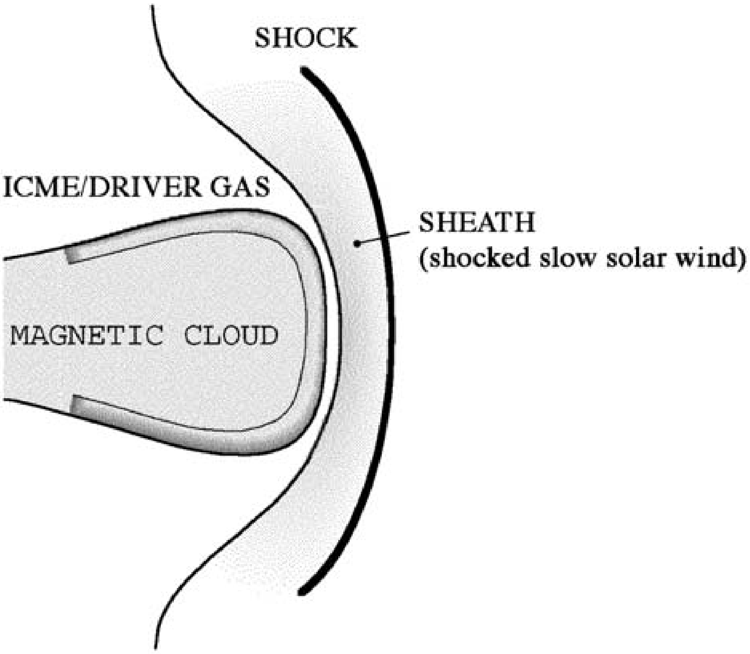
Session 1

Historical introduction



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Research on Historical Records of Geomagnetic Storms

G. S. Lakhina[1], **S. Alex**[1], **B. T. Tsurutani**[2], **and W. D. Gonzalez**[3]

[1]Indian Institute of Geomagnetism, Mumbai, India
email: lakhina@iigs.iigm.res.in,salex@iigs.iigm.res.in

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
email:Bruce.T.Tsurutani@jpl.nasa.gov

[3]Instituto Nacional Pesquisas Espaciais (INPE), Sao Jose dos Campos, Sao Paulo, Brazil
email:gonzalez@dge.inpe.br

Abstract.

In recent times, there has been keen interest in understanding Sun-Earth connection events, such as solar flares, CMEs and concomitant magnetic storms. Magnetic storms are the most dramatic and perhaps important component of space weather effects on Earth. Super-intense magnetic storms (defined here as those with Dst $<$ -500 nT, where Dst stands for the disturbance storm time index that measures the strength of the magnetic storm) although relatively rare, have the largest societal and technological relevance. Such storms can cause life-threatening power outages, satellite damage, communication failures and navigational problems. However, the data for such magnetic storms is rather scarce. For example, only one super-intense magnetic storm has been recorded (Dst=-640 nT, March 13, 1989) during the space-age (since 1958), although such storms may have occurred many times in the last 160 years or so when the regular observatory network came into existence. Thus, research on historical geomagnetic storms can help to create a good data base for intense and super-intense magnetic storms. From the application of knowledge of interplanetary and solar causes of storms gained from the spaceage observations applied to the super-intense storm of September 1-2, 1859, it has been possible to deduce that an exceptionally fast (and intense) magnetic cloud was the interplanetary cause of this geomagnetic storm with a Dst -1760 nT, nearly 3 times as large as that of March 13, 1989 super-intense storm. The talk will focus on super-intense storms of September 1-2, 1859, and also discuss the results in the context of some recent intense storms.

Keywords. Sun: solar-terrestrial relations

1. Introduction

The history of geomagnetism is about 400 years old. The science of geomagnetism was born with the publication of De Magnete by William Gilbert in 1600 AD. The first map of magnetic field declination was made by Edmund Halley in the beginning of eighteenth century. We will go back about 200 years ago, specifically from May 1806 to June 1807 in Berlin, where Alexander von Humboldt and a colleague observed the local magnetic declination every half hour from midnight to morning. On December 21, 1806, for 6 consecutive hours, von Humboldt observed strong magnetic deflections and noted the presence of correlated northern lights (aurora) overhead. When the aurora disappeared at dawn, the magnetic perturbations disappeared as well. Von Humboldt concluded that the magnetic disturbances on the ground and the auroras in the polar sky were two manifestation of the same phenomenon (Schröder 1997; Tsurutani *et al.* 1997). He gave this phenomenon involving large scale magnetic disturbances (possibly already observed by George Graham) the name "Magnetische Ungewitter," or magnetic storms von Humboldt 1808. The world-wide network of magnetic observatories later confirmed that such "storms" were indeed world-wide phenomena.

