Properties and Surprises of Solar Activity XXIII Cycle

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Abstract. The main properties of the 23rd cycle match almost completely those of average-magnitude solar cycles, and some of the features of the cycle may indicate a change in the generation mode of magnetic fields in the solar convection zone. If this is the case, the Sun enters a period of intermediate and weak cycles of solar activity (SA) in terms of the Wolf number, which may last for 3 to 6 solar cycles. The main development stages of solar cycle 23 are the following: minimum of solar cycle 22: April 1996 (W* = 8.0); maximum of the smoothed relative sunspot number: April 2000; global polarity reversal of the general solar magnetic field: July to December 2000; secondary maximum of the relative sunspot number: November 2001; maximum of the 10.7-cm radio flux: February 2002; phase of the cycle maximum: October 1999 to June 2002; beginning of the decrease phase: July 2002; the point of minimum of the current SA cycle: December 2008. Solar cycle 23 has presented two powerful flare-active sunspot groups, in September 2005 and December 2006 (+5.5 and +6.6 years from the maximum) which by flare potential occupy 4th and 20th place among the most flare-active regions for the last four solar cycles. The unprecedented duration of the relative sunspot numbers fall that has led to already record duration of the last solar cycle among authentic cycles (since 1849) became the next surprise of development of solar activity during the last cycle. The phase of the minimum began in May 2005 and lasted for 4.5 years. Thus, the new solar cycle 24 has begun in January 2009.

Keywords: Sun, solar activity, solar cycles, 23rd solar cycle

Introduction

12.5 years of the solar cycle 23 development have revealed its properties and most of the specific features of its evolution. Cycle 23 is the second component of the physical solar cycle 22 (Fig.1) whose development has contributed considerably to our knowledge of the properties and potential of solar cycles. It will suffice to recall the active flare regions of March 1989 and June 1991, which were the most powerful ones observed over the entire history of such observations. Let us briefly recall the principal characteristics of solar cycle 22. It was the even cycle with the largest Wolf number: W* = 158.1; it was the shortest cycle - its duration was 9.75 years only; this cycle had the shortest ascending branch, whose duration was 2.92 years; the cycle had a double-humped activity maximum: the second maximum was observed in January–February 1991 (W*=147.6), and coincided with the maximum of emerging fluxes and the maximum of radio flux at 10.7 cm; an unprecedented number of large flare sunspot groups were observed at latitudes >25° in both hemispheres with most of the powerful flares occurring in high-latitude active regions (ARs); the cycle was characterized by an unusually short period (half an year) of the reversal of the general solar magnetic field at the latitudes of formation of active regions (July–December, 1990), while in the three previous solar cycles, when observations of this process became possible, the field reversal took at least a year; all major flare events happened during the phase of maximum; no X-class solar flares occurred during the 3.5 years of the declining phase.

It was the major surprise of this 22-year solar cycle that contrary to the Gnevyshev–Ohl rule, for the first time during the entire actual history of solar-cyclicity studies (since 1849, Fig.1.), the trailing odd cycle was shorter than the leading even cycle.

Solar cycle 23

The current cycle 23 entered the family of intermediate-magnitude solar cycles (Ishkov, 2003) and, as evident from Fig. 2, its development matches completely the evolutionary pattern of the cycles that were similar to it both in terms of development rate and height, and whose Wolf numbers were in the interval (80< W* < 130). Consider now the main features of the current 23rd SA cycle after 151 months of its development:

– the current 23rd SA cycle formally started in May 1996 at the initial smoothed Wolf number W*min = 8.0;

– the first group of the current cycle appeared directly at its minimum (May 1996), whereas in all cycles so far studied the first groups of spots appeared at least 1–1.5 years before the point of minimum (Harvey, 1997);

– the cycle reached its maximum in terms of relative sunspot numbers in April 2000 (W*max=120.7), and the maximum of the 10.7-cm radio flux was observed in February 2002 (F*max=197.2); i.e., the maxima of these two main indices were separated in time, as in the case of the 22nd SA cycle;

– the reversal of the general magnetic field of the Sun (the complete sign reversal for solar structures at 70°N and 70°S) occurred during July–December 2000;

– the secondary maximum of the cycle in terms of relative sunspot numbers was observed in November 2001 (W*=115.6) and the relative sunspot number, W*, exceeded 113 over eight months.

