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Modeling of 1–2 September 1859 super magnetic storm

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Abstract

Based on an estimated solar wind condition around 1–2 September 1859, we were able to reproduce the Carrington magnetic storm magnetometer record, with the H-component depression of −1600 nT, made at Colaba Observatory in Mumbai, India. We used an updated Dst prediction model from Temerin and Li (2002), which provides a prediction efficiency of 0.91 for 1995–2002 interval using a fixed set of modeling parameters. The negative depression in the magnetometer record could be explained by assumptions as to the condition of the solar wind that, though far more geoeffective than any that have ever been observed, do not seem improbable given the known average speed of the interplanetary shock for this event. The extremely fast recovery of the magnetometer record, however, required that the dynamic pressure of the solar wind also be substantially larger than has ever been observed. We also showed how the strength of the magnetic storm would have depended on the season and the time of day. For the same solar wind conditions in GSM coordinates, the largest magnetic storms occur around the fall equinox and at the time of day when the dipole axis is most perpendicular to the solar wind velocity. Given the assumed very fast solar wind with a very large negative interplanetary magnetic field (IMF) B_z directly impacting the Earth, our model together with the known magnetometer record indicates that a super magnetic storm with minimum Dst less than −1600 nT could have occurred and thus can occur again. For the magnetic storm of 1–2 September 1859, however, the extremely fast recovery of Dst requires an extremely large pressure enhancement. This suggests that this particular event was doubly unusual.
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Keywords: Carrington event; Magnetic storms; Magnetic storm modeling; Modeling the 1–2 September 1859 magnetic storm

1. Introduction

An extremely bright (in visible wavelengths) solar flare was observed on 1 September 1859 and a very large magnetic storm started 17 h and 40 min later (Carrington, 1859; Cliver, this issue). A newly discovered near-equatorial record of the magnetic disturbance from this storm at the Colaba Observatory in Mumbai, India, has recently been analyzed by Tsurutani et al. (2003). They found that the H-component of the magnetometer record was depressed by −1600 nT (nanoTesla). If this decrease in the magnetic field were representative of the magnetospheric decrease characteristic of magnetic storms, it would be equivalent to a magnetic storm index (Dst) depression of about −1600 nT.

Tsurutani et al. (2003) also concluded on the basis of the 'equilibrium solution' to the Burton equation (Burton et al., 1975) and an estimated solar wind condition that the normal magnetospheric response to such a solar wind would have produced a Dst of −1760 nT or a negative deviation about three times bigger than any storms

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since 1957 (a Dst of −589 nT on March 14, 1989), the year the systematic official record of Dst begins. Dst is a measure of the average change (derived from magnetometer measurements from four stations) in the magnetic field near the equator and is used as an index to determine the onset and the strength of magnetic storms. For a dipole field the depression of the magnetic field at the center of the dipole is proportional to the total energy content of the plasma within the dipole (Dessler and Parker, 1959; Sckopke, 1966). Thus Dst, an hourly index, is often used as an approximate measure of the energy content of the ring current, which consists of trapped particles on quasi-dipolar field lines, but Dst also includes effects from currents on non-quasi-dipolar field lines: the solar wind, magnetopause, and magnetotail. The Burton equation predicts Dst on the basis of the solar wind electric field E_y component (equivalent to $V_x \times B_z$, the velocity of the solar wind towards the Earth from the Sun times the southward component of the IMF), a decay constant, and the solar wind pressure.

Tsurutani et al. (2003) estimated the solar wind electric field, E_y, on the basis of the magnetospheric electric field (which in turn was estimated from the known equatorward extent of the aurora) and a normal assumption for the reconnection efficiency at the magnetopause. Knowing the solar wind electric field allowed Tsurutani et al. to use the Burton equation to estimate Dst for the magnetic storm. They also used the average solar wind shock velocity (since the time of the flare and the time of the magnetospheric impulse are known) to estimate the solar wind velocity and magnetic field. Then assuming a southward direction for the interplanetary magnetic field (IMF) (since such a direction is necessary to produce a large magnetic storm) allowed them to double check their solar wind electric field calculation. Since in the Dst model used here we do not explicitly use the solar wind electric field, we find it more interesting to note that Tsurutani et al. assumed electric field is equivalent to a solar wind velocity of 1850 km/s and a purely southward IMF magnetic field of 87 nT.