An amateur German astronomer, S. Heinrich Schwabe, began observing the Sun and making counts of sunspots in 1826. In the year 1843, he reported a periodic behavior of 10 years in spot counts. A decennial period in the daily variation of magnetic declination was reported by Lamont from Munich in 1851, but he did not relate it to the sunspot cycle. From his extensive studies, Sabine (1852) discovered that geomagnetic activity paralleled the recently discovered sunspot cycle. However, it took nearly 100 years to gather sufficient statistics to make a convincing case for an association between large solar flares and severe storms (Hale 1931, Chapman & Bartels 1940, and Newton 1943).

2. Geomagnetic Storms

In recent times, there has been keen interest in understanding Sun-Earth connection events, such as solar flares, CMEs and concomitant magnetic storms. Magnetic storms are the most dramatic and perhaps important component of Space Weather effects on Earth.

A geomagnetic storm is characterized by a Main Phase during which the horizontal component of the Earth's low-latitude magnetic fields are significantly depressed over a time span of one to a few hours followed by its recovery which may extend over several days (Rostoker 1997). During intense magnetic storms, the auroral activity becomes intense and auroras are not confined to the Auroral Oval only, rather the Auroras could be seen at the sub-auroral to midlatitude stations. It is now believed that the major cause of solar wind energy transfer to the magnetosphere is magnetic reconnection between interplanetary magnetic fields and the Earth's magnetic field (Dungey 1961). Geomagnetic storms occur when solar wind-magnetosphere coupling becomes intensified during the arrival of fast moving ($\sim$700 km/s or more) solar ejecta, like CMEs, solar flares, fast streams from the coronal holes, etc. accompanied by long intervals of intense southward interplanetary magnetic field (IMF) (Gonzalez *et al.* 1994, Tsurutani & Gonzalez 1997) as in a "magnetic cloud" (Klein & Burlaga 1982). As a result, the magnetotail plasma gets injected into the nightside magnetosphere, with the energetic protons drifting to the west and electrons to the east, thus, forming a ring of current around the Earth. This current, called the "ring current", produces a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial stations, and is the cause of the main phase of the magnetic storm. The decay of the ring current starts the recovery phase of the storm.

Super-intense magnetic storms (defined here as those with Dst $<$ -500 nT) although relatively rare, have the largest societal and technological relevance. Such storms can cause life-threatening power outages, satellite damage, communication failures and navigational problems. The data for super-intense magnetic storms is rather scarce. For example, only one truly super-intense magnetic storm has been recorded (DST=-640 nT, March 13, 1989) during the spaceage since 1958 (Allan *et al.* 1989).

Last year, there was a great media-hype about the possible super magnetic storms in October-November, 2003. Though the solar flares on October 28 and 29 were of class X17 and X10, they failed to produce a super intense storm; they produced intense double storm of mere Dst -400 nT. A much weaker solar flare (and CME) of class M3.2/2N on 18 November resulted in a near super intense storm on November 20 with Dst -490 nT. This clearly shows that it is not only the energy of the solar flare and speed of the ejecta which control the strength of the geomagnetic storm, the solar magnetic field too play critical role!

Dessler & Parker (1959) and Sckopke (1966) have shown that the decrease in the equatorial magnetic field strength due to the ring current or Dst (disturbance storm time) index, is directly related to the total energy of the ring current particles, and thus is a good measure of the energetics of the magnetic storm. Though Dst index acts as a proxy for the strength of the ring current, other currents like magnetopause current can contribute to it as well. An empirical relationship between Dst and interplanetary parameters has been derived by Burton *et al.* (1975).

