

Extreme geomagnetic storms, recent Gleissberg cycles and space era-superintense storms

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ABSTRACT

Extreme historical and space era geomagnetic storms (ΔH or $Dst \leq -400$ nT) are studied in terms of their sunspot and Gleissberg solar cycle distributions. Interplanetary and magnetospheric processes associated with the Carrington storm are summarized and the intense storm of August 4, 1972 is discussed in the context of the possibility of having occurred as an extreme storm instead, if the polarity of the related magnetic cloud would have been opposite. We also discuss about superintense geomagnetic storms ($Dst \leq -250$ nT) that occurred in the space era, showing their solar cycle and seasonal distributions and also providing averages for the peak values of their main associated interplanetary parameters. A discussion about the possible occurrence of more Carrington type storms is also addressed.

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1. Introduction

Intense geomagnetic storms are usually defined when the storm Dst index gets values of ≤ -100 nT (Gonzalez et al., 1994), whereas storms with the Dst index ≤ -250 nT have been called superintense storms (e.g. Gonzalez et al., 2002; Echer et al., 2008).

When the Dst index gets to extreme values, such as ≤ -400 nT, due to the large intensity of the ring current and to the rarity of such Dst excursions, the storms of this type could be called extreme storms. During the space era there were only five extreme storms (as seen in Table 1) and during the last solar cycle (# 23) there was only one such event (November 20, 2003).

Tsurutani et al. (2003) reported extreme historical storms for which the Carrington storm of September 2, 1859 showed up as the most intense, whereas during the space era the most extreme recorded storm was that of March 13, 1989, with a peak Dst index of about -600 nT. The historical storms are reproduced in Table 2 (taken from Tsurutani et al., 2003), in which the peak ring current (ΔH) intensity values are mostly < -500 nT. We cannot be certain of course about the associated peak Dst values for the historical storms, since the Dst index started to be constructed and

published only since 1957. However, judging from the peak ΔH excursions observed in the low latitude magnetograms of the historical storms (see also Lakhina et al., 2005), one can claim that the associated Dst values would have been frequently as large as the proper ΔH values, as also studied by Echer and Gonzalez (2007) for superstorms and extreme storms in the range of -600 nT $\leq Dst \leq -250$ nT.

In the present article we will summarize the main findings about the Carrington storm, then we will discuss the storm of 1972, which could have resulted in an event as big as the Carrington storm, and show afterwards the solar cycle distribution of extreme storms (historical and space era events). Then, we will discuss about the superintense storms observed during the space era, presenting their solar cycle and seasonal distributions.

2. Historical storms

Among the historical storms that occurred before 1957, presented in Table 2, only the Carrington storm of September 2, 1859, has been extensively studied in terms of its solar origin and magnetospheric consequences (e.g. special issue of Advances of Space Research, edited by Clauer and Siscoe, 2006; Carlowicz and Lopez, 2002), due to the availability of solar and geomagnetic activity records for that event. Also, such extensive study was motivated by the extremely large incursion of the ΔH component of the geomagnetic field, recorded at the Colaba/Bombay low latitude magnetic station (Tsurutani et al., 2003).

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The historical storms discussed by Tsurutani et al. (2003) and reproduced in Table 2 involve the “remarkable” storms since 1857, described by Ellis (1900), Moos (1910) and by Chapman and Bartels (1940). The Chapman and Bartels listing is reproduced in Table 1 with the addition of Bombay and Alibag, India, magnetometer data, as described by Tsurutani et al. (2003) and by Alex et al. (2006).

One can see in Table 2 that the extreme historical storms have ΔH excursions of at least 450 nT, which is close to our defined extreme storm threshold for the Dst index (-400 nT). Since the historical storms had recorded ΔH values only at one low latitude station, we cannot make a direct comparison with the proper Dst index threshold. Nevertheless, as mentioned above, Echer and Gonzalez (2007) have shown that the peak ΔH and peak Dst

values are frequently comparable, at least for the range of superstorms and extreme storms studied during the space era.

A very intense solar flare was observed by Carrington (1859) on September 1, 1859, a day before the extreme storm event. Many intense auroras were observed on September 2, 1859 (Kimbal, 1960) in association with the extreme ΔH excursion of about -1600 nT, recorded at the Colaba/Bombay low latitude magnetic station.

With this information Tsurutani et al. (2003) constructed a chain of associated processes/events in interplanetary space and in the magnetosphere after the intense solar flare, observed by Carrington. For that purpose, the authors used the following assumptions and information collected from published results:

- Travel time of about 17.5 h of the solar ejecta to the magnetosphere.
- Function of solar wind speed at L1 in terms of the average ejecta/shock speed between the Sun and 1 AU, as studied by Cliver et al. (1990).
- Estimate of peak IMF intensity in terms of peak solar wind speed for ICMEs, as studied by Gonzalez et al. (1998).
- Estimate of peak value of the B_s component of the IMF for intense ICMEs, as studied by Gonzalez et al. (2004).
- Estimate of the reconnection/convection electric field, using studies about the efficiency of solar wind-magnetosphere coupling functions (Gonzalez et al., 1998).
- Observation of a very fast recovery of the large ΔH incursion, as measured by the Colaba/Bombay magnetometer.
- Observations of auroras recorded at very low latitudes (Kimbal, 1960).

