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Descriptive study of solar activity sudden increase and Halloween storms of 2003

A.A. Hady

Astronomy Department, Faculty of Science, Cairo University, Cairo 12613, Egypt

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ABSTRACT

During the declining phase of the last three solar cycles, secondary peaks have been detected 2–3 years after the main peak of sunspot number. The main peak of cycle 23 was in 2001, but a sudden increase of the solar activity occurred during the period October 17 to November 10, 2003 (the so-called Halloween storms). A similar storm occurred 1 year later, during the period October 3 to November 13, 2004. These events are considered as secondary peaks during the declining phase of cycle 23. Secondary peaks during declining phase of the last 10 solar cycles were detected by Gonzalez and Tsurutani [1990. Planetary and Space Science 38, 181–187]. During Halloween storm period, the sunspot area increased up to 1.11×10^{-9} hemisphere on October 19, and grow up to 5.69×10^{-9} hemisphere on October 30, 2003. Then it decreased to 1.11×10^{-9} hemisphere on November 4, 2003. Also, the radio flux of $\lambda = 10.7$ cm increased from 120 sfu on October 19, to 298 sfu on October 26, 2003, then decreased to 168 sfu on November 4, 2003. Two eruptive solar proton flares were released on 26 and 28 October 2003, the latter being the most eruptive flare recorded since 1976 (values reaching X17/4B).

The aim of this study is to follow the morphological and magnetic changes of the active region before, during, and after the production of high-energy flares. Furthermore, the causes of release of these eruptive storms have been discussed for the period, October–November 2003, during the declining phase of the solar cycle 23.

1. Introduction

During the declining phase of solar cycles, energetic solar events affect the earth's atmosphere, satellites, and human activities. Reames et al. (1994) and Reames (1995) revealed that the solar energetic particles (SEP) and the coronal mass ejections (CME), whose origins are different, are related to magnetic changes, in the active region, which produce the SPE, and are also related to the abundances, ionization states, and time production of the particles as well as to their longitude distribution. The SEP and CME events lead to severe effects in geospace and on earth, such as power blackouts, disruption of communications, and damage to satellites.

It is well known that solar activity exhibits an 11-year periodicity, and the more dramatic activities usually occur at the maximum of the cycle. The complex dynamics of magnetic fields play a key role in solar activity (Parker, 2001). Although the peak of solar cycle 21 took place in 1979, high-energy solar flares, or secondary peaks, occurred during the declining phase in 1981, 1982, and 1983 before the solar activity minimum in 1986. Likewise, the peak of the solar cycle 22 appeared in 1989; however high-energy solar flares occurred during the declining phase in 1991, 1992, and 1994, before the solar activity minimum in 1996. Thus secondary peaks occurred during an interval 2–3 years after the occurrence of the solar activity maximum, as deduced from the last five solar cycles (Beck et al., 2005; Hady, 2002; Shaltout, 1995).

The 11-year solar cycle 23 began in May 1996 with smoothed sunspot number of 8, and peaked in April 2000 at 128.8; the main peak of this cycle being in 2001. However, a sudden increase of activities occurred during the period of so-called Halloween storms, in October–November 2003. Similar storms occurred 1 year later, during the period from October 3 to November 13, 2004. They are considered secondary peaks during the declining phase of cycle 23. By the end of October 2003, NOAA space weather forecasters were engaged in the most active and demanding solar activity in the history (Wu et al., 2007).

From October 19 to November 7, 2003 the highest energetic solar flares were detected. During October 28 to November 2, 2003, three shocks generated by four solar flares were observed.

CMEs hitting the earth, can excite geomagnetic storms, and in the space beyond the protection of the earth's magnetic field, they typically drive shock waves that produce penetrating energetic particles which may damage electronic equipment and injure astronauts. So, predictions of the energetic particle events are of

E-mail address: aahady@cu.edu.eg

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vital importance for space navigation and mitigation of airline problems, Shaltout and Hady, 2001.

During the last three solar cycles, and during their declining phase, the occurrence of secondary peaks was given by Pontieri et al. (2003). The study of eruptive solar proton flares is particularly challenging because there are no adequate theoretical models for the production of such high energies in the solar atmosphere (Kunches, 2004).