Although there is a record of only one or two super intense magnetic storms during the space age, many such storms may have occurred many times in the last 160 years or so when the regular observatory network came into existence. Thus, the research on historical geomagnetic storms can help to create a good data base for intense and super-intense magnetic storms. From the application of knowledge, of interplanetary and solar causes of storms gained from the spaceage observations, to this super-intense storm data set one can deduce their possible causes and construct a data base for solar ejecta, e.g., frequency of occurrence of extremely large solar flares, evolution of solar ejecta, etc.

An other important reason for undertaking such study is to answer some basic questions, namely, i) how many super-intense magnetic storms have occurred in the last 160 years and what were their probable solar and interplanetary causes? ii) the frequency of occurrence of super-intense storms and under what circumstances? iii) Is a prediction of a certain number of (say 3) most severe magnetic storm during a solar cycle possible? iv) Can the possible damaging effect of supper intense magnetic storms on the modern society be predicted in advance? and v) what is the energetics of eruptive phenomena on Sun and Stars, etc.

Table 1 gives a partial chronological list of some large magnetic storms which had occurred during the past 160 years or so. The list includes the "Remarkable Magnetic Storms" described in Moos (1910)and Chapman & Bartels (1940)(Tsurutani *et al.* 2003). One can see that some of the events fall under the category of super-intense magnetic storms. Analysis of these events can form a very useful data base for the super-intense storms.

3. Case History: Super-Intense Storm of September 1-2, 1859

We shall focus on the super storm of September 1-2, 1859 which was associated with the Carrigton flare that occurred on September 01, 1859. We use recently reduced ground magnetometer data of Colaba Observatory, Mumbai, India for the September 1-3, 1859, published papers (Carrington, 1859), auroral reports, based on newspapers (Kimball, 1960) and recently obtained (space-age) knowledge of interplanetary and solar causes of storms, to identify the probable causes of this super storm (Tsurutani *et al.* 2003). Similar methodology (with improved techniques) can be used to analyze other historical magnetic storms.

3.1. *Solar flare of September 1, 1859, magnetic storm and auroras*

The solar flare of September 1, 1859 was observed and reported by R. C. Carrington (Carrington, 1859) and Hodgson (1859) in the Monthly Notices of the Royal Astronomical Society and became the best known solar event of all times. Of particular note was the intensity of the event as quoted in the articles.

"For the brilliancy was fully equal to that of direct sunlight (Carrington, 1859)." "I was suddenly surprised at the appearance of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye . . . . ." (Hodgson, 1859).

The solar flare was followed by a magnetic storm at the Earth. The time delay was 17 hrs and 40 min (stated in the Carrington paper). Although Carrington carefully noted this relationship, he was cautious in his appraisal: "and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere". While the contemporary occurrence may deserve noting, he would not have it supposed that he even leans towards connecting them "one swallow does not make a summer" (Carrington 1859).

The auroras occurred globally and have been reported by many. Kimbal (1960) has provided the most complete indexing of auroral sightings. "Red glows were reported as visible from within 23° of the geomagnetic equator in both north and southern hemispheres during the display of September 1-2". This is perhaps the most equatorward sighting of aurora that can be confirmed for this or any other storm event in past history (Silverman, 2001). Loomis (1861) has reported that during this magnetic storm, many fires were set by arcing from currents induced in telegraph wires (in both the United States and Europe).

3.2. *Interplanetary Causes of major Geomagnetic storms*

There are several solar and interplanetary drivers which can give rise to magnetic storms. Solar ejecta (CMEs, solar flares etc) having high solar wind speeds and unusually intense magnetic fields seem to be the most important for causing intense geomagnetic storms (Gonzalez *et al.* 1994). Magnetic clouds within fast interplanetary coronal mass ejections (ICMEs) (Klein & Burlaga, 1982) are a source of intrinsically high magnetic field strengths. Gonzalez *et al.* (1998) and Dal Lago *et al.* (2001) have shown that there is an empirical relationship between extremely fast ICMEs and extremely high magnetic cloud field strengths. Figure 1 shows the structure of a typical ICMEs based on in situ observations at 1 AU.