Fig. 1 summarizes the main results of the Tsurutani et al. (2003) study. A convection electric field of about 20 mV/m, obtained through the chain of processes listed on this figure, was used to study the ring current intensification and the inner magnetospheric dynamics related with ring current and plasmopause positions. These are in a good agreement with the latitudinal positions of the auroras observed during that event. Those ring current and plasmopause positions were estimated by

Table 1

List of superstorms ($Dst \leq -250$ nT) during the space era.

Date	Dst	Date	Dst
1957/01/21	-250	1989/03/14	-589
1957/03/02	-255	1989/09/19	-255
1957/09/05	-324	1989/10/21	-267
1957/09/13	-427	1989/11/17	-266
1957/09/23	-303	1990/04/10	-281
1958/02/11	-426	1991/03/25	-298
1958/07/08	-330	1991/10/29*	-254
1958/09/04	-302	1991/11/09	-354
1958/07/15	-429	1992/05/10	-288
1960/04/01	-327	2000/04/07*	-288
1960/04/30	-325	2000/07/16*	-301
1960/10/07	-287	2001/03/31*	-387
1960/11/13	-339	2001/04/11*	-271
1961/10/28	-272	2001/11/06*	-292
1967/05/26	-387	2003/10/30*	-353
1970/03/08*	-284	2003/10/30*	-383
1981/04/13*	-311	2003/11/20*	-422
1982/07/14*	-325	2004/11/08*	-373
1982/09/06*	-289	2004/11/10*	-289
1986/02/09	-307	2005/05/15*	-263

The events with asterisk are those for which solar wind measurements were available.

Table 2

Chronological list of extreme magnetic storms.^a

Storm	Year	Month	Day	H Range ^b (nT)	Dst (nT)	Station	Geomagnetic ^c Latitude N (deg)	Geomagnetic ^c Longitude E (deg)
1	1859	September	1–2	1720		Bombay	9.87	142.7
		September	1–2	> 700 ^{d,e}		Kew	54.47	82.5
2	1859	October	12	980		Bombay	9.87	142.7
3	1872	February	4	1020		Bombay	9.87	142.7
4	1882	November	17	450		Bombay	9.87	142.7
		November	17	> 1090 ^{d,e}		Greenwich	54.40	82.2
5	1903	October	31	820		Bombay	9.87	142.7
		October	31	> 950 ^{d,e}		Postdam	52.66	96.2
6	1909	September	25	> 1500 ^{d,e}		Postdam	52.66	96.2
7	1921	May	13–16	> 700		Alibag	9.61	142.7
		May	13–16	1060		Postdam	52.66	96.2
8	1928	July	7	780		Alibag	9.61	142.7
	1938	April	16	530		Alibag	9.61	142.7
		April	16	1900 ^d		Postdam	52.66	96.2
10	1957	September	13	580	-467	Alibag	9.61	142.7
11	1958	February	11	660	-426	Alibag	9.61	142.7
12	1989	March	13	640	-589	Kakioka	25.97	205.1

^a The list includes the “remarkable magnetic storms” described by Moos (1910) and Chapman and Bartels (1940).

^b H-range is defined as the difference between the maximum and the minimum value of H during the storm event.

^c Geomagnetic coordinates for all the observatories are computed for the year 1940 based on the IGRF model (courtesy NGDC site).

^d The values recorded at the mid-latitude stations could have an ionospheric component associated with the activity.

^e Saturation of the instrument.

Tsurutani et al. (2003) from cold and hot plasma population limits obtained from a general expression for the inner magnetospheric electric potential, once the convection electric field is determined.

The estimated peak Dst value of about -1160 nT is in a fairly good agreement with the measured peak Dst value of -1050 nT, obtained when the reported 15 min average values of ΔH from the Colaba magnetometer are averaged for one hour, as is usually done for the Dst index (although, of course, we are still dealing with the limitation of having only one low latitude station).

3. The August 4, 1972 storm

Vaisberg and Zastenker (1976) determined the average speed of the August 4, 1972, storm solar ejecta by measuring the time

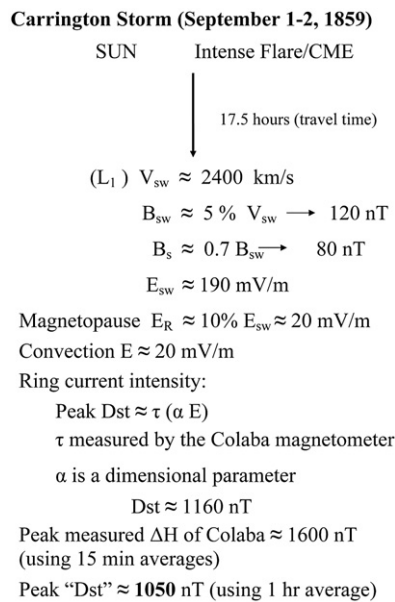


Fig. 1. Summary of the main results obtained by Tsurutani et al. (2003), using the assumptions and information published in the literature, as described in the text. The resulting magnetic fields are shown. The given magnitudes are peak values.

