Reply to comment by S.-I. Akasofu and Y. Kamide on "The extreme magnetic storm of 1–2 September 1859"

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[1] We welcome the comments by our esteemed colleagues *Akasofu and Kamide* [2005], but we have to disagree with many of their statements and conclusions. We have strong confidence in the accuracy of the Colaba Observatory magnetic data for the 1–2 September 1859 magnetic storm (the magnetometers worked perfectly before, during, and after the disturbed period of 1–6 September 1859), in the (relative) accuracy of our estimation of a peak ΔH value of about -1760 nT for the storm (designated in our work as "*Dst*"), and in the extraordinary value/usefulness of pre-space-age geophysical data. We think that there is much to learn from data such as those from Indian magnetic observatories and other similar data.

[2] *Tsurutani et al.* [2003] used the *Kimball* [1960] auroral observations and the *Wygant et al.* [1998] results on electric field penetration in our equation (1) [*Tsurutani et al.*, 2003; see also *Volland*, 1973; *Stern*, 1975; *Maynard and Chen*, 1975; *Nishida*, 1978] to estimate the magnetospheric convection electric field that was present during the storm's main phase. From the estimated electric field of $\sim$20 mV/m we assumed a reconnection efficiency of $\sim$10% to get an interplanetary electric field of $\sim$200 mV/m. We next used equation (6) of *Tsurutani et al.* [2003], the relationship between *Dst*, *Q* (the energy input given by *Burton et al.* [1975]), and τ (the ring current decay time). All values were taken at the peak of the storm. The value for τ was taken from the Colaba magnetogram.

[3] Several consistency checks were made: (1) We performed calculations based on timings provided by *Carrington* [1859] and empirical relationships developed in the space age to estimate the interplanetary electric field [see *Tsurutani et al.*, 2003, section 4.2]. (2) We noted the *Schulz* [1997] auroral magnetic latitude versus *Dst* relationship. (3) We noted the very large negative values of the Colaba ΔH observations (Colaba is a near-equatorial station ($10°$ magnetic latitude) away from the equatorial electrojet influence and away from severe storm time auroral ionospheric current influence). All of these additional checks gave us confidence in the extraordinarily large *Dst* value that we derived. However, it should be mentioned that all of the different empirical relationships that were used in our extrapolations were developed for moderate intensity magnetic storms/geomagnetic activity. A data set that could be used to determine whether these relations can be linearly extrapolated to higher values or not does not currently exist.

[4] The Colaba magnetometer peak decrease and profile give interesting and new information. The peak $\Delta H \approx -1600$ nT is the most negative value on record for a near-equatorial station. (It should be noted that Kakioka, Japan ($27°$ magnetic latitude) and Hermanus, South Africa ($-34°$ magnetic latitude), are located at middle latitudes and are potentially vulnerable to strong magnetic signatures caused by ionospheric currents. They would be useful for studying moderate-intensity magnetic storms but not extreme events such as the one in 1859.)

[5] The short duration of the "main phase" of the magnetic storm is indeed quite different from "typical" storms. However, herein lies the usefulness of the magnetic data for new and improved understanding of space weather phenomena. X.-L. Li et al. (Modeling of 1–2 September 1859 super magnetic storm, submitted to *Advances in Space Research*, 2005) have reproduced the Colaba magnetic profile and *Dst* peak value by assuming the existence of a high-density plasma plug that followed a magnetic cloud. This is not at all out of the question. *Plunkett et al.* [2000, and references therein] have noted that coronal mass injections (CMEs) near the Sun typically have three essential parts: bright outer loops, a dark region, and coronal filaments. It is thought that the dark regions are the magnetic clouds that have been detected in interplanetary space. However, the interplanetary signatures of loops and filaments have been more elusive. *Tsurutani et al.* [1998] have reported the possible detection of a plasma and field signature of loops at 1 AU for the 10–11 January 1997

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interplanetary coronal mass ejection (ICME) event. *Burlaga et al.* [1998], for this same interplanetary event, have detected a high-density plasma "plug" sunward of the magnetic cloud and have interpreted this as the first identification of a "coronal filament" at 1 AU. Thus there is evidence of high-density plasma plugs following magnetic clouds (however, the reason why they are detected so rarely is still a mystery). On the other hand, W. B. Manchester et al. (Modeling the Sun-to-Earth propagation of a very fast CME, submitted to *Advances in Space Research*, 2005), using a MHD code to model the compression of the leading edge of the magnetic cloud, obtained a *Dst* profile that matches the Colaba magnetogram. G. Siscoe and N. Crooker (*Dst* of the Carrington storm of 1859, submitted to *Advances in Space Research*, 2005) have assumed that a combination of sheath and magnetic cloud fields created the broader Colaba magnetic structure. Other interesting models/explanations are currently being developed.