– the current cycle was considerably behind other cycles in terms of the number of active regions before the decrease phase; however, the situation leveled off in the last three years: by 2005 the current cycle had caught up with the 20th cycle and slightly overtook the 22nd cycle;

– the sunspot groups of the cycle are smaller in size, have less complex magnetic structures, lower development rates, and longer lifetimes. These are characteristic features of stable (nonflare) ARs, which may be indicative of weaker circulation in the solar convection zone during this cycle compared to several previous cycles (18–22). The number of high-latitude (φ ≥ 30°) sunspot groups is close to "normal" as observed in reliably described cycles and is much smaller than the number of high-latitude groups observed during cycles 22 and 19;

– despite the leveling of the total number of active regions, the 23rd cycle is still behind cycles 19–22 in terms of the number of optical flares and major X-ray flares.

– the cycle demonstrates a protracted period of high flare activity during its decrease phase: the last flare region with high flare potential appeared in the beginning of December 2006 – almost 6.6 years after the maximum;

– one can see a statistically significant excess of the total number of proton events compared to the three previous cycles, as well as the number of increases in neutron monitor counts that accompany the flare events with protons with energies E>1 GeV;

– the cycle is characterized by an abrupt decrease of the fluences (total daily fluxes) of energetic electrons (E > 2 MeV): fluences very rarely reach 10^8 particles $s^{-1}m^{-2}sr^{-1}$ before the decrease phase (July 2002) of the current cycle but often exceeded 109 during the 21st and 22nd SA cycles. The situation changed abruptly in March 2003,

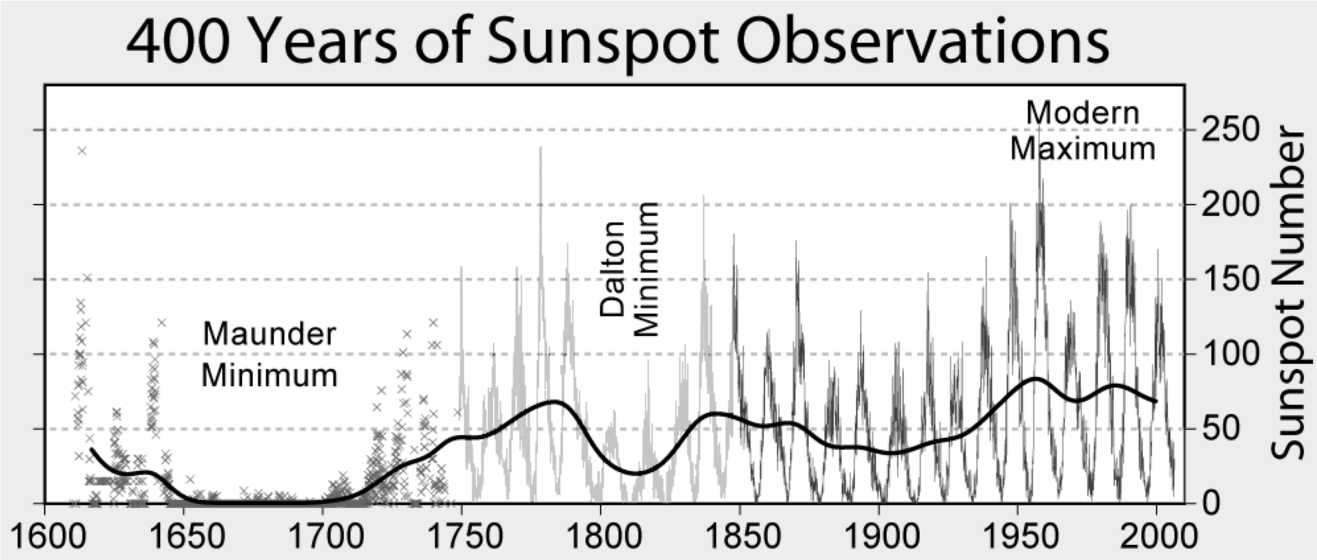

Fig. 1. Cycles of solar activity since 1610 in terms of annually averaged relative sunspot numbers. The black line shows reliably described solar cycles since 1849 (authentic cycles); the gray line shows the reconstructed numbered solar cycles since 1755 (poor data); and the crosses shows the solar cycles since 1610 reconstructed based on fragmentary data (very poor data); by http://www.globalwarmingart.com/wiki/File:Sunspot_Number.png