The aim of this present work is to study the different indices of solar activity during the most eruptive and energetic solar activity during October–November 2003, and to investigate the existence of secondary peaks during the declining phase of solar cycle 23. In particular we focus our study on the period from October 17 to November 10, 2003, and on the active region No. 10486, during the most eruptive flare storm since 1976. In addition, we study causes of the release of the eruptive flares on October–November 2003.

2. The declining phase of cycles 21, 22, and 23

Daily solar data prepared by the NOAA Space Environment Center have been used to perform this analysis. The most eruptive events at their peaks and during the declining phases of solar cycles 21, 22, and 23 are tabulated in Table 1, including data on proton flux, X-ray and optical flares, and the active regions and their location in the solar disk.

From Table 1, we note that:

1. Throughout the declining phase of the current solar cycle 23, there are sudden rises in the solar activity. During the period from October 28 to November 4, 2003, there was a sudden and high solar activity in the active region 10486, which produced one of the most eruptive flares recorded since 1976.
2. During the period from October 28 to November 4, 2003, the proton flux reached 29,500 pfu. X-ray flares were in the X17 class level, and reached the class level, X28 on November 4, 2003. In the mean time the H_α flare was 4B, and reached 3B on November 4, 2003. The X-ray sensors on-board of the GOES spacecraft were not able to record accurate X-ray intensities because they saturated. It appears that this X-ray flare peaked somewhere between the X30 and X40 class level.
3. During the declining phase of the solar cycles 21, 22, and 23 high-energy eruptive flares were recorded. Some of them were higher than the peaks of the solar cycle, as shown in solar cycle 23 (October 19 to November 4, 2003) and are named secondary peaks of the solar cycle during its declining phase.

The X-ray classification of solar flares is considered the most useful measuring tool of the strength of a flare. To classify the most energetic flares since 1976, the usual classification of flares uses the descriptive letter M if the X-ray power output is in the range 0.01–0.1 erg/cm^2/s and the letter X if it is above the value 0.1. A multiplier number is also attached to the description so that a X5.0 flare has a power of 0.5 erg/cm^2/s. M-class flares, particularly the less energetic ones, are likely to cause a fadeout on only the lowest frequencies of the high-frequency (HF) radio spectrum. X-class flares will cause a fadeout for all HF frequencies over the entire daylight hemisphere of the earth. X-class flares are also more likely to be associated with a host of interesting effects here on earth and in space. X-class flares are of the greatest importance concerning the sun. Secondary peak of the solar cycle

Table 1
Eruptive solar proton events and eruptive flares affecting the earth environment during the peaks and declining phases of the cycles 21, 22, and 23.

Proton flux			Flares			
Start date/UT	Max. date/UT	Proton flux (pfu at >10 MeV)	Flare max. date/UT	Importance X-ray/opt.	Loc.	Region No.
(*Peak of cycle 21*)						
19780923/1035	0924/0400	**2200**	0923/1023	X1/3B	N35W50	1294
(*Decline of cycle 21*)						
19811008/1235	1013/2247	**2000**	1007/2308	X3/1B	S19E88	3390
19820711/0700	0713/1615	**2900**	0709/0742	X9/3B	N17E73	3804
19821208/0010	1208/1000	**1000**	1207/2354	X2/0B	S14W81	4007
19840425/1330	0426/1420	**2500**	0425/0005	X13/3B	S12E43	4474
(*Peak of cycle 22*)						
19890308/1735	03 3/0645	**3500**	0306/1405	X15/3B	N35E69	5395
19890317/1855	0318/0920	**2000**	0317/1744	X6/2B	N33W60	5395
19890812/1600	0813/0710	**9200**	0812/1427	X2/2B	S16W37	5629
19890929/1205	0930/0210	**4500**	0929/1133	X9/EPL	S26W90	5698
19891019/1305	1020/1600	**40000**	1019/1258	**X13/4B**	S27E10	5747
19891130/1345	1201/1340	**7300**	1130/1229	X2/3B	N26W59	5800
(*Decline of cycle 22*)						
19910323/0820	0324/0350	**43000**	0322/2247	X9/3B	S26E28	6555
19910604/0820	0611/1420	**3000**	0604/0352	**X12/3B**	N30E70	6659
19910614/2340	0615/1950	**1400**	0615/0821	**X12/3B**	N33W69	6659
9910707/0455	0708/1645	**2300**	0707/0223	X1/2B	N26E03	6703
19940220/0300	0221/0900	**10000**	0220/0141	M4/3B	N09W02	7671
(*Peak of cycle 23*)						
20000714/1045	0715/1230	**24000**	0714/1024	X5/3B	N22/W07	9077 9213
20001108/2350	1109/1600	**14800**	1108/2328	M7/mult	N00-10 W75-80	9213 9213
20010924/1215	0925/2235	**12900**	0924/1038	X2/2B	S16E23	9632
20011104/1705	1106/0215	**31700**	1104/1620	X1/3B	N06W18	9684
20011122/2320	1124/0555	**18900**	1122/2330	M9/2N	S15W34	9704
(*Decline of cycle 23*)						
20020421/0225	0421/2320	**2520**	0421/0151	X1/1F	S14W8	9906
20031028/1215	1029/0615	**29500**	1028/1110	**X17/4B**	S16E08	10486
20031102/1105	1103/0815	**1570**				
20031104/2225	1105/0600	**353**	1104/1915	**x28/3b**	s19w83	10486

