# The extreme magnetic storm of 1–2 September 1859

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[1] The 1–2 September 1859 magnetic storm was the most intense in recorded history on the basis of previously reported ground observations and on newly reduced ground-based magnetic field data. Using empirical results on the interplanetary magnetic field strengths of magnetic clouds versus velocities, we show that the 1 September 1859 Carrington solar flare most likely had an associated intense magnetic cloud ejection which led to a storm on Earth of $D_{ST} \sim -1760$ nT. This is consistent with the Colaba, India local noon magnetic response of $\Delta H = 1600 \pm 10$ nT. It is found that both the 1–2 September 1859 solar flare energy and the associated coronal mass ejection speed were extremely high but not unique. Other events with more intense properties have been detected; thus a storm of this or even greater intensity may occur again. Because the data for the high-energy tails of solar flares and magnetic storms are extremely sparse, the tail distributions and therefore the probabilities of occurrence cannot be assigned with any reasonable accuracy. A further complication is a lack of knowledge of the saturation mechanisms of flares and magnetic storms. These topics are discussed in some detail. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* solar flares, interplanetary CMEs, extreme magnetic storms, auroras, space weather

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## 1. Introduction

[2] The solar flare of 1 September 1859 was observed and reported by *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].

[3] The solar flare was followed by a magnetic storm at the Earth. The time delay was ~17 hours 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]. Of course, it was later shown by *Hale* [1931], *Chapman and Bartels* [1940], and *Newton* [1943] that solar flares and magnetic storms were indeed linked.

[4] The auroras associated with the 1859 magnetic storm occurred globally and have been reported by many. *Kimball* [1960] has provided the most complete indexing of auroral sightings. One particularly noteworthy comment that he made was "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 the most equatorward sighting of aurora that can be confirmed for this or any other storm event in past history (S. Silverman, private communication, 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).

[5] *Chapman and Bartels* [1940] based on photographic recordings of ground based magnetic field variations,

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**Table 1.** Chronological List of Large Magnetic Storms[a]

| Storm | Year | Month | Day | H Range,[d] nT | DST, nT | Station | Geomagnetic[e] Latitude N | Geomagnetic[e] Longitude E |
|---|---|---|---|---|---|---|---|---|
| 1 | 1859 | September | 1–2 | 1720 | | Bombay | 9.87° | 142.7° |
| | | September | 1–2 | >700[b,c] | | 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[b,c] | | Greenwich | 54.40° | 82.8° |
| 5 | 1903 | October | 31 | 820 | | Bombay | 9.87° | 142.7° |
| | | October | 31 | >950[b,c] | | Potsdam | 52.66° | 96.2° |
| 6 | 1909 | September | 25 | >1500[b,c] | | Potsdam | 52.66° | 96.2° |
| 7 | 1921 | May | 13–16 | >700 | | Alibag | 9.61° | 142.7° |
| | | May | 13–16 | 1060[†] | | Potsdam | 52.66° | 96.2° |
| 8 | 1928 | July | 7 | 780 | | Alibag | 9.61° | 142.7° |
| 9 | 1938 | April | 16 | 530 | | Alibag | 9.61° | 142.7° |
| | | April | 16 | 1900[b] | | Potsdam | 52.66° | 96.2° |
| 10 | 1957 | September | 13 | 580 | −427 | 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]The values recorded at the mid-latitude stations could have an ionospheric component associated with the activity.
[c]Saturation of the instrument.
[d]H range is defined as the difference between the maximum and minimum value of H during the storm event.
[e]Geomagnetic coordinates for all the observatories are computed for the year 1940 based on the IGRF model (courtesy NGDC site).

