Statistical study on great geomagnetic storms during solar cycle 23*

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Abstract Characteristics of great geomagnetic storms during solar cycle 23 were statistically investigated. Firstly, we focused on the uniqueness of solar cycle 23 by analyzing both the great storm number and sunspot number from 1957 to 2008. It was found that the relationship between the sunspot number and great storm number weakened as the activity of the storms strengthened. There was no obvious relationship between the annual sunspot number and great storm number with $Dst \leq -300$ nT. Secondly, we studied the relationship between the peak Dst and peak Bz in detail. It was found that the condition $Bz \leq -10$ nT is not necessary for storms with $Dst \leq -100$ nT, but seems necessary for storms with $Dst \leq -150$ nT. The duration for $Bz \leq -10$ nT has no direct relationship with the giant storm. The correlation coefficient between the Dst peak and Bz peak for the 89 storms studied is 0.81. After removing the effect of solar wind dynamic pressure on the Dst peak, we obtained a better correlation coefficient of 0.86. We also found the difference between the Dst peak and the corrected Dst peak was proportional to the Dst peak.

Key words: geomagnetic storms; solar cycle 23; sunspot number; 4.5 solar cycles; peak Dst and peak Bz

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1 Introduction

It is well known that magnetic activity observed on the ground depends on solar activity. Chapman and Bartels (1940) found that geomagnetic activity is correlated with the sunspot number, so the occurrence of magnetic storms has the same period of the solar cycle.

A magnetic storm is a global geomagnetic field disturbance characterized by a distinct decrease in the horizontal component of the magnetic field at mid- and low-latitudes. It is generally accepted that the source of the magnetic disturbance is a westward ring current circling the Earth in the equatorial plane. The strength of a magnetic storm is usually estimated using the Dst index, which is derived from hourly values of the horizontal component of the geomagnetic field recorded at

four low-latitude stations. Gonzalez et al. (1994) defined the storms with $-30 \text{ nT} \leq Dst \leq -50 \text{ nT}$ as weak storms, those with $-50 \text{ nT} \leq Dst \leq -100 \text{ nT}$ as moderate storms and those with $Dst \geq -100 \text{ nT}$ as great or intensive magnetic storms, and the classification has been extensively adopted.

The input energy of geomagnetic storms comes from the Sun, and the energy is transferred into the Earth's magnetosphere by streams of solar wind. The energy from solar wind is injected into the magnetosphere only in the case when the interplanetary magnetic field (IMF) has a significant component parallel to the terrestrial magnetic dipole; i.e., an approximately negative (southward) Bz component of the IMF (Russell et al., 1974; Perreault and Akasofu, 1978; Tsurutani and Gonzalez, 1997; Gonzalez et al., 2007; Echer et al., 2008a, b). The mechanism for energy transfer between the solar wind and magnetosphere is the magnetic reconnection between the IMF and the Earth's magnetic field (Dungey, 1961), and the energy transfer efficiency is of the order of 10% during intensive magnetic

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storms (Gonzalez et al., 1989). Gonzalez et al. (2011a) reviewed the interplanetary causes of intensive geomagnetic storms, and pointed out that the most common interplanetary structures leading to the development of intensive storms were magnetic clouds, sheath fields, sheath fields followed by a magnetic cloud and corotating interaction regions at the leading fronts of high speed streams. Gonzalez and Tsurutani (1987) found that intensive storms with peak $Dst \leq -100$ nT are primarily caused by large fields with $Bz \leq -10$ nT and a duration longer than three hours. Kane and Echer (2007) examined the evolutions of severe geomagnetic storms ($Dst < 200$ nT) during solar cycle 23, and noticed that the phase delay between the maximum of interplanetary negative Bz and the maximum of negative Dst varied in a very wide range from storm to storm. Zhang et al. (2011) indicated that the product of solar wind density and the south component of IMF determine the development of the main phase of a geomagnetic storm.