23 occurred in its declining phase in October–November 2003 and was associated with the largest solar flares since 1976.

The daily solar data and Mg II core-to-wings ratio of the eruptive days during the peak and declining phase of solar cycle 23 are shown in Table 2.

Column 1 gives the date in year/month/day, Column 2 gives the radio flux 10.7 cm (2800 MHz) in units of 10 E–22/SqWm/Hz. Column 3 contains the sunspot numbers. The sunspot number for the indicated date is obtained from the daily solar region summary issued by the Space Environment Service Center (SESC). The SESC sunspot number is computed according to the Wolf sunspot number, $R = k\,(10g{+}s)$ where g is the number of sunspot groups (regions), s the total number of individual spots in all the groups, and k a variable scaling factor.

Column 4 indicates the sunspot area that is defined as the sum of the corrected area of all observed sunspots, in units of millionths of the solar hemisphere. The sunspot area increased from 4520 on October 28, 2003 to 5690 on October 30, 2003 and then decreased to 4420 on October 31, 2003. Such measurements had not been recorded previously.

Column 5 gives the X-ray background flux. The daily average background X-ray flux, measured on the SEC primary GOES8 satellite, is tabulated.

Column 6 gives the total number of X-ray flares observed during the day for X-ray flare class B, C, M, and X.

During the declining phase (October–November 2003) both X-ray background flux and total numbers of X-ray flares reach higher values than those recorded at the solar cycle peak.

Column 7 gives the Mg II core-to-wing ratio, which is derived by taking the ratio of H and K lines of the solar Mg II feature at 280 nm to the background or wings at approximately 278 and 282 nm. The H and K lines are variable chromospheric emissions while the background emissions are more stable. The result is a robust measurement of the chromospheric activity. This ratio has been shown to be in good agreement with solar UV and EUV emissions. Column 8 gives the source of the Mg II core-to wing ratio data. The data of Mg II core-to-wing ratio did not indicate dramatic changes during October–November 2003, as in the data of the SESC sunspot number; more details are given by Krivova et al. (2006).

Daily solar particle data of the most eruptive days, at the peak and during the declining phase of solar cycle 23, are given in Table 3. Proton fluences as daily integrated particle fluxes are given in this table. Protons in different energy bands, >1, >10, and >100 MeV in units of protons/cm^2/day/str, are measured by the primary Goes-8 spacecraft at geosynchronous orbit. The daily solar data show during October–November 2003 an increase of proton fluence at energy higher than 1 MeV. The maximum value was not recorded during October 28, the release time of the most eruptive flare, but was recorded on October 29, 2003. The same features are observed for proton fluence at energy >10 MeV, but were not observed in the proton flare energy band >100 MeV due to the higher speed of energetic solar protons in space. A study of the great solar proton events during solar cycle 23 is reported by Blagoveshchensky et al. (2005) and Hady et al. (2006).