listed the most "remarkable" storms since 1857 [see also *Ellis*, 1900; *Moos*, 1910]. The Chapman and Bartels listing is reproduced in Table 1 with the addition of Bombay and Alibag, India magnetometer data (given for the first time here). For more details of the derivation of the latter values, see S. Alex et al. (The Colaba magnetometer and great magnetic storms within the years 1858–1872, manuscript in preparation, 2003, hereinafter referred to as Alex et al., manuscript in preparation, 2003). The variation of the H-component of the magnetic field is given in Table 1 (here Chapman and Bartels have subtracted the maximum negative value from the maximum positive value to obtain the "range." Thus the "range" includes both the deviations associated with the storm initial and main phases). We have recorded the range of the 1–2 September 1859 magnetic storm in the same fashion, but later we quote only the negative deviation to compare with the $D_{ST}$ predicted value. There are both equatorial and midlatitude stations listed in Table 1. One should note that the midlatitude measurements could have significant ionospheric components included, making a direct comparison between these values and near-equatorial values difficult.

[6] It is noted that *Chapman and Bartels* [1940] listed the interval 28 August through 7 September 1859 (a series of magnetic storms) first and discussed the 1–2 September storm in greater detail (chapter 9.23, volume 1). In Table 1 we only list the Bombay value for the 1–2 September event.

[7] It is the purpose of this paper to describe a new observation on the intensity of the 1859 magnetic storm and to apply more recently acquired knowledge about the physical causes of storms to this particular magnetic storm case. It will be shown that the interplanetary causes of the storm and its extreme intensity can be explained.

[8] We will attempt to answer the following questions: (1) How intense was the storm? (2) What were the interplanetary cause(s)? (3) Can such an intense storm occur again? (4) Are even more intense events possible? (5) Can one assign probabilities to the occurrence of a similar storm or a greater intensity storm?

## 2. Causes of Magnetic Storms

[9] It is now well established that the major mechanism of energy transfer from the solar wind to the Earth's magnetosphere is magnetic reconnection [*Dungey*, 1961]. A schematic is shown in Figure 1. If the interplanetary magnetic fields are directed opposite to the Earth's fields, there is magnetic erosion on the dayside magnetosphere (by magnetic connection) and magnetic field accumulation on the nightside magnetotail region. Subsequent reconnection on the nightside leads to plasma injection at these local times and auroras occurring at high-latitude nightside regions. As the magnetotail plasma get injected into the nightside magnetosphere, the energetic protons drift to the west and electrons to the east, forming a ring of current around the Earth. This current, called the "ring current," causes a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial magnetic stations. *Dessler and Parker* [1959] and *Sckopke* [1966] [see also *Carovillano and Siscoe*, 1973] have shown that the decrease in the equatorial magnetic field strength 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.

[10] Although there are many solar phenomena which travel through interplanetary space that can cause geomagnetic activity (for a review, see *Tsurutani and Gonzalez* [1997]), certainly the most likely for such a storm as that in 1859 was a coronal mass ejection or CME. CMEs were first identified in the OSO-7 data [*Tousey*, 1973]. There is often a "magnetic cloud" [*Klein and Burlaga*, 1982] within the CME. Magnetic clouds that are geoeffective have a southward and then northward (or vice versa) magnetic field