Solar cycle 23 started in April 1996 with a sunspot number of 8.0 and reached its peak in March 2000 with a maximum sunspot number of 120.8. Afterward, the sunspot number for each year decreased toward a minimum. The maximum sunspot number of solar cycle 23 was lower than those of solar cycles 19, 21 and 22. However, cycle 23 was very active, and there were five giant magnetic storms with $Dst \leq -300$ nT in the declining years 2001, 2003 and 2004. Furthermore, three of these giant storms occurred within one month. In addition, there are more satellite data for the Sun and IMF in solar cycle 23 than that in previous solar cycles, which is favorable for research work on space weather. Solar cycle 23 is very interesting and has been the subject of much research (Dal et al., 2004; Gopalswamy et al., 2005; Gonzalez and Echer, 2005; Gonzalez et al., 2007).

In this paper, we statistically investigated characteristics of great geomagnetic storms during solar cycle 23. In section 2, we focused on the uniqueness of solar cycle 23 by analyzing both the great storm number and sunspot number from 1957 to 2008, which covers 4.5 solar cycles from the latter part of solar cycle 19 to solar

cycle 23. In section 3, we investigated the relationship between the peak Dst and peak Bz in detail. We believe that these studies are important for space weather forecasting.

2 The uniqueness of solar cycle 23

2.1 Data preparation

The one-hour Dst index obtained from the World Data Center for Geomagnetism, Kyoto was used to characterize the intensity of a magnetic storm. The Dst index has been published since 1957, so we studied storms latter than that year. The Dst index is available in its final form for the period from 1957 to 2003. It should be noted that the Dst index after 2003 is provisional, and that the Dst index after 2006 was given in real time when this work was undertaken, and hence the final index could be a little different. The international sunspot number was obtained from the National Geophysical Data Center of the National Oceanic and Atmospheric Administration. All magnetic storms with $Dst \leq -100$ nT from 1957 to 2008 were used.

2.2 Comparison between solar cycle 23 and other cycles

There were 402 great storms with $Dst \leq -100$ nT from 1957 to 2008, with an average of 7.7 storms per year; the maximum number of such storms was 20, both in 1960 and 1989. There were 71 great storms with $Dst \leq -200$ nT during the same period, with an average of 1.4 storms per year; the maximum number of such storms was 7 in 1957. There were 22 giant storms with $Dst \leq -300$ nT, with an average of 0.4 storms per year; the maximum number of such storms was three in 1957, 1958, 1960 and 2003. The years 1957, 1958 and 1960 were in solar cycle 19 and only the year 2003 was in solar cycle 23.

Table 1 shows the annual occurrence rate of great magnetic storms of different intensities. The table shows that the annual occurrence rate in cycle 23 was only lower than that in cycle 19 for storms with $Dst \leq -200$ nT and $Dst \leq -300$ nT.

Table 1 Annual occurrence rate of great magnetic storms with different intensities

Intensity of storms	Annual occurrence rate					
	All storms	Cycle 19	Cycle 20	Cycle 21	Cycle 22	Cycle 23
$Dst \leq -100$ nT	7.7	10.9	4.4	7.9	9.5	7.3
$Dst \leq -200$ nT	1.4	2.5	0.75	1.3	1.1	1.5
$Dst \leq -300$ nT	0.4	1.25	0.08	0.3	0.2	0.5

Figure 1 shows the ratio of the storm number to the maximum annual number of sunspots for each solar cycle. It can be seen that the ratio is the greatest in cycle 23 for storms with $Dst \leq -100$ nT or $Dst \leq -200$ nT.

There were 22 giant storms with $Dst \leq -300$ nT

from 1957 to 2008. Table 2 shows the occurrence date and times of these storms according to Dst. Among them, 10 storms appeared in cycle 19 and six storms appeared in cycle 23. Table 2 indicates that four of the 10 most intense giant storms appeared in cycle 23.