[6] We are in agreement that the September 1859 white light flare was not extraordinary and had mentioned this in our original paper. Flares with orders of magnitude greater intensities have been reported in the literature. Our late colleague, K. Harvey, also conveyed similar information. She had observed several optical flares where the brightness of the active area grew by double or more.

[7] *Akasofu and Kamide* [2005] argue that "the largest *Dst* decrease during the last century was about 500–600 nT...[therefore] it is hard to believe that a storm with a *Dst* decrease of more than 1500 nT occurred." We do not believe that this is a very compelling argument. Before the March 1989 magnetic storm (*Dst* = −589 nT) had occurred, there was a lot of discussion of whether "saturation mechanisms" were limiting storm intensities to a minimum of −300 to −400 nT. There are still discussions of "saturation" in the literature. We had presented arguments why we believe that the August 1972 ICME could have caused a storm as intense or with even greater intensity than the 1859 event. It was just happenstance that the magnetic field within the 1972 magnetic cloud was almost purely northward rather than southward [*Tsurutani et al.*, 1992]. This led to geomagnetic quiet [*Tsurutani and Gonzalez*, 1995; *Øieroset et al.*, 2005] rather than a superstorm.

[8] The 1–2 September 1859 ICME was the second fastest on record (the August 1972 event was the fastest). *Kimball* [1960] reported that auroras for the 1–2 September 1859 magnetic storm were detected as far south as Hawaii and Santiago, Chile (both at 23° magnetic latitude). Fires were set on the ground due to arcing from conductors, and people positioned near wires received electrical shocks [*Loomis*, 1861]. Thus the 1–2 September magnetic storm was exceptional in many ways. Other, less well documented magnetic storms in the past may also have had *Dst* values far exceeding −500 to −600 nT. *Chapman and Bartels* [1940] mention that auroras were seen over Bombay during the great magnetic storm of 4 February 1872. The *Times of India* reported the following in an article entitled "The Aurora Borealis" on Tuesday, 6 February 1872:

Will it surprise our readers to learn that the Aurora Borealis was plainly visible in Bombay on Sunday last? Such was indeed the case and its effects were felt too. After sunset on Sunday, the Aurora was slightly visible, and constantly kept changing colour, becoming deep violet,

when it was intense about 3 O'clock on Monday morning. It was distinctly visible until sunrise on Monday. The influence of this atmospheric disturbance was unpleasant both for our person and our correspondence. The cold was unpleasantly keen, and all telegraphic communication was stopped for some hours.

Both before and after its height, the aurora affected the working of both sections of the British-Indian Submarine cable, section running east and west and the other North and South. At 8 O'clock yesterday morning the magnetic disturbance in the telegraph offices was very strong. The extent of this disturbance may be gathered from the fact that all the lines to England in connection with the British-Indian Submarine cable were affected for hours and so were the Government lines. At Aden, Aurora was brilliant in the extreme.

Whether the aurora seen was overhead may be a moot point, but one cannot simply discount the possibility of aurora descending to low latitudes during superintense storms.

[9] Complex solar active regions such as the one that existed during the *Carrington* [1859] flare and the one that was present during the August 1972 flare are known to lead to continuous flaring and concomitant expulsion of CMEs (the "Halloween" 2003 events are a good example). This can lead to quite complex interplanetary phenomena. Study of solar-interplanetary-magnetospheric coupling for such events is only in its infancy. The assumption that one can use a "standard" ICME sheath/cloud as the cause of the geomagnetic activity (as *Akasofu and Kamide* [2005] suggest) may lead to erroneous conclusions. As an example, we invite readers to examine the August 1972 storm *Dst* profile and infer what the interplanetary/solar causes were. Readers will find that Mother Nature is not quite so simple.

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