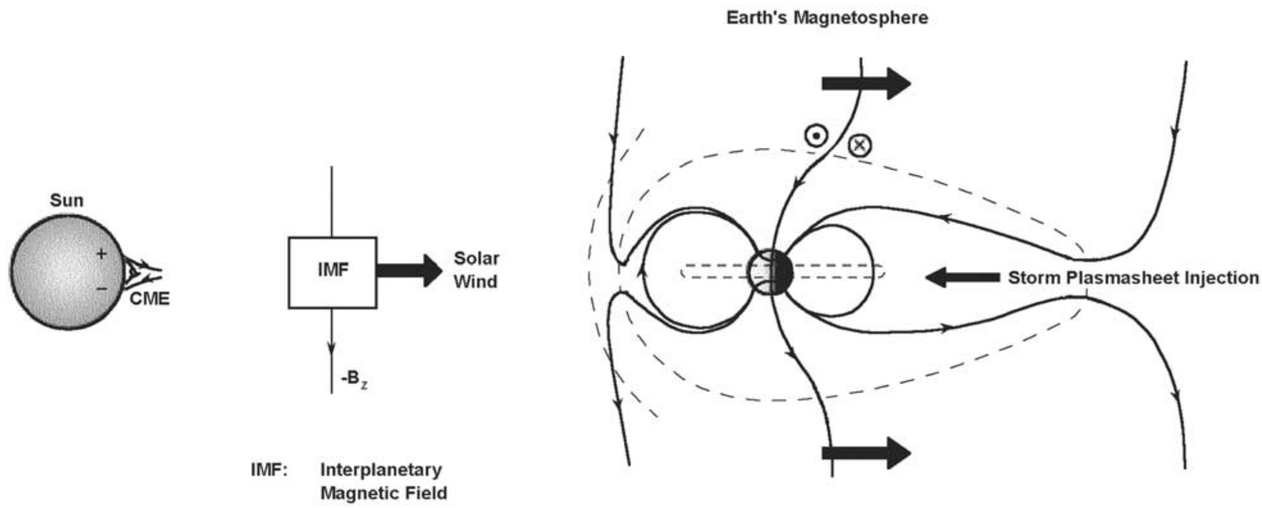


**Figure 1.** A schematic showing the magnetic reconnection process.

directional variation. When the magnetic cloud has a very high velocity (as the 1859 event did), it compresses the plasma ahead of it and forms a "collisionless" shock, as shown schematically in Figure 2. Behind this shock is a "sheath" which contains heated plasma and compressed magnetic fields. These intense sheath magnetic fields can also cause magnetic storms. If both the sheath field and the cloud field (if present) have the proper orientation, there will be magnetic reconnection from both phenomena, and a "double storm" [*Kamide et al.*, 1998] will result. In complex cases where there are multiple solar flarings there will be multiple solar ejecta, multiple shocks, and thus multiple plasma and field compressions. Triple storms, etc. will result. Thus by examining the profile of the magnetic storm using ground magnetic field data, storm generation mechanisms can be identified [*Tsurutani et al.*, 1999].

## 3. Description of the Magnetometers Used at the Colaba Observatory

[11] The instruments used for measuring the declination and horizontal magnetic field component at the Colaba Observatory in Bombay/Mumbai during 1846–1867 were made by Thomas Grubb of Dublin and are described in reports by the *Royal Society* [1842] and *Taylor* [1840]. In