However, Tsurutani et al. (2003) 'equilibrium solution' of the Burton equation has been questioned by Siscoe and others (e.g., Siscoe, 2004). The questioning, no doubt, arises in part from the fact that the magnitude of the storm (−1760 nT) is so much larger than any in the recent record and from the fact that the 'equilibrium solution' used a somewhat arbitrary time constant and that it has to take some time, more than is allowed by the data, to reach this equilibrium. Siscoe and Cooker (this issue) found that actually solving the Burton equation or the modified version of O'Brien and McPherron (2000) only gives an hourly Dst of about −700 nT for solar wind parameters similar in their overall effect to those assumed by Tsurutani et al. (2003).

Temerin and Li (2002) have developed a model that greatly improves the Burton result. Using solar wind parameters as input, the model predicts Dst at a 10-min resolution with a high prediction efficiency, PE, (PE = 1 − (mean squared residual)/(variance of data), where the residual is the difference between the data and the prediction). The accuracy of these predictions shows that the Earth's magnetospheric current systems are driven by the solar wind and are highly predictable. The model has recently been updated and now provides a PE of 0.91 for 1995–2002 interval using a fixed set of modeling parameters. During these eight years the most negative Dst of −387 nT occurred on March 31, 2001.

2. Model results

From the shock transit time of the 1859 Carrington event, Tsurutani et al. (2003) and Siscoe (2004) used statistical relations to infer the shock speed, the solar wind velocity, and the IMF strength. Using similar solar wind conditions to those estimate by Tsurutani et al. (2003) and Siscoe (2004), we ran the updated Temerin–Li model to see what would happen. (Siscoe and Cooker, this issue) has a more detailed discussion pertaining to the interplanetary modeling and about different possible solar wind conditions and (corresponding responses associated with this particular storm).

Fig. 1 shows the estimated solar wind conditions and a comparison between the magnetometer measurement in Colaba, India, and the modeled Dst. B_x, B_y, V_y, and V_z are set to zero in GSM coordinates and quiet solar wind conditions ($B_z = 2$ nT, solar wind density = 5/cm^3, and $V_x = -450$ km/s) are assumed before the arrival for the shock. We note that the modeled Dst basically reproduces the magnetometer measurement. This is a significant result showing >1600 nT depression of the H-component of magnetic field is possible. The magnetic data also showed an extremely fast recovery. In order to reproduce the fast recovery, we had to assume an additional extreme enhancement of the solar wind density after the negative B_z. Without this extreme solar wind density enhancement, keeping the solar wind density = 40/cm^3 after the arrival of the shock (dashed black curve in panel 3), the modeled Dst would have gone even a little more negative and recovered much slower, as shown by the dashed black curve. To match the fast recovery of the data using only the decay, one would need a decay constant of about 20 min to match the data. This cannot be done with any model we know about without tailoring the decay specifically for this storm.

Our modeled Dst is a sum of several terms: $dst = dst1 + dst2 + dst3 +$ (pressure term) + (direct IMF B_z term) + (offset terms). The 'offset term' may compensate for the secular variation of the Earth's internal magnetic field, its contribution is negligible over a short time period. The terms *dst1*, *dst2*, and *dst3* are all calculated in

