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Evolution of solar indices during the maximum of solar cycle 24

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Solar cycle 24 started in 2008-2009 and a first peak (~67) in sunspot number (12-month running means) occurred in February 2012. Recently, sunspot activity seems to have increased. The latest 12-month running mean attained a value 74.5 centered at September 2013 and is larger than the previous maximum 67. Thus, cycle 24 peak could be as high as ~75 but further increase is not ruled out. Several other solar indices (2800 MHz solar radio flux, Lyman-α, Mg II 280 index, total solar irradiance, all of origin in chromosphere or lower corona) also showed peaks at February 2012. But coronal indices, X-rays and coronal mass ejection (CME) frequency showed broad plateaus around February 2012. In interplanetary parameters, solar wind speed (V) showed a broad peak earlier than February 2012 (during September 2010 - October 2011) and a decline thereafter. The number density (N) did not seem to have any relationship with solar indices, but magnetic field (B) peaked near February 2012. The geomagnetic index (Ap) showed the same pattern as B. The decrease in maximum (peak) cosmic ray intensity at middle and high latitudes showed a delay with respect to peak of solar indices by several (more than ten) months. The main conclusion of the present communication is that during the maximum of cycle 24, the finer dynamic characteristics of the solar surface (photosphere) phenomena extend faithfully to the chromosphere and lower corona, but local dynamical effects occur higher up in the corona diluting the effects of the photospheric phenomena.

Keywords: Solar cycle 24, Solar indices, Sunspot number, Coronal indices, Interplanetary parameters

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1 Introduction

Sunspots (Rz) have an approximately 11-year cycle. The maximum sunspot number changes from cycle to cycle in a wide range (about 64-201). Cycles (one sunspot minimum to next sunspot minimum) have been numbered since 1749. The present cycle 24 started around December 2008. Prediction of the magnitude of the sunspot maximum Rz(max) is important for planning satellite launching, as large Rz(max) can cause damage and malfunction of satellite and aircraft electronics[1] and health hazards in space[2]. A Solar Cycle 24 Prediction Panel, composed of international scientists and presided by Douglas Biesecker (details available at http://www.sec.noaa.gov/SolarCycle/SC24/index.html), issued on 25 April 2007, a consensus opinion that: (i) cycle 24 would commence in March 2008 (±6 months) and (ii) the solar maximum would be 140±20 in October 2011 or 90±10 in August 2012. However, the observed minimum was not in the range March 2008 (±6 months). The new cycle commenced later, roughly in December 2008 (12 month running average 1.7) with monthly sunspot number zero in August 2009. As far as it is known, a zero in any month has never happened before.

For cycle 24, there were predictions for maximum sunspot number in a very wide range (Refs 3,4 and references therein), namely: (a) <70 (three predictions), (b) 70–90 (eight predictions), (c) 90–110 (eight predictions), (d) 110–130 (ten predictions), (e) 130–150 (seven predictions), (f) 150–170 (three predictions), and (g) >170 (four predictions). Table 1 lists some of the extreme (very low and very high) predictions. In the present communication, the evolution of solar indices in cycle 24 is examined from 2009 onwards.

2 Data

The sunspot numbers (Rz) data used in the present study is taken from the NOAA websites (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/AA and ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS). The other data for 2800 MHz solar radio flux is taken from http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/; Lyman-α and Mg II 280 index from http://lasp.colorado.edu/lisird/; total

Table 1 — Some extremely low and high predictions for sunspot number Rz(max) of cycle 24