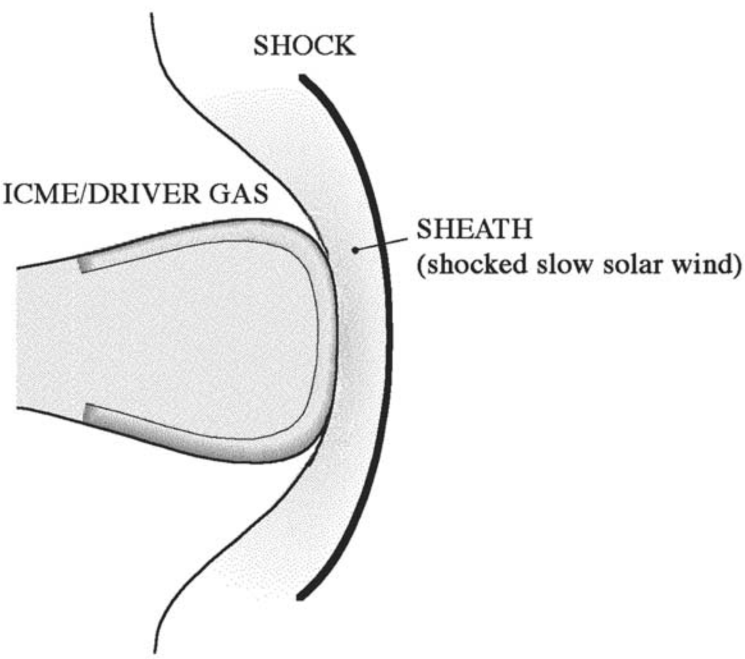


**Figure 2.** The configuration of a fast coronal mass ejection (CME) and its upstream sheath.

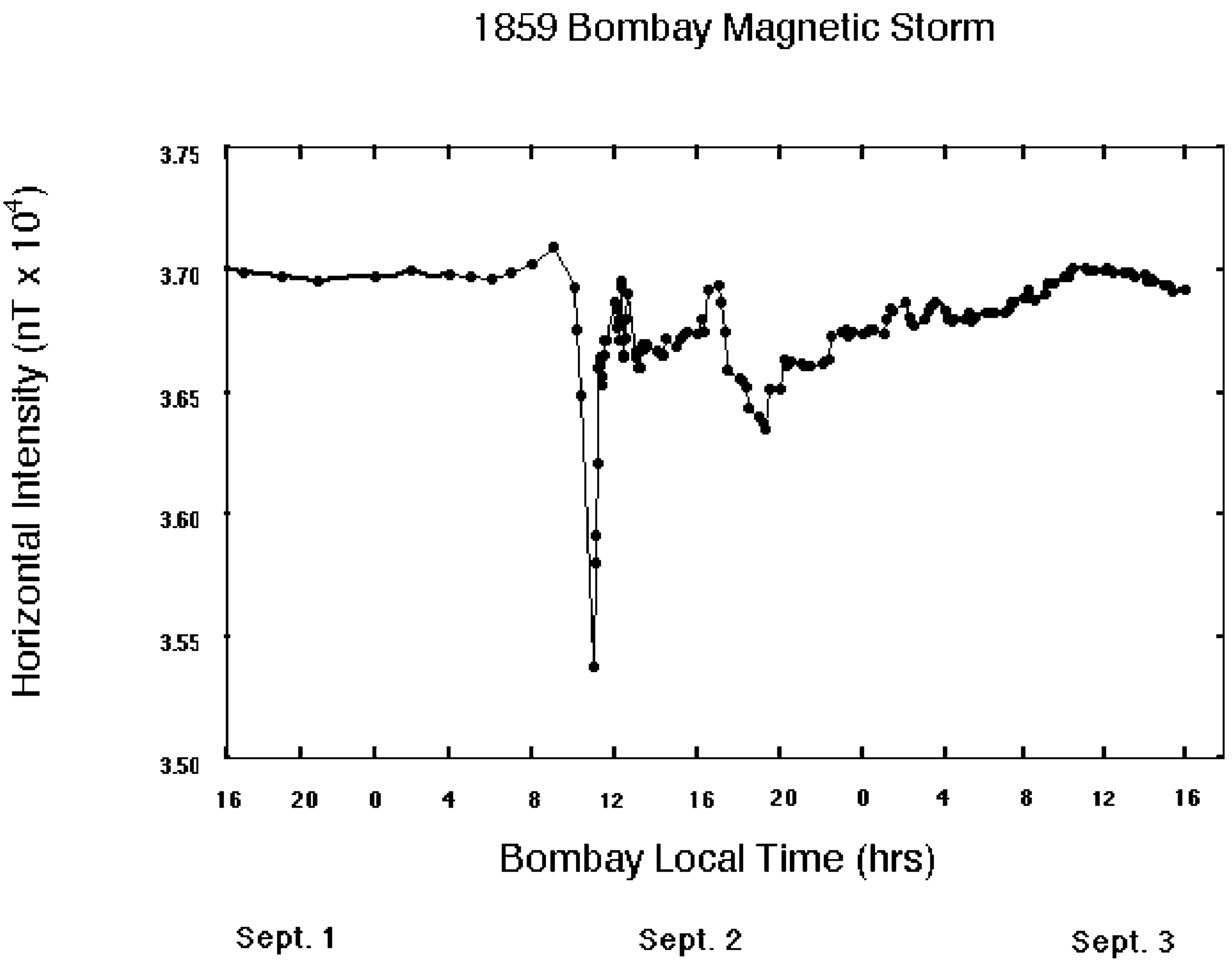


**Figure 3.** The Colaba (Bombay) magnetogram for the 1–2 September 1859 magnetic storm.

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 δ (in minutes) was calculated from: $\delta = 6'.841 \times (f - R) \times c$, where $6'.841$ is the adopted value of a unit of the declinometer scale, R is the true meridian reading, c is the torsion coefficient, and f is the observed scale reading.