TABLE 1. Evolutionary and flare characteristics of active regions with extreme solar flares in the current 23 solar cycle

AR9393 (N17L151, CMP 28,0.03.2001); Sp max = 2440 m.v.h., FKC, δ; XRI=>25.74 (30.24): X4>17.5+M24+C28; 22+115+S101; PFE I (43h) – 28 – 29.03 – X11.7+M11; PFE II (21h) – 02.04 – X3.22+M4;	**AR10486** (S17L283, CMP 29,3.10.03); Sp max = 2610 m.v.h., FKC, δ; XRI>62.56: X7>17.5+M16+C16; 41+32+17+S49; PFE I (59h) – 22 – 24.10 – X25.4+M69.9;7.6; PFE II (59h) – 27 – 29.10 – X217.4;10+M45;6.7; PFE III (63h) – 02– 05.11 – X28.3;>17.5+M65.3;
AR9415 (S22 L359, CMP 9.04.2001) Sp max= 880 m.v.h., EKI, δ; XRI=28.73: X514.4+M7+C15; 31+24+14+S34; PFE I (64h) – 3 – 5.04: X2+M2; PFE II (65h) – 9 – 12.04: X2+M3; PFE III (20h) – 14 – 15.04: X114.4+M1;	**AR10808** (S09L229, CMP 14,4.09.05; R2; Sp max = 1430 m.v.h., EKC, δ; XRI =49.21: X1117.1+M24+ C1; 31+29+112+S70; PFE I (91h) – 7 – 10.09 – X717.1+M126.2; PFE II(94h) – 12 – 16.09 – X41.7+M76.1

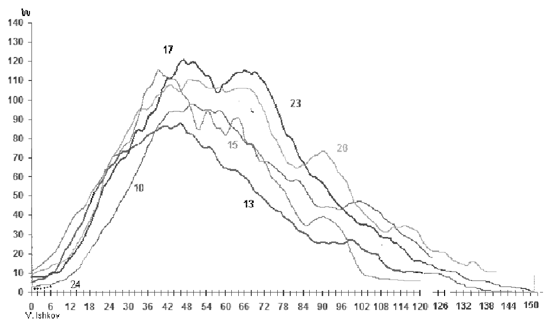

Fig. 2. Cycles of solar activity since 1610 in terms of annually averaged relative sunspot numbers. The black line shows reliably described solar cycles since 1849 (authentic cycles); the gray line shows the reconstructed numbered solar cycles since 1755 (poor data); and the crosses shows the solar cycles since 1610 reconstructed based on fragmentary data (very poor data); by http://www.globalwarmingart.com/wiki/File:Sunspot_Number.png

when the fluences exceeded 108 particles •s−1•m−2•sr−1 for 45 days, and it has reached 109 at least 10 times so far;

– the decrease in the flare activity resulted in a considerable increase in the number of days with quiet geomagnetic conditions. At the same time, the number of severe magnetic storms (Ap > 100) remains at the level of high solar cycles.

As is evident from Fig. 3, the descending branch of the cycle matches the descending branch of the previous odd cycle. However this branch was unusually tightened, having transformed 23rd cycle into the most long solar cycle among the authentic.

The first significant flares of this cycle are associated with the sunspot group AR8100 (S21 L352; X29.4 +M5+C23, XRI=12.26) in early November 1997. The flare potential of this group included the first proton flares, among which were the first (X9.4) flare of solar cosmic rays. five M-class flares, and 23 C-class flares. The flare index of this AR was equal to 12.26.