Dikpati *et al.*[5]	150-180
Tsirulnik *et al.*[6]	180
Horstman[7]	185
Hathaway & Wilson[8]	160±25
Clilverd *et al.*[9]	42±34
Badalyan *et al.*[10]	<50
Kane[11]	58.0±25.0
Lockwood *et al.*[12]	~60
Ahluwalia[13]	56.4±4.4

solar irradiance (TSI) from http://lasp.colorado.edu/data/sorce/tsi_data/daily/sorce_tsi_L3_c24h_latest.txt; X-ray background data from http://www.swpc.noaa.gov/ftpdir/indices/old_indices/; coronal mass ejection (CME) monthly frequency from http://cdaw.gsfc.nasa.gov/CME_list/; interplanetary data for solar wind V, number density N and total magnetic field B from http://www.swpc.noaa.gov/ftpdir/lists/ace2/201310_ace_mag_1h.txt, http://www.swpc.noaa.gov/ftpdir/lists/ace2/201310_ace_swepam_1h.txt, http://www.swpc.noaa.gov/ftpdir/ weekly/RecentIndices.txt, respectively; and cosmic rays from http://neutronm.bartol.udel.edu/ ~pyle/bri_table.html.

As the monthly values change erratically from month to month, 12-month running means are evaluated and used. The latest data for monthly sunspots were available up to October 2013; but the running mean process loses six months. So, the last Rz running mean refers to April 2013.

3 Results

Figure 1 shows the plots of 12-month running means of various indices. The top plot is for sunspot number Rz and shows a peak value of ~67 at February 2012, marked by a thick line and an arrow. A vertical line is drawn at the month February 2012. Since then, values decreased to reach 56.5 centered at March 2013 (13 months later), but further data showed that values have increased considerably since then (~75, last value centered at September 2013) and have, thus, exceeded the first maximum. The last value is not marked with an arrow as one is not sure that a second peak has already occurred. For that, one has to wait for a few months more.

The next plot is for 2800 MHz solar radio flux. This also shows a peak at around February 2012. The next plots for Lyman-α, Mg II 280 index also show broad peaks at February 2012 extended further to a few more months. The X-ray background data shows a broad level starting from the middle of 2011 but a maximum value at February 2012, decreasing very slowly thereafter. The total solar irradiance (TSI) plot is flat but does indicate a maximum at February 2012. The coronal mass ejection frequency has increased continuously and has not shown a maximum till beginning of 2013.