Figure 1 Ratio of the storm number to the maximum annual number of sunspots in each solar cycle for magnetic storms with $Dst \leq -100$ nT (a) and for magnetic storms with $Dst \leq -200$ nT (b).

Table 2 List of giant storms with $Dst \leq -300$ nT from 1957 to 2008

Order	Date a-mo-d	Time h:min	Dst	Order	Date a-mo-d	Time h:min	Dst
1	1989-03-13	01:28	-589	12	1960-11-12	13:49	-339
2	1959-07-15	08:03	-429	13	1958-07-08	07:49	-330
3	1957-09-13	00:46	-427	14	1960-03-31	04—	-327
4	1958-02-11	01:27	-426	15	1960-04-30	01:30	-325
5	2003-11-20	08:02	-422	16	1982-07-13	16:18	-325
6	1967-05-24	17:29	-387	17	1957-09-04	13:00	-324
7	2001-03-19	11:13	-387	18	1981-04-11	05—	-311
8	2003-10-30	16:36	-383	19	1986-02-06	13:12	-307
9	2004-11-07	18:28	-373	20	1957-09-22	13:45	-303
10	2003-10-29	06:11	-353	21	1958-09-03	08:41	-302
11	1991-11-08	06:47	-354	22	2000-07-15	14:37	-301

2.3 Relationship between the sunspot number and the great storm number from 1957 to 2008

Figure 2 shows the relationship between the annual sunspot numbers and great storm numbers from 1957 to 2008. The correlation coefficients for great storm numbers with $Dst \leq -100$ nT and $Dst \leq -200$ nT are 0.79 and 0.64, respectively. It is obvious that there is no relationship between the annual sunspot number and great storm number with $Dst \leq -300$ nT in the figure.

Figure 3 shows the annual sunspot numbers and the numbers of great storms with different intensities to make their relationship clearer. The curve indicates the distribution of sunspot numbers, and the columns lists the numbers of great storms with $Dst \leq -100$ nT,

$Dst \leq -200$ nT, $Dst \leq -300$ nT, $Dst \leq -400$ nT and $Dst \leq -500$ nT, respectively. The sunspot number curve shows five obvious periods from solar cycle 19 to solar cycle 23. The year of the cycle maximum and corresponding annual mean sunspot number are 1957, 190.2; 1968, 105.9; 1979, 155.4; 1989, 157.6 and 2000, 119.6, respectively. The relation between the sunspot number and great storm number weakened as the intensity of magnetic storms strengthened. For example, the annual sunspot number of the solar cycle 23 maximum is only larger than that of the solar cycle 20 maximum, but both the number of intense storms with $Dst \leq -200$ nT and the number with $Dst \leq -300$ nT in solar cycle 23 are only less than the numbers for solar cycle 19, which was the most active solar cycle among the five studied.

Figure 2 Relationship between the annual sunspot number and great storm number from 1957 to 2008. (a) For magnetic storms with $Dst \leq -100$ nT, (b) for magnetic storms with $Dst \leq -200$ nT, (c) for magnetic storms with $Dst \leq -300$ nT.

Figure 3 Annual sunspot numbers and great storm numbers for different intensities.

3 Relationship between the peak Bz and the peak Dst in solar cycle 23

3.1 Analysis method

One-hour data of the IMF parameters were obtained from the Goddard Space Flight Center at the Na-

tional Aeronautics and Space Administration and had a shift of ~ 200 Re (~ 0.01 AU) upstream of the Earth (1 AU). Therefore, we do not need to consider the propagation time between Lagrangian point L_1 , where the Atmospheric Chemistry Experiment satellite is orbiting, and the Earth. We selected great storms with $Dst \leq -100$ nT in solar cycle 23 from 1996 to 2008. There were 89 magnetic storms with $Dst \leq -100$ nT during the period, including 18 storms with $Dst \leq -200$ nT, six storms with $Dst \leq -300$ nT and one storm with $Dst \leq -400$ nT. The annual and monthly distributions of these storms are similar to those reported by Zhang et al. (2007). Comparing with the storms of cycle 23 used by Zhang et al. (2007), two magnetic storms appearing in April and December of 2006 are added in this paper, and the storm appearing on August 7, 1998 is excluded because we believe it cannot be considered to be an individual storm according to the magnetic field variation on that day. Therefore, the magnetic storm number in this paper is one more than that in the work of Zhang et al. (2007).