delay between the flare onset to the shock detection at 1 AU. Their average speed estimate was of 2850 km/s, leading to a delay time of 14.6 h, which is smaller than that estimated for the Carrington storm. Thus, for this event one could estimate an associated reconnection/convection electric field of about 25 mV/m, using a similar reasoning as that shown in Fig. 1 for the Carrington event.

Unfortunately there was no IMF measurement for the 1972 storm near 1 AU, but Tsurutani et al. (1992a), examining in detail the Pioneer 10 data at about 2 AU observed that the magnetic cloud responsible for this event had its axis highly tilted from the ecliptic. Tsurutani et al. (2003) also suggested that the IMF intensity, extrapolated back to the Earth from its point of measurement by Pioneer 10, could have been as large as 80 nT or more.

Fig. 2 shows the polarities of magnetic clouds with rotations (a) in the XZ plane, as regular geoeffective magnetic clouds usually have, and (b) in the XY plane, as it could have been the case for the 1972 event. Since the B_z field of the 1972 cloud was observed being mostly northward by Pioneer 10, the polarity of the cloud probably was as that depicted in Fig. 2b. However, if the rotation of the cloud could have been in the opposite direction (clockwise), the associated B_z field would have been southward, which could have then produced an extreme storm at Earth.

Thus, if the 1972 event would have involved an ICME with its axis on the ecliptic, or a rotation of the cloud in the opposite sense (clockwise) of that shown in Fig. 2b, the resulting storm at Earth would have been as intense as the Carrington event or perhaps even more (because its ejecta speed was larger).

4. Solar cycle dependence of extreme storms

Fig. 3 shows the solar cycle distribution of extreme storms from the historical records plus storms from the space era. In addition, two more historical storms were added for cycle # 9, those of September 23, 1846, and of October 24, 1847, both recently obtained from the Colaba magnetometer records, with peak ΔH incursions of about < -500 and < -525 nT, respectively. Before 1846 there are not much available data, mainly due to the lack of reliable measurements. In this figure, the height of the vertical bars indicate the measured range of H for the historical

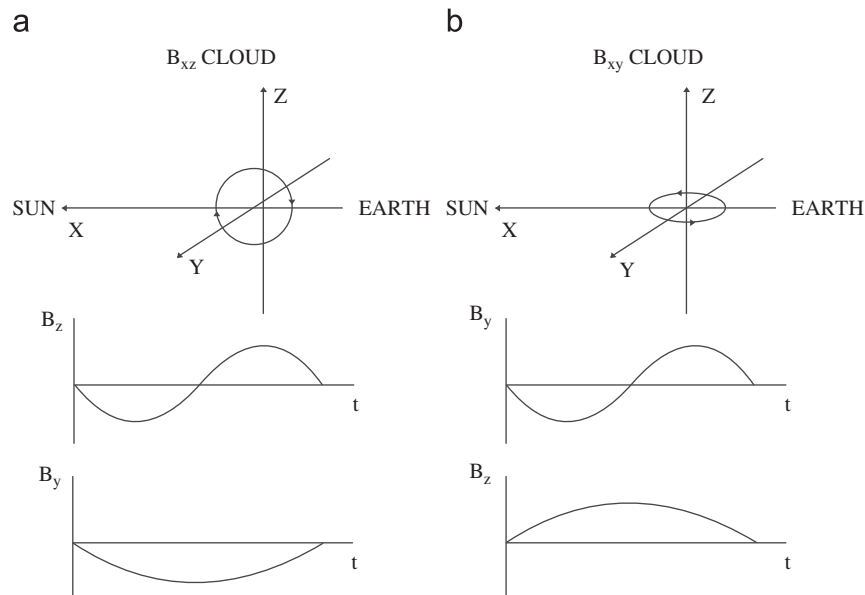


Fig. 2. Polarities of magnetic clouds, (a) for a cloud with a rotation in the X-Z plane, (b) for a cloud with a rotation in the X-Y plane.