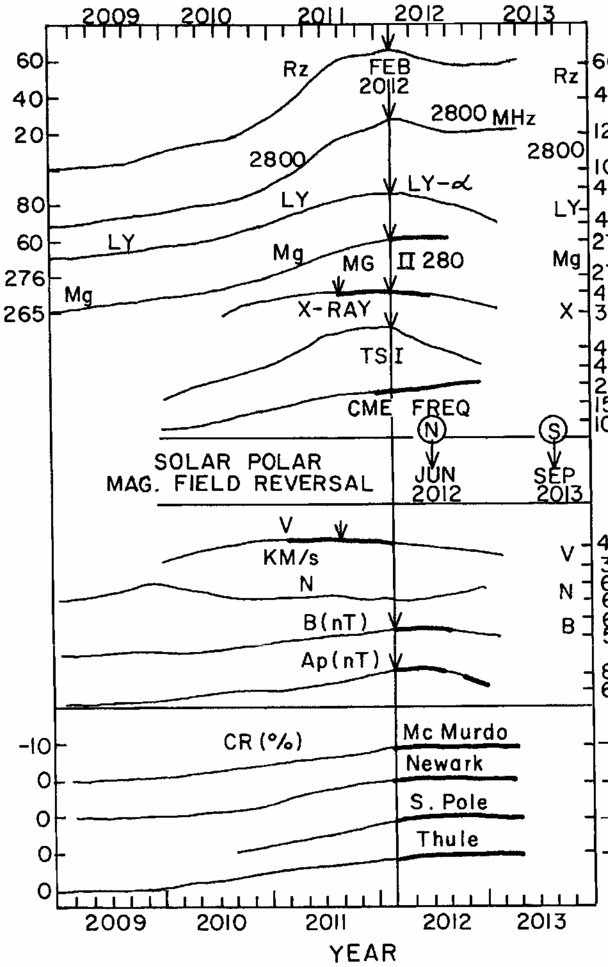

Fig. 1 — Plots of 12-month running means of the various indices: top plot is for sunspot number (Rz), followed by 2800 MHz solar radio flux, Lyman-α and Mg II 280 index, background X-ray flux, total solar irradiance (TSI) and coronal mass ejection (CME) occurrence frequency; solar polar magnetic field reversals at the northern (N) and southern (S) poles are indicated; further plots are for interplanetary parameters, solar wind speed (V), number density (N), magnetic field (B); geomagnetic disturbance index (Ap) (2 nT); bottom plot is for cosmic ray (CR) neutron monitor intensity at the middle and high latitude locations South Pole (90°S), McMurdo (78°S, 167°E), Thule (77°N, 69°W) and Newark (40°N, 76°W)

An interesting feature of solar activity is the reversal of solar polar magnetic field near the sunspot maximum. The northern polar field reversed in June 2012 (4 months after the sunspot maximum of

February 2012). The southern polar field reached the reversal point in September 2013 (16 months after the northern reversal). During the previous similar polarity reversal in 1989-1991, the northern polar field reversed 14 months before the southern polar field reversal, very similar to the situation during cycle 24 (Ref. 14). In Fig. 1, the reversals of the northern polar field N and the southern polar field S are indicated.

There is another peculiar feature of solar maxima. In general, the smoothed sunspot activity rises almost monotonically from minimum to maximum (just one single peak) in about 4-5 years and then falls monotonically from maximum to minimum in about 5-6 years. However, in some cycles, there ia a fine structure. Having reached a maximum level, there are fluctuations for several months and after a slight drop, a second maximum appears. This double peak structure (and a gap in between) are termed as Gnevyshev peaks and gaps[15] and are discussed in detail by Kane[16]. The plots of the 11-year cycle of sunspot number Rz were shown for all cycles 0-22 by Kane[17]. In most of the cases, there was a single peak (cycles 0, 1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 15, 18, 19). However, in some cycles, there were double peaks (cycles 5, 6, 14, 16, 17, 20, 21, 22, 23). The in between gap between the two peaks was very shallow, and the separation between the two peaks varied in a wide range of 12±6 months. In the present cycle 24, the first peak is at February 2012. The possibility of a second peak is not ruled out. The 12-month running means centered up to March 2013 are still low but since then a rising tendency is indicated. Recently, sunspot activity seems to have increased. The monthly sunspot numbers in February and March 2014 were 102.8 and 92.2, respectively. As a result, the latest 12-month running mean attained a value 74.5 centered at September 2013 and is larger than the previous maximum 67. Thus, cycle 24 peak could be as high as ~75 but further increase is not ruled out. So, one needs to wait for a few months to see whether a second peak has occurred. In any case, it would be larger than the first peak, an unusual situation, as in all previous cases of double peaks, the second peak was either lower (lesser) than the first peak or just comparable within a few units.

In the plots for interplanetary parameters, solar wind speed (V) shows a broad peak a few months earlier, in the latter part of 2011. The number density (N) shows no peak at all, only a broad minimum. However, the total magnetic field (B) shows a broad peak at February 2012, extended to a few months further. The geomagnetic disturbance index (Ap) shows the same features as of B.

The bottom plot in Fig. 1 is for cosmic ray (CR) neutron monitor intensity at four middle and high latitude locations South Pole (90°S), McMurdo (78°S, 167°E), Thule (77°N, 69°W) and Newark (40°N, 76°W). Since CR variations are anti-parallel to sunspot variations, the scale used is here upside down, so that increases imply larger CR decreases. The largest CR depression is not at February 2012 (vertical line) but several months later, starting in June 2012 and still continuing at the same level in early 2013 at all the four locations (though Ahluwalia & Ygbuhay[18] mentioned that the baseline of the neutron monitors at McMurdo and South Pole are unstable). This is the well known delay of CR intensity with respect to sunspots, Rz. The CR modulation starts with a delay with respect to sunspots and the delay is reported to be larger in odd cycles (19, 21, 23) as compared to the delay in even cycles (20, 22) (Refs 19,20).