Another important source is the strong sheath fields which could be produced by fast forward shock compression of slow stream magnetic fields (and plasmas), leading to larger (compressed) field strengths. If these sheath fields have strong southward components, they can cause major (Dst > -250 nT) magnetic storms (Gonzalez & Tsurutani, 1987; Tsurutani *et al.* 1988; Tsurutani *et al.* 1999). If both the sheath field and the cloud field (if present) have the proper orientation, a "double storm" (Kamide *et al.* 1998) will result. On the other hand, the compound streams, where one stream overtakes an upstream fast stream event (Burlaga *et al.* 1987) and the overtaking shock may compress the already compressed upstream sheath fields (Tsurutani *et al.* 1999) and magnetic cloud fields (Wei *et al.* 2003) may also lead to double storms. The triple and quadruple stream events, etc., produce even further magnetic compression and may lead to triple storms, etc.

3.3. *Magnetic Data of Colaba Observatory*

Magnetometers for measuring Declination and horizontal magnetic field component at Colaba Observatory during 1846-1867 were made by Thomas Grubb of Dublin and are described in Royal Society reports (1840; 1842). In the Declinometer, a scale and lens attachment to the magnet and the telescope set up made it possible to read the scale position manually based on the movement of the north end of the magnet. The absolute easterly declination (in minutes) was calculated from the relation: $d = 6'.841.(f - R).c$, where $6'.841$ is the adopted value of a unit of the declinometer scale, R is the true meridian reading, c the torsion co-efficient and f is the observed scale reading.

The Grubb Horizontal force magnetometer consisted of a rectangular bar magnet suspended horizontally, and carrying a collimator scale. The position of the magnet could

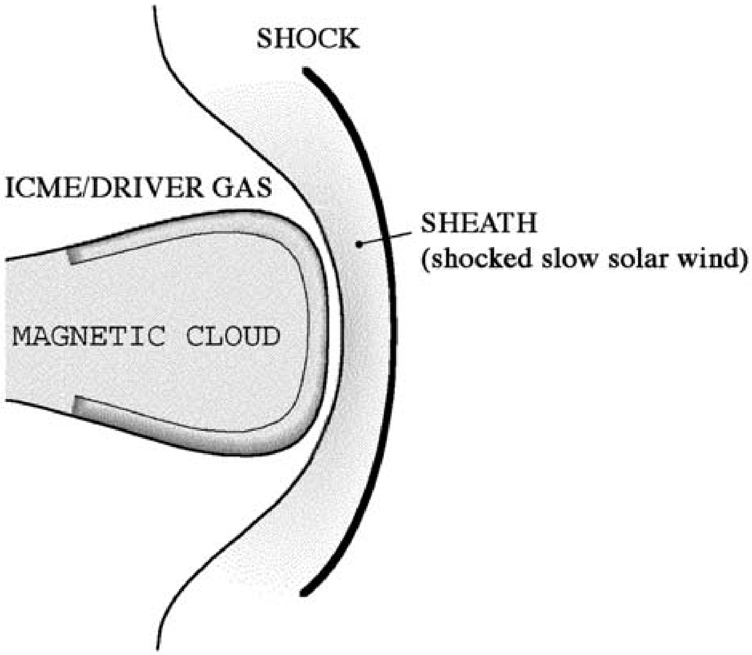

Figure 1. The configuration of a fast coronal mass ejection (CME) and its upstream sheath in the interplanetary medium, i.e., the so called ICME.

be determined by reading the scale with a properly placed telescope. The entries in the data book contained the scale reading of hourly observations taken at Gottingen mean time, which is almost one hour ahead of GMT. The computed hourly and fifteen minutes observations of the horizontal component from the scale readings were in units of grains and feet and the conversion factor used to compute the scale readings in to mm-mg-s was 0.46108. Measurements were taken at hourly intervals 24 hrs a day. When a magnetic storm (main phase) was occurring, measurements were made at 15 min. intervals. The final absolute values "H" plotted in Figure 2 are in nT (as converted from the c.g.s units.).