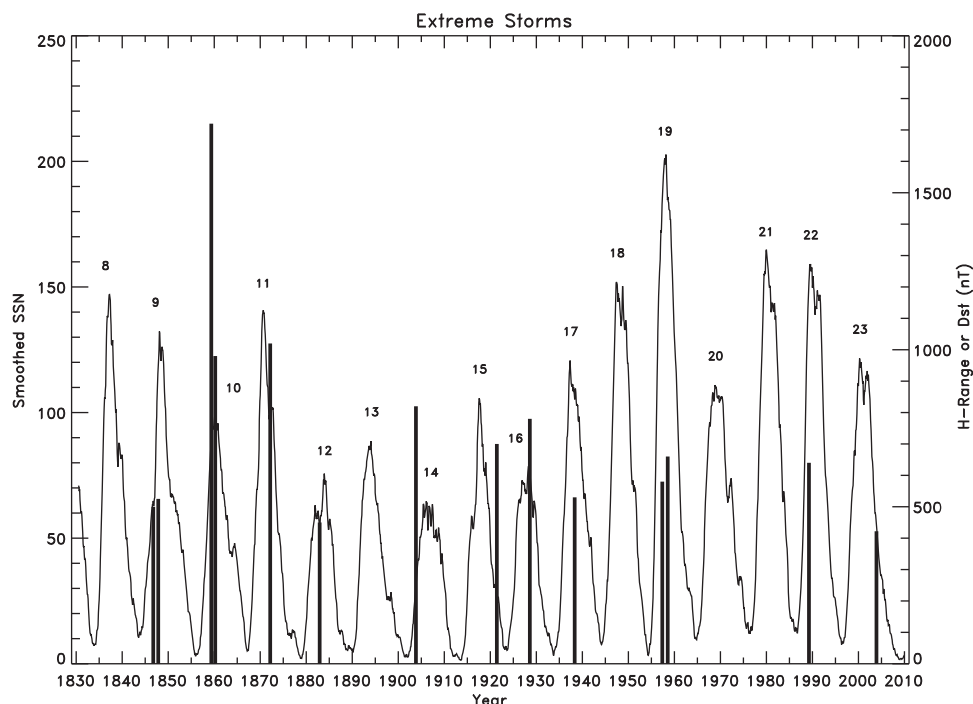


Fig. 3. Solar cycle distribution of the historical and space era extreme storms, with the bar heights indicating the observed ΔH or Dst intensity incursions.

events, as reported in Table 2, or the measured peak Dst values for the events of the space era. In this figure we also added cycle # 8 (with no recorded extreme storms) for reasons mentioned below.

From Fig. 3 one can observe the following:

- There is at least one extreme event for most of the solar cycles. In 1958 there were two events (shown only as one in this figure). From the 14 extreme events of this figure, nine occurred around solar maximum or at the early descending phase of the cycles, three events occurred during the ascending phase and two at the late descending phase of the cycles. None occurred at solar minimum.
- There is a tendency for the intensity of the events to have been larger for most of the historical events as compared with the intensity of the recent extreme events, although this apparent tendency could be related to the fact that we have plotted the range of H for the historical storms, whereas for the space era events we plotted the real Dst values (which are expected to be smaller, but see the results of Echer and Gonzalez, 2007).

Hoyt and Schatten (1997) have studied the Gleissberg solar cycle/modulation of the regular solar cycles, with a duration of about 8–10 solar cycles between the minima of such a modulation. These authors place the last two Gleissberg minima centered approximately around 1900 and 2010, with the maxima centered approximately at 1839 and 1958.

In Fig. 4, we join with dotted lines the Gleissberg maximum and minimum years. Hoyt and Schatten (1997) also reported that solar cycles 11 and 21 are secondary maxima and are located at the descending phases of the last two Gleissberg cycles.

The Carrington extreme storm occurred on a cycle (# 10) right before the secondary maximum of the Gleissberg cycle. It is interesting to note that the 1972 storm, which could have been as intense as the Carrington event, as discussed above, occurred on a cycle (# 20) also right before the secondary maximum of the last Gleissberg cycle. Further, both cycles, 10 and 20, had similar peak amplitudes in their sunspot numbers (around 100) and also had

two extreme storms, with peak $\Delta H/Dst$ values of about -500 nT, occurred during their previous cycles (9 and 19). Cycle 11, one after that with the Carrington event, had an extreme event. By analogy, cycle 21 had a superintense storm on July 14, 1982 (the Bastille event), which was close to being an extreme event.

However, due to the limited statistics of the extreme storms one cannot try for a more extended study.

5. Distribution of superintense storms during the space era

Echer et al. (2008) studied the superstorms ($Dst \leq -250$ nT) that occurred during solar cycle 23. Among their results, they concluded that the main interplanetary causes of those storms were large and sustained B_s fields in magnetic clouds, sheath regions of ICMEs and their combined structures. Similar results were reported before by Tsurutani et al. (1992b) also for superintense storms, involving the interval of 1971–1986.

Although we do not study extensively in this article the superstorms that occurred during the space era, we show below some important distributions of them and leave for a future work a more complete study. Table 1 presents the list of superstorms of the space era, with their dates of occurrence and peak Dst values.

Fig. 5 shows the solar cycle distribution of the yearly number of superstorms. We can see from this figure 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 with a similar behavior of the extreme storms. Fig. 6 shows the average solar cycle distribution of that shown in Fig. 5. This figure clearly shows a dual-peak distribution of superintense storms, as it was also found before for intense storms (Gonzalez et al., 1990a). The first peak occurs at solar maximum and the second one at the descending part of the solar cycle.