The mechanism for CR modulation consists of time-dependent heliospheric drifts and outward propagating diffusive barriers from the Sun [Merged Interaction Regions (MIRs) (Ref. 21)]. All MIRs are effective in modulation but in various degrees. Since very strong MIRs are very effective in modulating CRs throughout the heliosphere[22]; Global MIR (GMIR) were conceived, which are regions extending 360^{o} around the Sun, mostly in the ecliptic plane and responsible for the step-like changes in CR counting rates. There are two mechanisms operating. Thus, there is a convection-diffusion mechanism, which is independent of the sign of the solar magnetic field and operates similarly in every 11-year sunspot cycle[23,24]. Then, there is the drift mechanism which gives opposite effects with the changing sign of the solar magnetic field in alternate cycles[25-28]. Recently, Potgieter[29] has reviewed the situation about CR modulation in the heliosphere with emphasis on numerical modeling and said that the present understanding of the mechanisms of the global solar modulation of galactic CRs in the heliosphere is considered essentially correct, an amazing accomplishment for Parker’s theory that was developed in the early 1960s. The main obstacles and challenges are insufficient knowledge of the spatial, rigidity and especially the temporal dependence of the diffusion coefficients, covering the underlying features of solar wind and magnetic field's turbulence. Evidently, this field of research is alive and well with many aspects remaining a work in progress.

However, cycle 24 is an even cycle and the delay expected is small (only a few months). Instead, the delay so far is already more than 10 months. Thus, for cycle 24, the CR delay is large, not as per theoretical expectations. Potgieter[29] has also mentioned the solar minimum of 2007–2009 as unusual.

4 Discussion and Conclusion

Solar cycle 24 started in 2008-2009 and the peak value ~67 in sunspot number (12-month running means) occurred in February 2012, followed by a slow decline thereafter. However, recently, sunspot activity has started increasing and the latest value (12-month running mean) is 74.5, centered at September 2013, thus exceeding the previous peak ~67. Hence, the maximum of sunspot cycle 24 is either 74.5 as occurred now or may rise still further in the next few months. One needs to wait a few months to confirm. Several other solar indices [2800 MHz solar radio flux, Lyman-α, Mg II 280 index and total solar irradiance (TSI), all originating in the chromosphere and lower corona] also show peaks in February 2012; but coronal indices X-ray background and coronal mass ejection (CME) frequency show broad levels around February 2012. In interplanetary parameters, solar wind speed (V) shows a broad peaking earlier than February 2012 (during September 2010 - October 2011) and a decline thereafter. Number density (N) does not seem to have any relationship with solar indices; but magnetic field (B) has a broad peak near February 2012 with the same level continuing for the next few months. Geomagnetic index (Ap) shows the same pattern as of B. Cosmic ray intensity maximum, decreases at middle and high latitudes, shows a delay with respect to peak of solar indices by several (more than ten) months.

The main conclusion of the present communication is that during the maximum of cycle 24, the finer dynamic characteristics of the solar surface (photosphere) phenomena extend faithfully to the chromosphere and lower corona; but higher up in the corona, local dynamical effects occur, diluting the effects of the photospheric phenomena. In an earlier communication by Kane[17], the evolution of solar and other indices was examined during sunspot maximum (notably during the double peaks[15]) and sunspot minimum years. The conclusion was that in general, the chromospheric indices seemed to evolve similar to sunspots, but the evolution of coronal indices was not always similar to sunspots, and may differ considerably amongst them. The results for cycle 24 show a similar behaviour.

The maximum value ~67 for sunspot number for cycle 24 is far below the average value of ~115 for the last 14 cycles (10-23). Thus, all predictions mentioning values above average have proved grossly incorrect. But the values have increased further since then to reach 74.5. Even at this value, the observed value is far below the average value of ~115, but one needs to wait and see whether 74.5 is the second peak or values would increase further. In any case, predictions of values below average have probably proved correct.

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