3. Halloween storms and its active region

The source region of the Halloween storms is in the strong active region, NOAA AR 10486. Its configuration is classified as beta–gamma–delta, which indicates its extreme potential and that it contains a large amount of free energy. The active region passed across, or transited the frontal solar disk from October 12 to November 04, 2003, producing 8 X-class flares and extremely fast halo CMEs with speeds of more than 2000 km/s (NOAA NWS Service, 2004).

Active region AR 10486 was located at S17 L283 on October 28, and passed through the solar disk from October 23 to November 4, 2003. This region has rotated behind the western limb and out of view on November 4, 2003. After 14 days it crossed to the far side of the sun on 18 November 2003, and produced a high-energy flare on November 19, 2003, as in Fig. 1, which was given by EIT camera on-board SOHO spacecraft for the spectral lines 308 Å of Fe II.

This region produced the two most important solar flares during the period 1976–2003. The first flare was released on 12:15 UT on 28 October 2003 with importance X17/4B, and the second flare was released on 22:25 UT on 4 November 2003 with importance X28/3B. As shown in Fig. 1, on October 28, 2003 the

Table 2
Daily solar data of most robust eruptive days during the peak and declining phase of solar cycle 23.

Sunspot GOES8										
Date	Radio flux	SESC sunspot number	Area 10E−6 hemis	X-ray bkgd. flux	X-ray flares				Mg II core-to-wing ratio	Mg II source
					B	C	M	X		
20000714	204	243	1560	C2.9	4	2	1	15	–	No data
20000715	213	229	1120	C2.6	8	1	0	28	–	No data
20001108	173	171	910	C1.1	8	3	0	6	0.2780	GOME
20001109	166	149	730	M1.1	1	3	0	3	0.2786	GOME
20010924	279	315	3160	C1.8	8	0	1	0	0.2841	NOAA 16
20010925	275	320	2860	C2.5	3	3	0	0	0.2844	NOAA 16
20011104	227	186	1820	C1.7	5	0	1	12	0.2806	NOAA 16
20011105	235	159	2320	C3.3	7	4	0	9	0.2817	NOAA 16
20011122	190	143	1310	B8.1	6	3	0	7	0.2821	NOAA 16
20011123	177	144	1120	M1.5	4	0	0	4	0.2823	NOAA 16
20020421	173	160	1030	C1.3	4	0	1	2	0.2803	NOAA 16
20020422	170	155	980	C1.0	8	0	0	5	0.2795	NOAA 16
20031028	**274**	**230**	**4520**	**C3.2**	**5**	**0**	**1**	**31**	0.2802	NOAA 16
20031029	**279**	**330**	**5160**	**C3.3**	**4**	**2**	**1**	**16**	0.2811	NOAA 16
20031030	**271**	**293**	**5690**	**C2.8**	**6**	**2**	**0**	**2**	0.2816	NOAA 16
20031031	**249**	**266**	**4420**	**C1.8**	**7**	**2**	**0**	**12**	0.2810	NOAA 16
20031101	210	277	4170	C1.8	9	3	0	10	0.2801	NOAA 16
20031102	190	174	4050	C1.9	1	2	1	9	0.2801	NOAA 16
20031103	167	76	2830	C3.2	3	1	2	6	0.2774	NOAA 16
20031104	168	79	1100	C2.3	3	3	1	1	0.2752	NOAA 16

region had maximum area, maximum intensity, and highest temperature compared with other days of the development of the region on the solar disk, Michalek et al. (2004).

Table 3
Daily solar particle data of most robust eruptive days during the peak and declining phase of solar cycle 23.