Fig. 7 shows the seasonal distribution of the studied superstorms, in which we can see the equinoctial peaks and also some indication of the July peak, initially found for the distribution of intense storms (Clúa de Gonzalez et al., 2001).

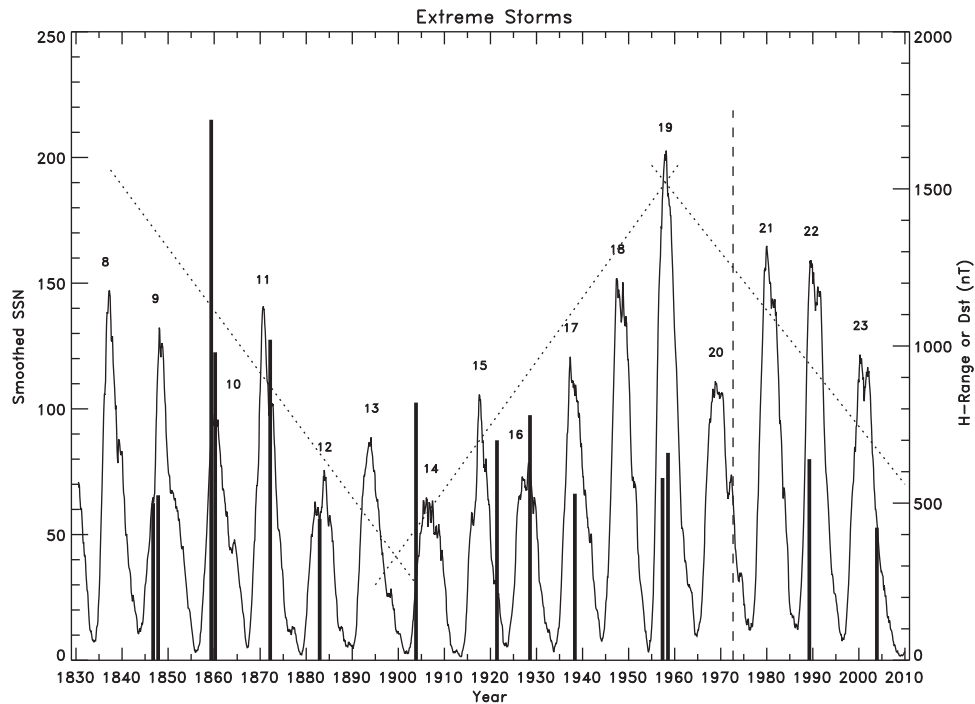


Fig. 4. Same as in Fig. 3, with the dotted lines joining the years of maximum and minimum of the last two Gleissberg cycles of the solar activity. The dashed vertical line indicates the failed Carrington type storm of August 1972.

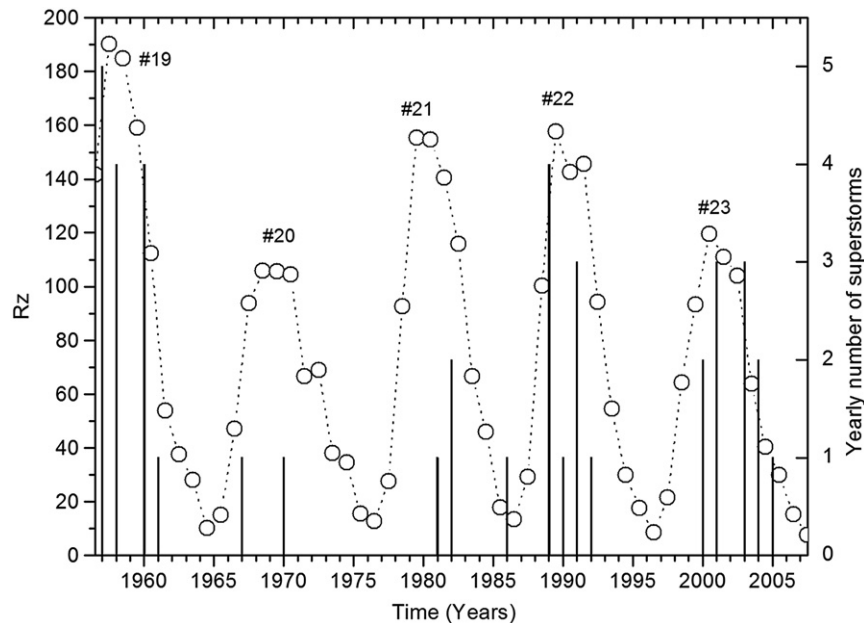


Fig. 5. Solar cycle distribution of the yearly number of superstorms for the space era (bars). The open circles are the sunspot numbers.