Further we will consider only those active regions in which have occurred extreme solar flare events. For the characteristic of sunspot group gives its serial number in system of Sun Service NOAA; localization (N, S for heliolatitudes and L absolute heliolongitudes); the area of spots (Sp max); evolutionary and magnetic classes in a maximum of development. Further are resulted flares the characteristics including flare potential of AR: – X-ray flare index of the sunspot group introduced by P. McIntosh. The latter is computed as a sum of the X- and M-class flares, where X- and M-class flares produce unit magnitudes and tenths of magnitudes: X-class flares yield units and M-class flares yield tenths; – the total quantity of flares of X-ray importance X+M+C, the bottom index shows quantity of flares of the given importance, and the top index shows importance of the largest flare on intensity soft X-ray; total quantity of flares of optical importance; – the periods of large and middle flare (PFER – period of the flare energy realization) concentration in dates, hours and the quantity of flares, the top index gives importance of greater flares. Table 1 gives a shorthand presentation for the basic characteristics these flare-active regions.

The first powerful period of extreme solar flares occurrence has come in late March to early April 2001, which was associated with the passage across the solar disk of two sunspot groups 200° apart in heliographic longitude: AR 9393 (L151°) and AR9415 (L359°) The first flare of this series occurred on March 29 and caused a severe magnetic storm on March 31. The concentration of flare activity peaked on April 2–3, when four X-class flares occurred within 17 hours in these active regions. During one of these flares (at 21:32 UT on April 2) the soft X-ray flux in the 1–8 Å wavelength interval exceeded the saturation threshold of the soft X-ray detector of the GOES satellite (X > 17.5), and the detector downtime (τ) reached five minutes. The class of this flare was estimated at X22, making it the second most powerful flare in the current SA cycle. On the whole, the arrivals of six interplanetary shocks, five magnetic storms, and seven solar proton events were registered during the period from March 25 to April 10 in the Earth's environment.

The flare activity in the current cycle reached its peak concentration during the period from October 19 through November 5, 2003, when three large and flare-active sunspot groups passed simultaneously across the visible solar disk: one in the southern hemisphere – the largest area sunspot group in the 23rd SA cycle – and two sunspot groups in the northern hemisphere (Veselovsky et al., 2004). The period began with the appearance of the sunspot group AR10484 (N03 L354; X21.2+M6+C28; XRI=5.73) from behind the eastern limb (October 17) and it went in full development behind the western limb on October 29. After it appeared to the visible solar disk (October 21), the sunspot group AR10486, which developed into a large sunspot group on the invisible side of the Sun, exhibited X5.4/1A and X1.1/1N flares on October 23 and an M7.6/1N flare on October 24. On October 24–25, 2003, a new emergence of a powerful magnetic flux occurred in this AR. This emergence increased by almost two times the area of the sunspot group and produced X1.2/3B-class (October 26) and M5.0/1F and M6.7/1F class (October 27) flares. The emergence of the next magnetic flux (October 27–28) increased the area of the sunspot group to a record level of Sp=2610 m.v.h. for this cycle and allowed the third most powerful flare of the cycle with a class of X17.3/4B to occur. The geomagnetic storm grew to a very strong one (October 29–31) with the arrival of the disturbances produced by the last flare and became the most powerful extreme magnetic storm of the cycle. The same flare brought high-energy solar protons to the Earth's environment, where they caused a severe proton event (29500 particles $s^{-1}cm^{-2}sr^{-1}$). The next period of flare-energy release in this AR began on November 2, 2003, with an X8.3/2B flare and continued on November 4 with a flare that demonstrated the highest X-ray intensity in the current cycle and was of X-ray importance higher than 17.5/3A (τ=11m). This flare occurred near the western solar limb and had no appreciable effect on the geomagnetic situation, although very powerful solar proton events occurred in the Earth's environment, with maxima on November 2 and 4, 2003. The third sunspot group, AR10488 (N08 L291; X33.9 + M7 + C17; XRI=8.57), formed on October 27 in the central region of the northern hemisphere of the Sun and despite its rapid development produced only intermediate-class flares before October 3, whereas the X2.7 and X3.9 flares occurred there on November 3.