Figure 4 shows Bz and Dst profiles during inten-

sive magnetic storms from April 17 to April 19, 2001 as an example of the analysis. The Dst and Bz peaks are identified by the labels Dst_{peak} and Bz_{peak} . There are two dotted vertical lines passing through the Dst and Bz peaks in the figure to illustrate the delay time between peaks ΔT_1 . A dotted horizontal line for $Bz = -10$ nT is also shown, and the duration for which $Bz \leq -10$ nT is denoted ΔT_2 . If Bz is still lower than -10 nT after the Dst peak or Bz peak, then we define ΔT_2 as being until Bz_{peak} when Bz_{peak} lags behind Dst_{peak} , and being until Dst_{peak} otherwise.

Figure 4 Bz and Dst profiles during intense magnetic storms from April 17 to April 19, 2001. The peak values of Bz and Dst are denoted Bz_{peak} and Dst_{peak} , the delay between the Dst and Bz peaks is denoted ΔT_1 , and the duration with $Bz \leq -10$ nT is denoted ΔT_2 .

To remove the effect of solar wind dynamic pressure on Dst_{peak} , we corrected Dst_{peak} as Dst_{peak}^* according to Burton et al. (1975).

$$Dst_{peak}^* = Dst_{peak} - b \cdot P^{1/2} + C, \quad (1)$$

Where P is the solar wind dynamic pressure and b and C are constants. We set $b = 8.74 \text{ nT}(\text{nPa})^{-1/2}$ and $C = 11.54 \text{ nT}$ (Turner et al., 2001).

This procedure was performed for each storm. For those storms with multiple peaks, only the highest peak was considered. If there were two continuous Dst peaks of the same magnitude, we chose the one with the higher Dst_{peak}^* as the final Dst peak. Considering that the magnetosphere/ring current response time to Bz was one hour (Akasofu, 1981), the Dst value was corrected for this time; i.e., the Dst curve was shifted one hour back in time.

3.2 Results

Table 3 shows the averages and standard deviations of storm parameters for the 89 storms sorted by the storm activity. The number of storms (N_s), Dst peak (Dst_{peak}), Bz peak (Bz_{peak}), delay between the peaks of Bz and Dst (ΔT_1), duration of $Bz \leq -10$ nT (ΔT_2) and difference $\Delta(Dst_{peak} - Dst_{peak}^*)$ between the Dst peak and the corrected Dst peak are listed. It was found that the Bz peak and $\Delta(Dst_{peak} - Dst_{peak}^*)$ had close relationships with the Dst peak; i.e., the Bz peak and $\Delta(Dst_{peak} - Dst_{peak}^*)$ increased as the Dst peak increased. However, no clear relationship was found between ΔT_1 or ΔT_2 and the Dst peak.

Table 3 shows that the average and standard deviation of the peak Bz for the 89 storms studied were -18.34 and 10.31 nT, respectively. The distribution of the storm number as a function of the Bz peak is shown in Figure 5. It was found that more than half (62.9%) of the Bz peaks were between -10 nT and -20 nT and 91% were between 0 and -30 nT.