Table 3 presents the results of a preliminary study about the solar wind parameters associated with the superintense storms of the space era for which solar wind data were available. Those events are marked with an asterisk on Table 1. We show the average peak values of the solar wind speed, of the IMF intensity, of the southward component of the IMF (B_s) and of the interplanetary electric field (E_y), together with their corresponding standard deviations and median values. As expected for superstorms, both the solar wind speed and the IMF attained very large values, of about 800 km/s and 42 nT, respectively. Also the B_s and E_y parameters attained large values, of 34 nT and 24 mV/m, respectively. The implication of these large

interplanetary values for the occurrence of superstorms is discussed below.

6. Discussion

From the considerations of Section 3 about the 1972 intense storm, we can learn that magnetic clouds accompanying very fast ejecta can lead to the occurrence of extreme events depending on the polarity of the cloud. If the axis of the cloud is in the ecliptic the chances to have an extreme storm are large, whereas if the axis is more transverse to the ecliptic, as in the 1972 case, an

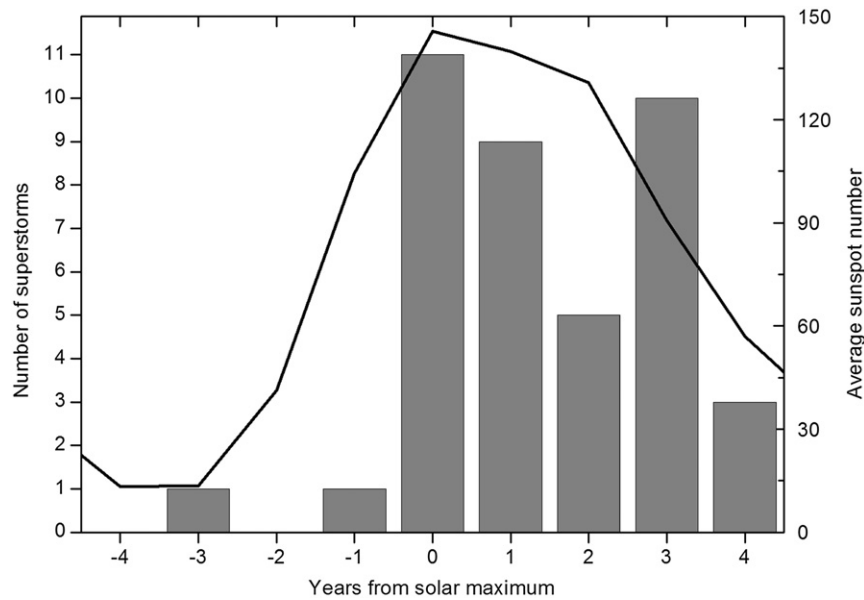


Fig. 6. Average solar cycle distribution of the superstorms shown in Fig. 5, with a dual-peak type.

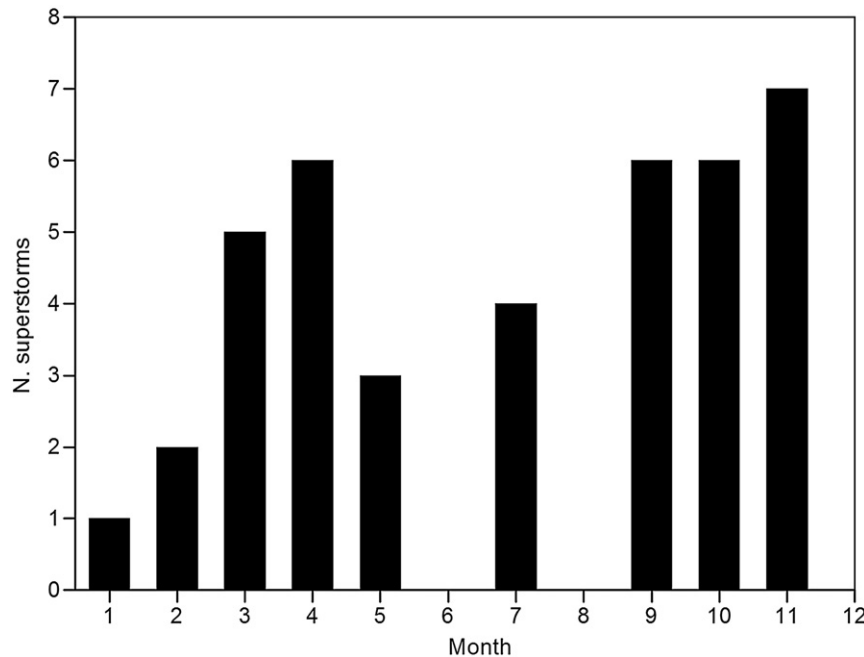


Fig. 7. Seasonal distribution of the superstorms for the space era.

Table 3

Average of peak values for some interplanetary parameters associated with superstorms of the space era, for which data were available (events marked with asterisk on Table 1).