Date	GOES8 proton flounce Protons/cm2-day-sr		GOES8 electron flounce Electrons/cm2-day-sr			Neutron Monitor
	>1 MeV	>10 MeV	>100 MeV	>0.6 MeV	>2 MeV	% of bkgd
20000714	3.3e+08	2.3e+08	1.1e+07	4.5e+09	1.2e+06	−1.90
20000715	2.6e+09	1.0e+09	4.7e+06	2.8e+09	5.7e+05	−5.40
20001108	7.2e+05	3.6e+04	3.2e+03	5.2e+09	5.8e+06	−0.90
20001109	1.3e+09	7.5e+08	1.3e+07	8.3e+09	4.9e+07	0.54
20010924	4.8e+07	3.1e+07	2.9e+05	1.5e+09	4.2e+04	−0.50
20010925	1.1e+09	2.7e+08	1.8e+06	4.6e+09	7.0e+06	−0.80
20011104	2.7e+07	2.0e+07	1.1e+06	6.8e+08	1.1e+06	2.04
20011105	9.3e+08	5.3e+08	3.6e+06	2.7e+09	1.2e+04	1.15
20011121	3.2e+07	2.3e+05	2.4e+03	4.4e+09	3.3e+06	−0.40
20011122	1.1e+07	1.2e+05	1.0e+04	4.1e+09	2.2e+06	−1.40
20020421	1.9e+08	1.3e+08	1.2e+06	2.4e+10	1.0e+07	–
20020422	3.3e+08	8.0e+07	2.9e+05	2.2e+10	5.6e+07	–
20031028	**2.8e+08**	**1.8e+08**	**5.2e+06**	**8.7e+09**	**4.8e+06**	**100.70**
20031029	**3.0e+09**	**7.7e+08**	**4.2e+06**	**2.1e+09**	**4.7e+06**	**88.60**
20031030	**7.7e+08**	**1.4e+08**	**2.6e+06**	**7.9e+09**	**1.9e+07**	**81.80**
20031031	**9.8e+07**	**7.0e+06**	**2.2e+04**	**1.6e+09**	**3.4e+06**	**81.30**
20031101	1.6e+07	7.6e+05	2.5e+03	3.6e+10	1.5e+08	84.30
20031102	3.1e+07	1.5e+07	5.0e+05	4.7e+10	4.3e+08	89.00
20031103	3.6e+08	8.9e+07	2.2e+05	2.9e+10	2.2e+08	93.40
20031104	4.3e+08	1.0e+07	1.7e+04	8.3e+09	7.0e+07	95.00

Fig. 2a shows the solar disk on October 28, 2003; its active region 10486 is shown with sunspot groups and its morphology is displayed in the corner of the figure, with courtesy of NASA/SOHO, animation by Max Riesman. Region No.10486 is of the largest sunspot area in the current solar cycle. This sunspot did not change its structure considerably, following the major X-class flare. The magnetic polarities are shown in the upper part of Fig. 2a, and the magnetic properties of the sunspot complex are maintained.

In Fig. 2b, the photospheric vector magnetogram in the active region 10486 is shown. The dashed contours indicate the longitudinal field of positive polarity (white), and negative polarity (black). The arrows mark the transverse field. The magnetograms of the region are overlaid with H_α image see Deng et al. (2003). This figure is taken from Wang et al. (2003).

A mega-flare starting at 19:29 UT on November 4, 2003 was produced from active region 10486. This one saturated the X-ray detectors on the NOAA's GOES satellites. This record-breaking X-class of this solar flare is shown in Fig. 3. The region 10486 is shown in this figure, before the rotation of the region behind the western limb of the sun (Fig. 3a). X-ray sensors on-board the GOES spacecraft recorded X-ray intensities up to the X-28 class level. This solar mega-flare saturated the X-ray detectors for 11 min, then the detectors not being able to detect the biggest solar flare X28/3B seen in recent years, and 15 M-class occurred in this region. The mentioned region is shown in details when the X-28 flare started growing as shown in Fig. 3a. Daily solar data given from NOAA Space Environment Center, have been used for this analysis. Radio flux (10.7 cm), SESC sunspot number, sunspot area,