The magnetogram for the September 1-2, 1859 of the Colaba Observatory (Figure 2) shows that the magnitude of the storm sudden commencement (SSC) was about 120 nT. The maximum negative intensity recorded at Colaba was $\Delta H \approx$ -1600 nT, and the duration of the main phase of the storm (corresponding to the plasma injection) was $\sim$ 1-1/2 hour duration. The location of Colaba ($\sim$ 12 LT) was not ideal to detect the maximum magnetic response to the storm. However, based on observation from this one station, one can say that this is now the most intense magnetic storm on record. Magnetometers at high latitude, e.g. Kew and others, were either saturated or non-operational for this event.

3.4. *What caused Super storm of September 1-2, 1859?*

We will apply the recently gained knowledge about Sun-Earth connection and use other related information, and make these determinations by a process of elimination.

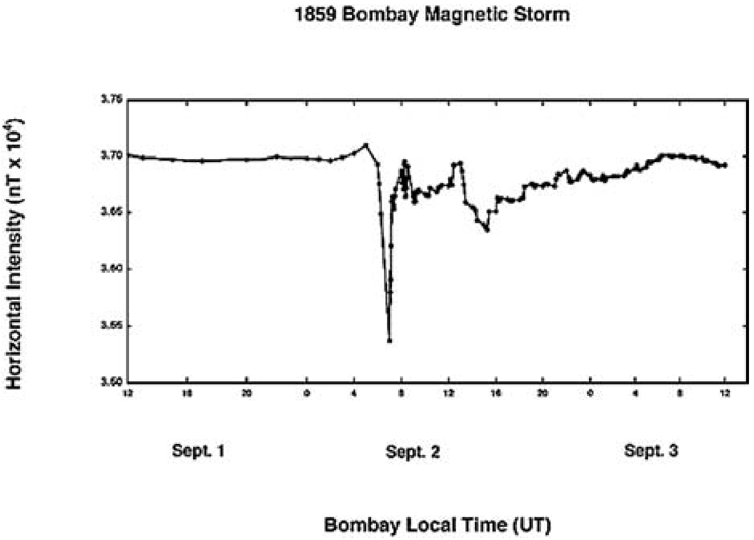

Figure 2. The Colaba (Bombay) magnetogram for the September 1-2, 1859 magnetic storm.

3.4.1. *Estimation of Magnetospheric Convection Electric Field*

The lowest latitudes of the auroras being 23° (Kimbal, 1960) was used to identify the Plasmapause location, which in turn was used to determine the magnetospheric convection electric fields, from the relation (Volland 1973; Stern 1975; Nishida 1978) for electric potential:

$$\Phi = -KR_E^2/r - A^*(r/R_E)^2 sin\Psi + \mu M/(qr^3), \tag{3.1}$$

where K=14.5 mV/m, R_E is the earth radius, r and Ψ are the radial distance and the azimuthal angle measured counter-clockwise from the solar direction, M is the Earth's dipole moment, q is the particle charge and μ is the particle transverse kinetic energy divided by the field magnitude, i.e., the first adiabatic constant. A^* is a coefficient given by Maynard & Chen (1975) and modified by Heppner (1977) and Wygant *et al.* (1998). The first and second terms on the left-hand side of equation (1) represent the corotation electric field and the shielded convection electric field, respectively. The third term represents the particle curvature and gradient B drifts.

A convection electric field, $E_C \sim 20$ mV/m, is needed for ring current at L=1.6 and plasmapause at L=1.3 (23° magnetic latitude).

These results are consistent with extrapolated magnetic latitude values for the auroral diameter given by Schulz (1997) as a function of Dst. Starting from a basic auroral boundary at about 65°, Schulz suggests that this boundary moves equatorwards 2° for each change of -100 nT in Dst.

3.4.2. *Estimation of the Interplanetary Electric Field*

From Carrington paper, the transit time of the ICME from the sun to Earth: ∼ 17 hours and 40 min. This indicates an average shock transit speed of $V_{shock} \sim 2380$ km/s.

Cliver *et al.* (1990) found a relationship between the solar wind speed at 1 AU and the average shock transit speed of (limited to events below 1200 km s-1)

$$V_{sw} = 0.775 V_{shock} \tag{3.2}$$

Gonzalez *et al.* (1998) have found an empirical relationship between ejecta speeds at 1 AU and magnetic cloud magnetic field magnitudes given by:

$$B(\mathrm{nT}) \approx 0.047 V_{sw} (\mathrm{km\,s^{-1}}) \tag{3.3}$$

where V_{sw} is the peak solar wind speed of the ejecta at 1 AU. The expression was determined by a linear regression, where the correlation coefficient was 0.71. The data were limited to peak speeds less than $\sim$ 750 km s^{-1} and peak magnetic fields less than $\sim$ 35 nT.