Parameter	Average of peak values	SD	Median
Dst (nT)	324.3	67.3	302.0
V_{SW} (km/s)	799.1	160.6	743.0
B_{mag} (nT)	41.7	10.8	39.1
B_s (nT)	34.3	13.5	27.2
E_y (mV/m)	23.5	11.6	16.9

extreme event can be expected only when the polarity of rotation of the cloud is such that a large B_s field is produced. For the 1972 case, the polarity was of the (b) type in Fig. 2, namely

counter-clockwise, thus producing a large northward B_z field. If the polarity would have been clockwise, a large southward B_z field could have existed, thus leading to the development of an extreme storm. This polarity may depend on some solar cycle features that are worth investigating. For clouds with the axis on the ecliptic, such a polarity could depend on the polar magnetic polarity of the Sun that alternates from cycle to cycle. But, for this class of clouds, the difference in polarity only leads to a different sequence of north–south B_z , or south–north B_z in the approaching cloud, leading to some but not large differences in the magnetospheric response and in the intensity of the developing storm (Gonzalez et al., 1990b).

If the 1972 event would have involved a magnetic cloud with an appropriate polarity, the consequent storm would have been an extreme event, with an intensity as large as that of the

Carrington storm or perhaps even larger. We were lucky, since the ground electric technology present in 1972 was certainly much more vulnerable than that of 1859. It is known that in 1859, the very intense ionospheric currents at middle latitudes produced very intense geomagnetic induction currents that rendered inoperable many telegraphic systems in Europe and in the US (e.g. Kappenman, 2006; Carlowicz and Lopez, 2002).

If the considerations mentioned in Section 4 with respect to the possible occurrence of Carrington-type storms is reasonable, by comparing the time of occurrence of the Carrington storm and of the failed extreme storm of 1972 with respect to the Gleissberg cycle of solar activity, one could suggest that such a type of extreme events can be expected to occur one at about every century, with a tendency to appear before and close to the secondary maximum of the descending phase of the Gleissberg cycle. Thus, according to this reasoning, and since we are presently at a minimum of the Gleissberg cycle, we may still be at about six solar cycles distant from the next possible Carrington type storm.

For four out of the five extreme storms of the space era, unfortunately, we cannot study their associated geoeffective interplanetary structures, since for the three events of 1957 and 1958 there were no interplanetary monitors yet, and for the March 1989 event no solar wind data were recorded due to the strong saturation of the instruments. Only for the extreme storm of November 2003, we had solar wind data, showing a magnetic cloud as the structure responsible for the storm development (Echer et al., 2008). Such a magnetic cloud had its axis normal to the ecliptic, as in the 1972 event, with the polarity of the cloud having a clockwise rotation, thus producing an intense southward B_z field, contrary to what occurred in the 1972 event. This fact reinforces even more the considerations made above about the 1972 event, as being a failed Carrington type storm. In the November 2003 event the cloud speed had peak values of only about 800 km/s, whereas the 1972 cloud speed attained values of about 2800 km/s. Considering the B – V relationship studied by Gonzalez et al. (1998) for magnetic clouds, this difference in the cloud speeds between the 2003 and the 1972 extreme storms could imply in a peak Dst storm of about -1400 nT for the 1972 event, since the storm of 2003 reached a peak Dst value of only about -400 nT. Thus, if the magnetic cloud of the 1972 event would have carried a polarity with a clockwise rotation, the ensuing extreme storm could have been even more intense than the Carrington storm (that apparently reached a peak Dst value of only about -1100 nT).

The solar and seasonal distributions of superintense storms shown in Figs. 6 and 7 show similar results as those obtained before for intense storms, namely that they have a dual-type distribution in the solar cycle, one at solar maximum and the second at the descending phase of the cycle (Gonzalez et al., 1990a), and a seasonal distribution showing the equinoctial peaks and an additional peak in July (Clúa de Gonzalez et al., 2001).

The average peak values of the solar wind parameters involved in the superintense storms, as presented in Table 3, indicate the presence of fairly large values of the solar wind speed, of the IMF and of the B_s field. These large solar wind values certainly imply in a reconnection process at the magnetopause also becoming very intense, and in the consequent large values of the inner magnetospheric convection and ring current energization parameters (Gonzalez et al., 1994). Intensities of the ring current/ Dst of about -1000 nT or less, as in the Carrington event, can be expected from theory (Vasyliunas, private communication). Also, the ring current intensity does not seem to saturate with large values of the solar wind parameters (speed and B_s) due to the consequences of a closer x -line location, although the polar cap electric potential seems to do (e.g. Lopez et al., 2009).

One final comment refers to the abnormally long solar minimum of cycle 23. From Fig. 4 one can notice that this minimum coincides with a Gleissberg minimum (Hoyt and

Schatten, 1997). This combination could explain in part this abnormality and probably also the low peak sunspot number expected to come.

