top panel*), the monthly mean sunspot numbers (*middle panel*), and the monthly mean sunspot areas (*bottom panel*) from 1976 May to 2009 June. Their corresponding smoothed values (*thick lines*) are also shown in the figure.

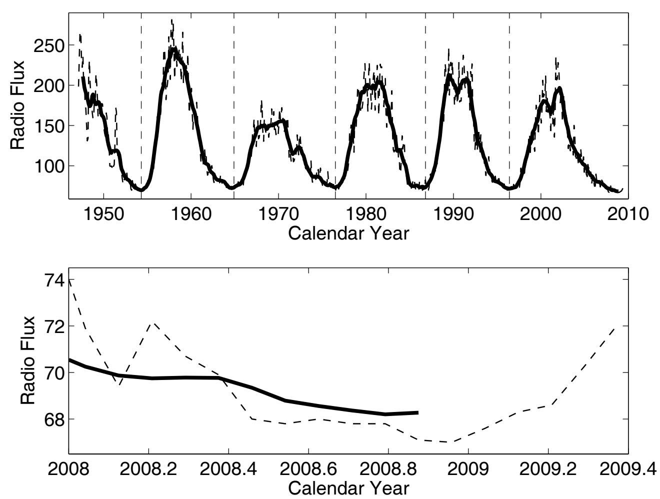

Fig. 6 *Top panel*: the monthly values (*thin dashed line*) of the solar radio adjusted flux density at 2800 MHz from 1947 February to 2009 May and their smoothed values (*thick solid lines*). *Bottom panel*: the monthly values (*thin dashed line*) of the solar radio adjusted flux density at 2800 MHz from 2008 January to 2009 May and their smoothed values (*thick solid lines*).

example, can be found in its association with the Earth's long-term global temperatures from 1861 to 1989 (Friis-Christensen & Lassen 1991; Harvey & White 1999). (2) Sunspot groups at high latitudes appear at lower latitudes for cycle 24 than those for other cycles since the start of modern solar activity cycles, and the highest latitude of sunspot groups belonging to cycle 24 is just about 35° at present, which is the lowest among the highest latitude of a cycle for the modern solar activity cycles. (3) Only one or no sunspots appear at high latitudes during any month from 2003 December to 2008 October, surprisingly spanning as long as 58 months, which is the first time this has been observed since the start of modern solar activity cycles.

The Sun is now staying at a rather low activity level, even probably at the lowest level of solar activity since the start of modern solar activity cycles: (1) the minimum smoothed monthly mean sunspot number is about 1.7 (or lower), occurring in 2008 December (or later), which is the smallest one among the minimum smoothed sunspot numbers of cycle 16 onwards, and even probably among the modern solar activity cycles. Thus, the maximum smoothed monthly mean sunspot number is inferred to be 58.0 ± 26.6 for cycle 24; and (2) once the time interval between the first observations of two neighboring sunspot groups is larger than 14 d, it should be approximately regarded as an observation of no sunspots on its disk, called a spotless event. For observations of the Sun since cycle 16, spotless events appear with the highest frequency around the minimum time of cycle 24, and the longest spotless event lasted 53 d, also occurring around the minimum time of cycle 24.

The secular trend of sunspot activity is believed to be altering from an obvious increase in cycles 12 to 19 to a decrease from cycle 20 onwards and even into cycle 24. Solar dynamo theory proposes that sunspot activity should be created by the so-called solar dynamo. The solar dynamo is believed to be decreasing at present (also see Jiang et al. 2007).

Radio flux density measurement seems to agree with the results inferred from sunspot observations.

Sunspot activity is expected to present a rather low activity level, lower for cycle 24 than for any of cycles 16 to 23 and even the lowest since the start of modern solar cycles. Time will tell.

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