[12] The Grubb magnetometer used to measure the Horizontal force consisted of a rectangular bar magnet suspended horizontally and carrying a collimator scale. The position of the magnet could 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 hours 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 3 are in nT (as converted from the c.g.s. units).

## 4. Results

[13] The Colaba (Bombay/Mumbai) magnetic data for the 1–2 September 1859 storm have been recently calibrated and reduced and are shown in Figure 3. The temporal resolution of the storm main phase is one point per 15 min. The temporal resolution of the storm initial phase was one point per hour. At this latter temporal resolution, magnetospheric compression by a shock [*Araki*, 1977] cannot be resolved, but the peak initial phase amplitude $\Delta H$ was $\cong$ 120 nT. It is clear that the main phase of the storm (corresponding to the plasma injection) lasted only from 11 to 12 + hours local time or a $\sim$1 to 1 1/2 hour duration.

[14] The maximum negative intensity observed at Colaba was $\sim -1600$ nT. The error is estimated at ±10 nT (Alex et al., manuscript in preparation, 2003). 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.

[15] The profile of the $D_{ST}$ 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 (see later reference to the 1989 storm; this latter storm was quite complex, lasting ~24 hours). The most likely mechanism for this intense, short duration storm would be a magnetic cloud with intense $B_S$ fields. We will later show that the sheath fields would not have been intense enough and can be ruled out.

[16] For comparison, a storm in more recent history was the March 1989 storm [*Allen et al.*, 1989]. This storm had a ~590 nT peak (one hour) decrease in the near-equatorial field strength ($D_{ST}$) as reported by the World Data Center, Kyoto, Japan. This storm caused the Hydro-Quebec (Canada) power grid to go down for nine + hours and caused a loss of ~ \$360 to \$645 million. The eastern U. S. seaboard power grid was almost put down as well (J. Kappenman, personal communication, 2001).

### 4.1. Estimates of the Magnetospheric Convection Electric Field Derived From Ground Based Observations

[17] With knowledge of the convection electric field value at the inner plasma sheet, one can try to determine the ring current and the plasmapause locations [*Volland*, 1973; *Stern*, 1975; *Heppner*, 1977; *Wygant et al.*, 1998; *Schulz*, 1997] (V. Vasyliunas, private communication, 2001). The plasmapause is defined as the location where the convection electric field and the corotation electric field become equal. However, for the real case, the above models also take into account the polarization electric field (Alfvén layer), which partially counteracts the convection field. For the ring current location we computed the combined drifts for particles of several energy values and have used the deepest penetration positions.

[18] We assume that the location of the observed oxygen and nitrogen auroras marks the average L-position of the ring-current, and that the location of the 6300 Å red auroras map to the plasmapause (R. M. Thorne, private communication, 2002).

[19] The electric potential for drifting particles is given by the general equation [*Volland*, 1973; *Stern*, 1975; *Nishida*, 1978]:

$$\phi = -KR_E{}^2/r - A^*(r/R_E)^2 \sin\psi + \mu M/\left(qr^3\right), \qquad (1)$$

where K = 14.5 mV/m, $R_E$ is the Earth radius, r and $\psi$ are the radial distance and the azimuthal angle measured counterclockwise from the solar direction, respectively, M is the Earth's magnetic dipole moment, q is the particle charge, and $\mu$ is the transverse kinetic energy of the particle divided by the magnetic field magnitude. A* is the coefficient given by *Maynard and Chen* [1975], modified according to the works of *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.

[20] Thus from equation (1) and Figure 6 of *Wygant et al.* [1998], a ~20 mV/m convection electric field is needed for a ring-current location of L = 1.6 and a plasmapause location of L = 1.3 (as reported by the auroral locations given by *Kimball* [1960]).