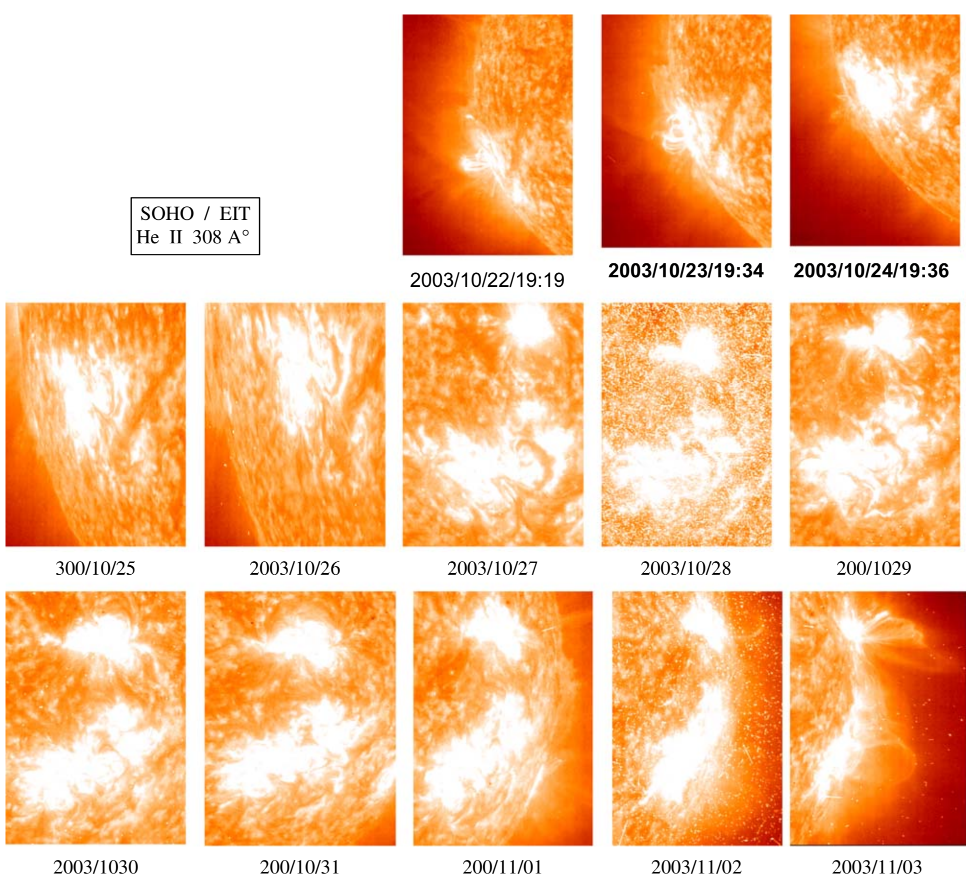

Fig. 1. The behavior of region No. 10486 from October 22, 2003 to November 3, 2003 before the region rotated behind western limb and out of view on November 4, 2003.

X-ray background flux, optical flares, and X-ray flares were extracted from October 25 until November 10, 2003. See for example Kunches (2004).

From the SOHO observations, four solar flares were observed during October 28, 2003. Two very distinct geomagnetic storms, associated with two of these flares (X17/4B and X10/2B), ranked as two of the largest storms of the solar cycle 23. The fast CMEs caused extreme disturbances of solar wind flow. When impinging the earth's magnetosphere, extreme disturbances of the entire magnetosphere including the radiation belts were observed.

The 2003 Halloween storms had profound impacts. The international space station switched to a ground-commanded power down, and crews onboard took shelters in the service module during the peak exposure times. About 24% of the space missions turned off their instruments or took other protective actions. One Japanese satellite (ADEOS-2) is believed to have completely failed due to this storm. The NASA/ESA's SOHO satellite and the German satellite CHAMP failed temporarily, while the NASA satellite ACE was damaged beyond repair. Some satellite-based communication companies (TV and radio) reported several short-lived interruptions. Airlines restricted flight paths on several occasions due to degraded communications. GPS users reported degradation and outages with some applications (NOAA NWS Service, 2004).