Combining (2) and (3), the maximum possible electric field for extremely fast interplanetary events such as the September 1-2, 1859 event can be expressed as:

$$E_{IP} \approx 2.8 \times 10^{-5} V_{shock}^{2} \mathrm{mV/m} \tag{3.4}$$

Assuming $V_{shock} \approx 2380$ km s^{-1}, we get $E_{IP} \sim 160$ mV/m.

This estimates compares well with the convection electric field, $E_C \sim 20$ mV/m, derived above if a reasonable value of the penetration efficiency of $\sim$ 12% of the interplanetary electric field is considered (Gonzalez *et al.* 1989).

3.4.3. *Estimation of Peak Storm Magnetic Intensity (Dst)*

Burton *et al.* (1975) gave an empirical relation for the evolution of ring current:

$$\frac{dDst}{dt} = Q - \frac{Dst}{\tau}, \tag{3.5}$$

where Dst is the disturbance storm time index which acts as a proxy for the energy of the ring current, Q is the energy input and τ is the decay constant. For energy balance of the ring current at the peak of the storm, we take

$$Dst = \tau Q \tag{3.6}$$

Further, for very intense storms, we can make use of the empirical relation derived by Burton *et al.* (1975) (neglecting the -0.5 mV/m constant value in Burton et al. due to the extremely large storm fields):

$$Q = \alpha V_{sw} B_S \tag{3.7}$$

where α is empirically $\sim 1.5 \times 10^{-3}$ nT s^{-1} $(\mathrm{mV/m})^{-1}$ and $V_{sw} B_S$ is in mV/m. Here B_S denotes the southward component of the interplanetary magnetic field. Considering τ=1.5 hrs (taken from Colaba magnetogram), we get from (6) and (7), $Dst \approx$ -1760 nT, a value consistent with Colaba measurement of $\Delta H \approx$ -1600 nT. This is also in fair agreement with the prediction of the theoretical model of Siscoe (1979).

The profile of the Dst index for this storm indicates that it was due to a simple plasma injection, and there is no evidence for the possibility of a complex storm. The most likely mechanism for this intense, short duration storm would be a magnetic cloud with intense B_S fields. Storm main phase “compound” events or “double storms” (Burlaga *et al.* 1987; Kamide *et al.* 1998) due first to sheath fields and then to cloud fields (Tsurutani *et al.* 1988) appear to be unlikely due to the (simple) storm profile The only other possibility that might be the cause of the storm is sheath fields. This can be ruled out because the compression factor of magnetic fields following fast shocks is only $\sim$ 4 times (Kennel *et al.*

1985). Since typical quiet interplanetary fields ~ 3 to 10 nT, the compressed fields would be too low to generate the inferred interplanetary and magnetospheric electric fields for the storm. Thus by a process of elimination the interplanetary fields causing this storm have been determined to be part of a fast magnetic cloud.

3.4.4. *Solar Flare Energies*

How rare was the September 1-2, 1859 solar flare/solar ejecta event? Is it possible that an event of this intensity could happen again in the near future? To answer these question we note that in addition to “white light”, solar flares radiate at a variety of other wavelengths as well. Using general scaling, Lin and Hudson (1976) have estimated total energy of August 1972 flare to be $\sim 10^{32}$ to 10^{33} ergs. Kane *et al.* (1995) has estimated the June 1, 1991 flare energy to be $\sim 10^{34}$ ergs.

The energy of the 1859 solar flare energy based on the white light portion as described in Carrington (1859) report, has been calculated by D. Neidig (private comm., 2001) to be $\sim 2 \times 10^{30}$ ergs. K. Harvey (private comm., 2001) has estimated the total energy of this event as $\sim 10^{32}$ ergs. The comparison shows that September 1, 1859 Carrington flare was not exceptional in term of total energy released.