[21] These results are also consistent with extrapolated magnetic latitude values for the auroral diameter given by *Schulz* [1997] as a function of $D_{ST}$. Starting from a basic auroral boundary at about 65°, Schulz suggests that this boundary moves equatorwards 2° for each change of −100 nT in $D_{ST}$. Values for the ring current and plasmapause locations, similar to those obtained by these two methods, are also found from the knowledge of the magnetopause position by scaling these locations in the inner magnetosphere during an extremely large compression as that expected for the 1859 event (V. Vasyliunas, private communication, 2001).

### 4.2. Estimate of the Interplanetary Electric Field

[22] The auroral observations imply a magnetosphere electric field of ~20 mV/m. Assuming a 10% magnetic reconnection efficiency [*Gonzalez et al.*, 1989], the external solar wind electric field is ~200 mV/m.

[23] Recent work, based on empirical means, has derived expressions that allow one to estimate solar wind parameters for extreme events such as the 1–2 September 1859 solar interplanetary ejecta. *Cliver et al.* [1990] using a modified event listing from *Cane* [1985] have derived a least square fit of:

$$V_{SW} \approx 0.755\overline{V}_{shock}. \qquad (2)$$

The term $V_{SW}$ is the solar wind velocity at 1 AU and $\overline{V}_{shock}$ is the average shock speed between the Sun and 1 AU. The average shock speed is estimated using solar flare energetic particle arrival times at Earth and subsequent storm onset times. The correlation coefficient is 0.72 and the average shock speed is limited to events below 1200 km $s^{-1}$.

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

$$B(nT) \approx 0.047\, V_{SW}(km/s), \qquad (3)$$

where $V_{SW}$ is again the 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 speeds less than ~750 km/s and magnetic fields less than ~35 nT.

[25] The interplanetary electric field is given by:

$$E = -V_{sw} \times B_S. \qquad (4)$$

If one combines equations (2) through (4), the maximum possible electric field for extremely fast interplanetary events such as the 1–2 September 1859 event can be expressed as:

$$E \approx 2.8 \times 10^{-5}\overline{V}^2_{shock} mV/m. \qquad (5)$$

[26] The above expression assumes purely southward interplanetary magnetic fields. The average speed of the shock ahead of the 1859 magnetic cloud (assuming a distance of 1 AU is traversed in 17.5 hours) is ~2380 km/s.

Assuming this value for $\overline{V}_{shock}$, the solar wind electric field is ~160 mV/m, in relatively good agreement with the estimate of ~200 mV/m based on auroral and reconnection efficiency estimates. The solar wind speed at 1 AU would be ~1850 km/s.

[27] It is noted that although the extrapolations of solar wind velocity and cloud field strengths have large uncertainties, the estimate of the interplanetary electric field is surprisingly good. An 11% increase in the solar wind speed to 2068 km/s at 1 AU is all that is needed to obtain a ~200 mV/m electric field. This is well within the uncertainty of the extrapolations.

[28] The average quiet interplanetary magnetic field is typically 5.5 nT and on occasions twice this strength (~10 nT). Shocks ahead of the fast magnetic cloud can compress the magnetic field to a maximum value of four times [*Kennel et al.*, 1985] that of the quiet field. Thus under ordinary circumstances the sheath field strength can have maximum values of ~20–40 nT. This is much too low for the required electric field. Thus the sheath magnetic fields ahead of the interplanetary coronal mass ejection (ICME) can be ruled out as a major possible source of the interplanetary electric field for this magnetic storm.