In the beginning of September, 2005 helioseismology methods had been certain passage of the big sunspot group on an invisible hemisphere of the Sun. On September 7th it has appear on a visible disk of the Sun and the same day in it there was a fourth superflare on importance X17.1/3B. Active region 10808 has been a big surprise: this region, has presented us in a 10-day period with 11 X-class flares and 19 M-class flares. Similar powerful burst of flare activity in 5.5 years after a maximum of a solar cycle were carried out was observed only second time: first such case was observed in solar cycle20 in July 1974. The basic development of sunspot group AR10808 has occurred near east solar limb, therefore it is impossible to describe parameters of a magnetic flux which has given such power output, but possible to assume, that its capacity and speed of emergence was we shall compare to a magnetic flux in active region AR9393 of March, 2001.

How can we compare this impressive solar region with other regions observed over the past twenty years? One method of comparison is to calculate the total output of X-ray flares by the region (XRI-idex). The following table 2 is based on his data.

Table 2.Most flare productive active regions 1986 – 2007

№	CMP	AR	Φo	Lo	Sp max	R, S, G	XRI	M±y
1	09.09.1991	6659	N31	248	2300	R5/S4/G4	>86.5	+2
2	2.10.2003	10486	S17	354	2610	R5/S5G5	>62.56 (73.06)	+3.5
3	12.03.1989	5395	N34	257	3600	R5/S4/G5	57.0	-0.5
4	13.03.1991	6555	S23	188	2530	R4/S5/G-	32.6	+1.5
5	10.04.2001	9415	S22	359	880	R4/S3/G-	28.73	+1
6	08.08.1989	5629	S17	076	1320	R5/S4/G4	≥26.8	-0.5
7	28.03.2001	9393	N20	152	2440	R5/S2/G-	>25.74 (28.24)	+1
8	17.05.1990	6063	N34	321	940	R3/S3/G-	23.1	+1
9	12.01.1989	5312	S31	308	1800	R3/S1/G-	22.4	-0.5
10	15.01.2005	10720	N09	177	1630	R4/S3/G4	21.5	+4.7
11	11.12.2006	10930	S06	009	680	R4/S2/G4	20.8	+6.6
XX	04.08.1972	0331	N12	010	1330	R5?/S5/G5	>26.0	+3.5

Here CMP - time of the central meridian active region passage; AR - number of active region in system NOAA; Φ° - average heliolatitudes of active region; L° - average a Carrington longitude of active region; XRI - the X-ray flare index (XRI); R, S, G - classes of the maximal events from flares in the given active region in the Earth's space environment; M±y - distance in years from a point of a solar cycle maximum (accuracy 0.5). Bold and italic allocates lines represents of the current 23 solar cycle active regions.

Conclusions

It follows from the above that the 23rd cycle is developing according to a scenario that is typical of normal SA cycles. According to this scenario, the most powerful flare events occur during the growth phase and especially during the declining phase of the cycle. Some of the features of the development of the current 23rd solar-activity cycle and the pattern of the development of ARs typical of this cycle may be indicative of a change in the generation mode of magnetic fields in the solar convection zone. This may mean that the Sun is entering a period of intermediate and small SA cycles, which may last about five to six solar cycles (50–70 years). A decrease in the number of ARs may result in an increase in the number of coronal holes and, consequently, in the number of recurrent high-velocity solar-wind streams, which will cause in the Earth's environment a relative increase in the number of recurrent minor geomagnetic disturbances. A significant decrease in the number of flare events will result in a decrease in the number of usually stronger sporadic geomagnetic disturbances and in an increase in the periods of quiet geomagnetic conditions. The weakening of the regime of carrying out of solar magnetic fields will result in the shrinking of the modulation zone of galactic cosmic rays in interplanetary space and in a significant increase in their intensity in the Earth's environment and, consequently, in an increase in the radiation background throughout the entire solar cycle, not only during the epoch of cycle minimum. Sporadic heating of the Earth's atmosphere will decrease significantly, resulting in even stronger pollution of the Earth's environment (unfavorable regime of the removal of cosmic garbage from low-Earth orbit), and other, possibly unfavorable, consequences.

Acknowledgements

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