Table 3 Average storm parameters for 89 Storms (1996–2008) sorted by the storm activity

Activity of storms	N_s	Average $\pm$ Standard deviation				
		Dst_{peak}	Bz_{peak}	ΔT_1	ΔT_2	$\Delta(Dst_{peak} - Dst_{peak}^*)$
All Storm	89	-160.2 ± 74.5	-18.34 ± 10.31	2.25 ± 2.25	4.27 ± 3.51	7.39 ± 9.25
$-200 \text{ nT} < Dst \leq -100 \text{ nT}$	71	-128.4 ± 24.8	-14.35 ± 4.00	2.37 ± 2.33	4.23 ± 3.78	5.46 ± 7.78
$-300 \text{ nT} < Dst \leq -200 \text{ nT}$	12	-243.8 ± 35.1	-30.87 ± 12.05	1.42 ± 1.98	3.83 ± 2.29	15.64 ± 10.56
$Dst \leq -300 \text{ nT}$	6	-369.8 ± 40.5	-40.58 ± 10.95	2.5 ± 1.38	5.67 ± 2.25	18.5 ± 8.96

Figure 6 shows the distribution of the storm number as a function of the delay ΔT_1 between the Bz and Dst peaks. Fifty-two storms (58.4%) had a delay of 0–2 hours. Four storms (less than 5%) had a negative delay between the Bz and Dst peaks; i.e., the Dst peak occurred before the Bz peak.

Figure 7 shows the distribution of the storm number as a function of the duration ΔT_2 that $Bz \leq -10$ nT. It is seen that ΔT_2 was between one and four hours for 48 (53.9%) great storms. There were 11 (12.4%) great storms with $\Delta T_2 = 0$, which means that the peak value of Bz did not reach -10 nT for these storms. The Dst

Figure 5 Distribution of the storm number as a function of the Bz peak for 89 great storms from 1996 to 2008.

Figure 7 Distribution of the duration with $B_z \leq -10$ nT for 89 great storms from 1996 to 2008.

Figure 6 Distribution of the storm number as a function of the delay ΔT_1 between the Bz and Dst peaks for 89 great storms from 1996 to 2008 (corrected by 1 hour).

peak values were larger than -120 nT for nine of these storms (with $\Delta T_2=0$), and the Dst peak values for the other two storms were -136 and -148 nT. The maximum of ΔT_2 was 16 hours for the storm starting on November 13, 1998, for which $Dst_{peak}=-131$ nT.

Figure 8 shows the correlation of the Dst peak and the Bz peak for the 89 storms studied. The formula for the least squares line is

$$Dst_{peak} = -53.15 + 5.84 \times Bz_{peak}. \quad (2)$$

The correlation coefficient is 0.81, which means that there was a relationship between the Dst peak and the Bz peak. However, the Bz peaks did not align with the fitting line when Dst was very high.

Figure 9 is a plot of the difference value $\Delta(Dst_{peak} - Dst_{peak}^*)$ versus peak Dst. There were 50

Figure 8 Correlation of the Dst peak and Bz peak for the 89 storms studied.

Figure 9 Correlation of the Dst peak and difference $\Delta(Dst_{peak} - Dst_{peak}^*)$ between the Dst peak and the corrected Dst peak for 89 great storms from 1996 to 2008.

storms (56.2% of all studied) with $0 \text{ nT} \leq \Delta(\text{Dst}_{\text{peak}} - \text{Dst}_{\text{peak}}^*) \leq 10 \text{ nT}$. There were 12 storms with $\Delta(\text{Dst}_{\text{peak}} - \text{Dst}_{\text{peak}}^*) < 0$. The correlation coefficient is -0.445 .

Figure 10 shows the correlation of $\text{Dst}_{\text{peak}}^*$ and Bz_{peak} . The formula for the least squares line is

$$\text{Dst}_{\text{peak}}^* = -42.55 + 6.75 \times \text{Bz}_{\text{peak}}. \quad (3)$$

The correlation coefficient is 0.86. Hence, the correlation coefficient is higher than that for the relationship between Dst_{peak} and Bz_{peak} , and the Bz peaks align with the fitting line.