### 4.3. Estimation of the Peak Storm Magnetic Intensity ($D_{ST}$)

[29] For energy balance for the ring-current at the peak of the storm we have (Gonzalez, W. D., et al., Estimate of magnetic storm-peak intensity from halo-CME speed observations: 1. Magnetic clouds, submitted to *Geophysical Research Letters,* 2003):

$$D_{ST} = \tau Q, \qquad (6)$$

where Q is the energy input and $\tau$ the ring-current decay time value at the peak of the storm. $D_{ST}$ is the average magnetic disturbance at the near-equator discussed earlier. An empirical expression for the magnetic storm intensity as a function of interplanetary parameters has been developed by *Burton et al.* [1975], which for very intense storms can be written as:

$$Q = \alpha V_{sw} B_S, \qquad (7)$$

where $\alpha$ is empirically found to be $1.5 \times 10^{-3}$ nT s$^{-1}$ (mV/m)$^{-1}$ and $V_{sw}B_S$ in mV/m (the −0.5 mV/m constant value given by Burton et al. is negligible due to the extremely large storm fields considered here). In this calculation we assume that the IMF in the cloud was totally in the southward direction, as has happened for some great magnetic storms [*Tsurutani et al.*, 1992a]. We assume $\tau$ = 1.5 hrs (taken from Figure 3). Thus from equations (6) and (7) we get peak $D_{ST} \approx -1760$ nT, a value consistent with the Colaba measurements of $\Delta H = -1600 \pm 10$ nT. *Siscoe* [1979] had previously predicted that the 2 September 1859 extreme magnetic storm would have a $D_{ST}$ intensity of the order of −2000 nT. However, his prediction is based on a model which treats pressure as a constant along the flux tubes, neglects pressure anisotropy, and uses a truncated series for the magnetic field produced by the ring current, i.e., retaining only the effects of the dipole term and neglecting all higher order forms. The maximum average error introduced by the use of the truncated field representation alone is estimated as 17% [*Siscoe*, 1979]. Thus correcting this error, his predicted value would be ~ −1660 nT which compares well with our predicted value of −1760 nT and the Colaba measurements of $\Delta H = -1600 \pm 10$ nT.

### 4.4. Solar Flare Energies

[30] How rare was the 1–2 September 1859 solar flare/solar ejecta event? Is it possible that an event of this intensity could happen again in the near future?

[31] Since the early measurements of visible "white light" flares, scientists have determined that there is radiation at a variety of other wavelengths as well. Using general scalings, *Lin and Hudson* [1976] have estimated the August 1972 flare to have had a total energy ranging from $10^{32}$ to $10^{33}$ ergs. *Kane et al.* [1995] have estimated the more recent 1 June 1991 flare to have had an extreme energy of $10^{34}$ ergs.

[32] For comparison, D. Neidig (private communication, 2001) has calculated the 1859 white light flare energy based on the *Carrington* [1859] report. The assumptions made are the peak flux is equal to the brightest white light flares measured thus far (~100% enhancement over the background photospheric intensities), duration of ~5 min, area ~ $7 \times 10^{17}$ cm$^2$. Assuming a typical flare photometric spectrum (up to 300% brighter in the near-UV), Neidig derived a total optical output of ~$2 \times 10^{30}$ ergs. K. Harvey (private communication, 2001) has estimated that this flare was most probably ~$10^{32}$ ergs.

[33] There have been several papers on the topic of the frequency of occurrence of very energetic solar flares. These may be of interest to the readers. Two are *Lingenfelter and Hudson* [1980] and *Hudson* [1991]. However we note that these were published before the *Kane et al.* [1995] work.

### 4.5. Ejecta Velocities

[34] *Vaisberg and Zastenker* [1976] determined the average speed of the August 1972 ejecta by measuring the time delay between the flare onset to the shock detection at 1 AU. Their ejecta average speed estimate of the 4 August 1972 measurement is 2850 km s$^{-1}$ (a delay time of 14.6 hrs), smaller than that of the *Carrington*, [1859] flare-storm delay time. *Zastenker et al.* [1978] determined that the shock speed at 1 AU was >1700 km/s. *Cliver et al.* [1990] also point out that the 1972 event had the highest transit speed on record. Using equations (2), (3), and (5), the expected magnetic field strength at 1 AU would be 103 nT and a maximum interplanetary electric field of 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?