Cliver *et al.* (1990) have pointed out that the 1972 event had the highest transit speed on record with a delay time of 14.6 hrs and the average ejecta speed ~ 2850 km s^{-1} (Vaisberg & Zastenker, 1976). The shock speed at 1 AU was > 1700 km s^{-1} (Zastenker *et al.* 1978). There was no measurement of the magnetic fields for the ejecta for the 1972 event at 1 AU. Using equations 2, 3 and 4, we get at 1 AU , $B \sim 103$ nT and a maximum interplanetary electric field $E_{IP} \sim 229$ mV/m.

If the August 1972 event had such high shock velocities why didn’t the ejecta or sheath cause a great magnetic storm? To answer this, we note that Pioneer 10 measured $B \sim 15$ nT at 2.2 AU. Assuming an r^{-2} drop-off of the field intensity with radial distance and no super-radial expansion (due to high internal pressure), the extrapolated $B \sim 75$ nT at 1 AU.

The flux rope model (R. Lepping) indicate that Pioneer 10 passed through the edge of the cloud which was tilted at 84° relative to the ecliptic plane and cloud magnetic field orientation was northward (Tsurutani *et al.* 1992b). Extrapolating the data to the time of Earth passage, it was noted that during the interval when the magnetic cloud passed the Earth, the Dst index indicated a storm recovery phase, and AE and Kp were unusually low (<100 nT and 0+, respectively). This is consistent with the picture that the magnetosphere becomes extremely quiet during intense B_N events (Tsurutani *et al.* 1995; Borovsky & Funsten, 2002). Thus, the most probable reason for the failure of the August 1972 event to excite any major magnetic storm was due to the fact that the interplanetary magnetic field within the magnetic cloud was directed almost totally northward (rather than southward).

4. Summary and Conclusions

The September 1-2, 1859 magnetic storm is the most intense magnetic storm in recorded history. The auroral sightings were as low as 23° magnetic latitude (Hawaii and Santiago), and the estimated Dst ≈ -1760 nT. The Colaba station magnetic decrease of $\Delta H \sim$ - 1600 nT is consistent with this estimate.

The 1859 flare/CME ejecta was not unique. The August 1972 flare was definitely equally (or more) energetic, and the interplanetary ejecta speed faster. So, 1859 like super magnetic storms can occur again in the near future. How often can they occur? The one big flare per solar cycle (11 years) has the potential for creating a storm with a similar intensity. However in reality, we know that this was the largest storm in the last 143 years (13 solar cycles).

At this stage it is difficult to answer: “are even more intense events possible?, can one assign probabilities to the occurrence of a similar storm or to a greater intensity storm?”

The predictability of similar or greater intensity events requires knowledge of either full understanding of the physical processes involved in the phenomenon or a good empirical statistics of the tail of the energy distribution. For the former, if one knows the physical processes causing solar flares or magnetic storms, then the high energy tail (extreme event) distributions could be readily ascertained. Knowing the physical processes, of course means understanding mechanisms of saturation. The sun and the magnetosphere are of finite size, have finite magnetic field strengths, etc., and therefore will have cutoff energies.

Since we do not fully understand these specific saturation processes, it is therefore not known whether flares with energy $> 10^{34}$ ergs or magnetic storms with Dst < -1760 nT are possible or not. Then, the other possibility is to use statistics to infer the probabilities of flares with energies less than, but close to 10^{34} ergs and storms with Dst < -1760 nT? Unfortunately, the statistics for extreme solar flares with energies greater than 10^{32} ergs and extreme magnetic storms with Dst < -500 nT are poor. The shapes of these high energy tails are essentially unknown. One can therefore assign accurate probabilities to flares and storms for only the lower energies where the number of observed events are statistically significant.

There does not exit any strong relationship between the strengths of the flares and the speed and magnetic intensities of the ICMEs. Nevertheless, it is certainly noted that the most intense magnetic storms are indeed related to intense solar flares, i.e., the two phenomena have a common cause: magnetic reconnection at the sun. Recently it is found that the previously thought “upper limit” of 10^{32} ergs for the energy of a flare can be broken by a wide margin (Kane *et al.* 1995). It is quite possible that we may have not detected events at the saturation limit (either flares or magnetic storms) during the short span of only hundreds of years of observations. Most probably the sun cannot have flares at superflare energy ($10^{38} - 10^{39}$ ergs) levels (Lingenfelter & Hudson 1980), but perhaps 10^{35} ergs is feasible for our sun. If it were so, the effects of an accompanying super-intense magnetic storm might be catastrophic for the modern society!