Figure 10 Correlation of the corrected Dst peak and the Bz peak for 89 great storms from 1996 to 2008.

4 Discussion and conclusions

Comparing solar cycle 23 with other solar cycles, it was found that the ratio of the storm number to the maximum annual number of sunspots is greatest in cycle 23 for storms with $\text{Dst} \leq -100 \text{ nT}$ or $\text{Dst} \leq -200 \text{ nT}$. Considering the low number of sunspots, the magnetic activity of solar cycle 23 appears severe.

Figure 3 shows that there was a close relationship between the sunspot number and great storm number in the period from 1957 to 2008. The contribution of the sunspot number is still consistent with that of the great storms with $\text{Dst} \leq -100 \text{ nT}$. We can conclude from Figure 2 that the relationship between the sunspot number and the great storm number weakened as the activity of the storms strengthened. There was no obvious relationship between the annual sunspot number and great storm number with $\text{Dst} \leq -300 \text{ nT}$. Echer et al. (2011) studied 1 377 geomagnetic storms with peak $\text{Dst} \leq 50 \text{ nT}$ for the period from 1957 to 2008, and indicated that less intense storms have their peak occurrences in the

declining phase, while more intense storms tend to have higher occurrence rates near solar maximum. Gonzalez et al. (2011b) studied the distribution of superintense ($\text{Dst} \leq -250 \text{ nT}$) storms during the space era, and pointed out that superstorms occurred during all phases of the solar cycle, although with a higher tendency around solar maximum and at the early descending phase of the cycle. Thus, for storm-forecasting purposes, it is hard to predict the great storm with $\text{Dst} \leq -300 \text{ nT}$ based on the expected sunspot number or the phase of the solar cycle.

The Bz peak had an average magnitude of -18.15 nT , and 87.6% of studied great storms had $\text{Bz} \leq -10 \text{ nT}$. The peak value of Bz did not reach -10 nT for 11 studied storms, and the Dst peak values for these storms were larger than -150 nT . It was found that the condition $\text{Bz} \leq -10 \text{ nT}$ was not necessary for storms with $\text{Dst} \leq -100 \text{ nT}$, but seems necessary for storms with $\text{Dst} \leq -150 \text{ nT}$. $\text{Bz} \leq -10 \text{ nT}$ can be regarded as the threshold of causing strong storms with $\text{Dst} \leq -150 \text{ nT}$. Of course, more examples are needed to prove it.

The maximum duration with $\text{Bz} \leq -10 \text{ nT}$ was 16 hours for the storm that started on November 13, 1998, and the Dst peak for this storm was -131 nT . It is found that the duration with $\text{Bz} \leq -10 \text{ nT}$ is not in proportion to the strength of a storm.

The average delay time between the Dst and Bz peaks was 2.25 hours. For different groups of storm sorted by the storm activity, the average delay time did not vary too much. The maximum delay was 10 hours. The result is similar to that of Gonzalez and Echer (2005), which was derived from 64 intense geomagnetic storms ($\text{Dst} \leq 85 \text{ nT}$) from 1997 to 2002. 58.4% of the studied storms had a delay of 0–2 hours. Four storms had a negative delay between the Bz and Dst peaks. The delay time may suggest a physical response time of the ring current to the solar wind driver at the peak interval of an intense magnetic storm, and could be applied to model the ring current dynamics and studies of loss processes near the peak of the storm.

There was a close relationship between the Dst peak and Bz peak for the 89 storms studied, with the correlation coefficient being 0.81. After removing the effect of solar wind dynamic pressure on the Dst peak, we obtained a better correlation coefficient of 0.86. During geomagnetic storms, Bz plays an important role in energy transfer from the solar wind to the magnetosphere and Dst are usually used as measurement of the westward ring current. Above result suggest that Dst are closer to the energy of ring current after removing the

effect of solar wind dynamic pressure.

We believe that these results are of practical importance for spaceweather applications.

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