[35] Unfortunately, there was no measurement of the magnetic fields for the ejecta for the 1972 event at 1 AU. There was, however, a deep space magnetic field measurement made by Pioneer 10 at 2.2 AU [*Smith*, 1976]. The field strength of the magnetic field was ~15 nT. Assuming an $r^{-2}$ drop-off of field intensity with radial distance and no superradial expansion (due to high internal pressures), the field would have been ~73 nT at 1 AU. With greater internal pressures, the field strength could have been higher. Using a flux rope model for the cloud, R. Lepping (personal

communication, 2001) estimates that Pioneer 10 passed through the edge of the cloud. It was estimated that the cloud was tilted at 84° relative to the ecliptic plane.

[36] *Tsurutani et al.* [1992b] have examined the Pioneer 10 data in detail. They have noted that the magnetic cloud magnetic field orientation was northward (consistent with the recent R. Lepping finding). Extrapolating the data to the time of Earth passage, the authors found that during the magnetic cloud interval, the $D_{ST}$ 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 and Gonzalez*, 1995; *Borovsky and Funsten*, 2003]. Thus because the interplanetary magnetic field within the August 1972 cloud event was directed almost totally northward (rather than southward), no major magnetic storm occurred.

## 5. Summary and Conclusions

[37] The 1–2 September 1859 magnetic storm intensity was the most intense magnetic storm in recorded history. The auroral sightings were as low as 23° magnetic latitude (Hawaii and Santiago), and the storm index was estimated to be −1760 nT. The Colaba station magnetic decrease of −1600 nT is consistent with this estimate.

[38] It is somewhat surprising to find that the 1859 flare/interplanetary ejecta was not unique. The August 1972 flare was definitely equally (or more) energetic, and the interplanetary ejecta speed was faster. It is therefore expected that magnetic storms of the 1859 intensity 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).

[39] To recapitulate the answers to the questions posed in the Introduction section: (1) the storm intensity is estimated to be $D_{st} = -1760$ nT, (2) the interplanetary cause was most likely a fast magnetic cloud with intense $B_S$, and (3) it is possible for a storm with such intensity to occur again. The August 1972 interplanetary coronal mass ejection (ICME) was almost such an event.

[40] The last two questions (4) "are even more intense events possible?" and (5) "can one assign probabilities to the occurrence of a similar storm or to a greater intensity storm?" are more difficult to answer. The same questions apply to solar flares, and we will attempt to address both sets of questions together.

[41] The predictability of similar or greater intensity events requires knowledge of one of two things: full understanding of the physical processes involved in the phenomenon or 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 even if one can prove that the distributions are log-normal (see arguments for log-normal storm energy distributions given by M. W. Liemohn and J. U. Kozyra, Lognormal form of the ring-current energy content, submitted to *Journal of Geophysical Research,* 2003). 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 $D_{ST} < -1760$ nT are possible or not.

[42] Can one use statistics to infer the probabilities of flares with energies less than but close to $10^{34}$ ergs and storms with $D_{ST}$ smaller (less negative) than −1760 nT? Unfortunately, not with any accuracy. Even assuming that there are no major internal changes in the Sun or the magnetosphere ("stationarity," in a statistical sense), one easily notes that the statistics for extreme solar flares with energies greater than $10^{32}$ ergs and extreme magnetic storms with $D_{ST} < -400$ 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 is statistically significant.

[43] In this article we have discussed the intensity of the 1859 solar flare and other intense solar flares for comparative purposes. Although it is not expected that there is a strong relationship between the strengths of the flares and the speed and magnetic intensities of the ICMEs, 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. The recent *Kane et al.* [1995] results have shown that the previously thought "upper limit" of $10^{32}$ ergs for the energy of a flare can be broken by a wide margin. Our time span of observations has been quite limited (only hundreds of years), and it is therefore doubtful that we have detected events at the saturation limit (either flares or magnetic storms). Can the Sun have flares at superflare energy ($10^{38}$–$10^{39}$ ergs) levels? Most probably not [see *Lingenfelter and Hudson*, 1980], but perhaps $10^{35}$ ergs is feasible for our Sun. The effects of an accompanying perfect magnetic storm might be catastrophic.

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