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References

- Alex, S., Mukherjee, S., Lakhina, G.S., 2006. Geomagnetic signatures during the intense geomagnetic storms of October 29 and November 20, 2003. *J. Atmos. Sol. Terr. Phys.* 68, 769.
- Carlowicz, M.J., Lopez, R.E., 2002. *Storms from the Sun*. Joseph Henry Press, Washington D.C.
- Carrington, R.C., 1859. Description of a singular appearance seen in the Sun on september. *Mon. Not. R. Astron. Soc.* XX, 13.
- Chapman, S., Bartels, J., 1940. *Geomagnetism*. Oxford University Press.
- Clauer, C.R., Siscoe, G., 2006. The great historical geomagnetic storm of 1859: a modern look. *Adv. Space Res.* 38 (special issue).
- Cliver, E.W., Feynmann, J., Garret, H.B., 1990. An estimate of the maximum speed of the solar wind, 1938–1989. *J. Geophys. Res.* 95, 17103.
- Clúa de Gonzalez, A.L., Silbergleit, V.M., Gonzalez, W.D., Tsurutani, B.T., 2001. Annual variation of geomagnetic activity. *J. Atmos. Sol. Terr. Phys.* 63, 367–374.
- Echer, E., Gonzalez, W.D., 2007. Ring current asymmetry during superintense magnetic storms. In: Paper presented at the 10th International Congress of the Brazilian Geophysical Society, Rio de Janeiro, Brazil, 19–22 November.
- Echer, E., Gonzalez, W.D., Tsurutani, B.T., 2008. Interplanetary conditions leading to superintense geomagnetic storms ($Dst \leq -250$ nT) during solar cycle 23. *Geophys. Res. Lett.* 35. doi:10.1029/2007GL031755.
- Ellis, W., 1900. The relation between magnetic disturbance and sunspot frequency. *Mon. Not. R. Astron. Soc.* 60, 142.
- Gonzalez, W.D., Clúa de Gonzalez, A.L., Lago, A.D., Tsurutani, B.T., Arballo, J.K., Lakhina, G.S., Buti, B., Ho, C.M., Wu, S.T., 1998. Magnetic cloud field intensities and solar wind velocities. *Geophys. Res. Lett.* 25, 963.
- Gonzalez, W.D., Clúa de Gonzalez, A.L., Tsurutani, B.T., 1990a. Dual-peak solar cycle distribution of intense geomagnetic storms. *Planet. Space Sci.* 38, 181.
- Gonzalez, W.D., Clúa de Gonzalez, A.L., Vieira, L.E.A., Tsurutani, B.T., 2004. Prediction of peak Dst from CME/magnetic cloud-speed observations. *J. Atmos. Sol. Terr. Phys.* 66, 161.
- Gonzalez, W.D., Lepping, R.P., Schwenn, R., Kroehl, H.W., Rostoker, G., Tsurutani, B.T., Vasyliunas, V.M., 1994. What is a geomagnetic storm? *J. Geophys. Res.* 99 5771–5792.
- Gonzalez, W.D., Tsurutani, B.T., Lee, L., 1990b. Comment on the polarity of magnetic clouds. *J. Geophys. Res.* 95, 17267.
- Gonzalez, W.D., Tsurutani, B.T., Lepping, R.P., Schwenn, R., 2002. Interplanetary phenomena associated with very intense geomagnetic storms. *J. Atmos. Sol. Terr. Phys.* 64, 173.
- Hoyt, D.V., Schatten, K., 1997. *The Role of the Sun in Climate Change*. Oxford University Press.
- Kappenman, J.G., 2006. Great geomagnetic storms and impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921. *Adv. Space Res.* 38, 188.
- Kimball, D.S., 1960. A study of the aurora of 1859. *Sci. Rept.*, UAG-R 109, University of Alaska, Fairbanks, Alaska.
- Lakhina, G.S., Alex, S., Tsurutani, B.T., Gonzalez, W.D., 2005. Research on historical records of geomagnetic storms. In: Dere, K.P., Wang, J., Yan, Y. (Eds.), *Coronal Mass Ejections*. Proceedings of IAU Symposium.
- Lopez, R.E., Lyon, J.G., Mitchell, E., Bruntz, R., Merkin, V.G., Brogi, S., Tofolletto, F., Wiltberger, M., 2009. Why doesn't the ring current injection rate saturate? *J. Geophys. Res.* 114. doi:10.1029/2008JA013141.
- Moos, N.A.F., 1910. Magnetic observations made at the government observatory. Bombay 1846–1905, part II, Government Central Press, Bombay, India.
- Tsurutani, B.T., Gonzalez, W.D., Lakhina, G.S., Alex, S., 2003. The extreme magnetic storm of 1–2 september 1859. *J. Geophys. Res.* 108, 1268.
- Tsurutani, B.T., Gonzalez, W.D., Tang, F., Lee, Y.T., 1992b. Great magnetic storms. *Geophys. Res. Lett.* 19, 73.
- Tsurutani, B.T., Gonzalez, W.D., Tang, F., Lee, Y.T., Okada, M., Park, D., 1992a. Solar wind ram pressure corrections and an estimation of the efficiency of viscous interaction. *Geophys. Res. Lett.* 19, 1993.
- Vaisberg, O.L., Zastenker, G.N., 1976. Solar wind and magnetosheath observations at earth during August 1972. *Space Sci. Rev.* 19, 687.