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Table 1. A partial chronological listing of large magnetic storms. The October-November 2003 storms have been added in the list.

Sr.No.	YEAR	MONTH	DAY	H Range[‡] (nT)	DST(nT)	Station	Geographic(Lat.,Long.)
1	1859	September ”	1-2 ”	1720 >700[†*]	- -	Bombay Kew	18.89° ; 72.82° 51.50°; 359.70°
2	1859	October	12	980	-	Bombay	18.89°; 72.82°
3	1872	February	4	1020	-	Bombay	18.89°; 72.82°
4	1882	November ”	17 ”	450 >1090[†*]	- -	Bombay Greenwich	18.89°; 72.82° 51.48°; 0.00°
5	1903	October ”	31 ”	820 >950[†*]	- -	Bombay Potsdam	18.89°; 72.82° 52.38°; 13.06°
6	1909	September	25	>1500[†*]	-	Potsdam	52.38°; 13.06°
7	1921	May ”	13-16 ”	>700[†*] 1060[†]	- -	Alibag Potsdam	18.63°; 72.87° 52.38°; 13.06°
8	1928	July	7	780	-	Alibag	18.63°; 72.87°
9	1938	April ”	16 ”	530 1900[†]	- -	Alibag Potsdam	18.63°; 72.87° 52.38°; 13.06°
10	1957	September	13	580	-427	Alibag	18.63°; 72.87°
11	1958	February	11	660	-426	Alibag	18.63°; 72.87°
12	1989	March	13	640	-589	Kakioka	36.23°; 140.18°
13	2003	October ”	29 30	432 453	-370 -406	Alibag Alibag	18.63°; 72.87° 18.63°; 72.87°
14	2003	November	20	531	-491	Alibag	18.63°; 72.87°

Discussion

Kahler: Does the size distributions of intense storms, measured by Dst, look like a power-law, similar to earthquakes and floods? If so, this suggests a self-organized system.

Lakhina: Yes, the studies so far are consistent with power-laws, but only for weak magnetic storms. The data for super-intense storm is very scarce, I am not aware of self-organized criticality occurring in the Sun-Earth plasma system as far as magnetic storms (intense to super-intense) are concerned.

S. T. Wu: Comments: According to the work of S. Kane in the 70's (If I remember correctly), the highest energy contents of a flare could be as high as 10^{40} ergs, which is very unusual, but it is possible.

[‡] H range is defined as the difference between the maximum and minimum value of H during the storm event.

[†] The values recorded at the mid-latitude stations could have an ionospheric component associated with the activity.

[†*] Saturation of the instrument. In addition, the value recorded at this station could have an ionospheric contribution.

LAKHINA: I am not aware of this work. Personally, I doubt that energies $\sim 10^{40}$ ergs for solar flares are possible.

GOPALSWARY: You mentioned that the Sep. 1-2 Storm was simple. But the plot shows one or two additional SSC's and a second dip suggesting a normal superstorm. Is it possible that the first big spike is an artefact? Also, what are the possibilities we are looking at a complex storm?

LAKHINA: The major main phase appears to be a clean single injection event. However there is a possibility of another pressure/shock wave during the recovery phase. So far we have not looked into this aspect, but will do that soon.

JUN LIN: The intensive flares occurring in October and November 2003 did not cause any significant geoeffectiveness. So according to your investigations, which kind of flares is most likely to cause magnetic storms?

LAKHINA: It is not only the energy of the flare and the ejecta speed at 1 AU, but the magnitude and southward direction of the IMF, which play important roles in geoeffectiveness. Although solar flares on October 28 and 29, 2003 had the energies to cause super-intense storm, the southward component of IMF in the magnetic cloud was not strong, therefore they could not produce a super storm. On the other hand, a weaker flare on Novermber 18, 2003, gave rise to a stronger magnetic storm than October 28/29 solar flares, as it has a stronger southward IMF lasting for several hours.