4. Conclusion

From our analysis and results, we conclude:

1. During the declining phase of the last three solar cycles (21, 22, and 23) high-energy eruptive flares were recorded. Some of them are stronger than those occurring at the peaks of the cycles. The main peak of cycle 23 was in 2001, but an explosion of activities occurred during the period October 17–November 10, 2003 (so-called Halloween storms).
2. After releasing the high-energy flares, the protons and electrons fluences in different energy bands increased suddenly as measured by GEOS satellites, for most of the flares. However for the eruptive energetic flare on 28 October 2003,

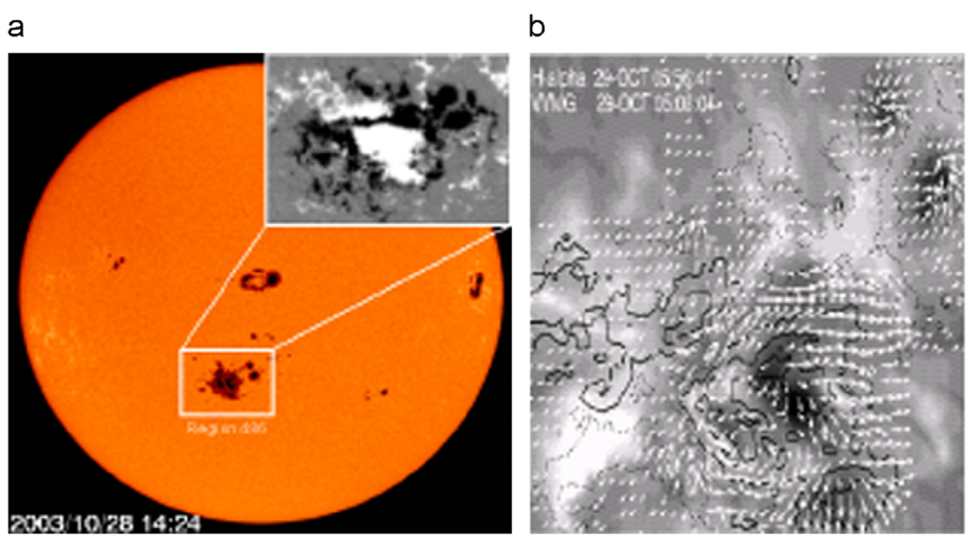

Fig. 2. The solar disk active region No. 10486, and sunspot during the first large storm (a), and photospheric vector magnetograms in this region (b), (http://www.spacew.com/astroalert.html).

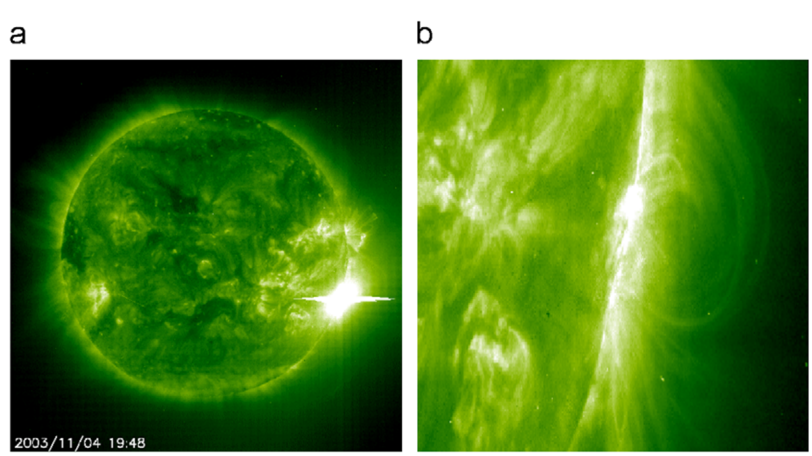

Fig. 3. Solar disk before the region 10486 rotated behind the western limb at 19:29 UT on November 4, 2003. This active region and X-28 flare, are derived from (http://sohowww.nascom.nasa.gov/).

dramatic increases were recorded, and the satellite sensors were not able to record the full events.

3. The geomagnetic indices had increased after the high-energy flare was released, 1–2 days after the beginning of the solar flares, due to the coronal mass ejection and geomagnetic storm occurrence.
4. There was a pronounced increase in the radiation belt indices detected from relative intensities of NOAA/POES energetic particles 1–2 days after the release of those high-energy flares.
5. From this analysis, we conclude that the release of the eruptive flares on October–November 2003, are due to the large area of the active region AR 10486 and to a very strong solar magnetic field.

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