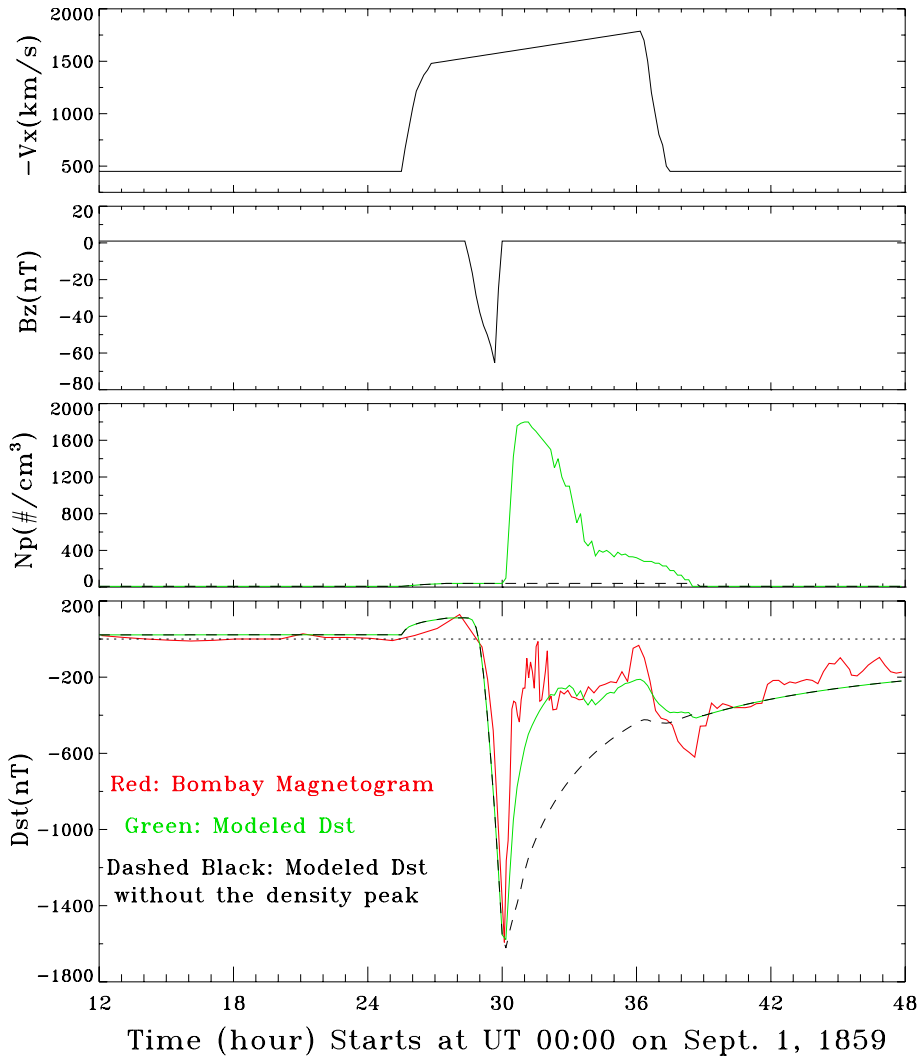

Fig. 1. Assumed solar wind parameters (every 10 min) and comparisons between modeled Dst (every 10 min) and the H-component of the magnetometer record (every 15 min during the main phase and every 5–10 min during the recovery phase) made in the Colaba Observatory in Mumbai in 1859.

a similar way: $dstx(t + \mathrm{d}t) = dstx(t) + (\text{driver term}) - (\text{decay term})$. The pressure term and the direct IMF B_z term are calculated directly from the solar wind (Temerin and Li, 2002). Our model uses a 10 min time step and produces 10 min model results. For comparison with the longer time interval data, we average our results accordingly.

Fig. 2 shows the contribution from the different terms for this event. It is evident that the *dst1* term dominates the decrease of Dst and the pressure term dominates the fast recovery of Dst seen in Fig. 1. For magnetic storms that occurred between 1995 and 2002, *dst1* and *dst2* made comparable contributions to Dst during the main phase of storms. The *dst1* term generally decays more slowly than the *dst2* term. The decay of both terms is nonlinear and consequently their decay times decrease with larger absolute amplitudes Temerin and Li (2002). For example, for this particular storm, the decay times for different magnitude of *dst1* are 3.22 h, 4.77 h, 1.86 days, and 17.5 days corresponding to *dst1* equal to −1500 nT, −1000, −100, and −10 nT, respectively. Similarly, for example, the decay times for *dst2* are 7.67 h and 2.32 days for *dst2* equal to −100 and −10 nT. The decay time for *dst3* is a constant of 2.82 h.

The *dst1* term may represent the contribution of the main ring current while the *dst2* and *dst3* terms probably represent the contribution of so-called 'partial' ring current and magnetotail currents. By adjusting the density and thus the pressure, the fit between the model and the magnetometer shown in Fig. 1 could have been made better but we made no attempt to try to exactly duplicate the magnetometer data.

In the results shown in Figs. 1 and 2, the IMF was assumed to be either purely southward or northward. Fig. 3 shows how the modeled amplitude of the Dst index would have changed had the magnetic field been

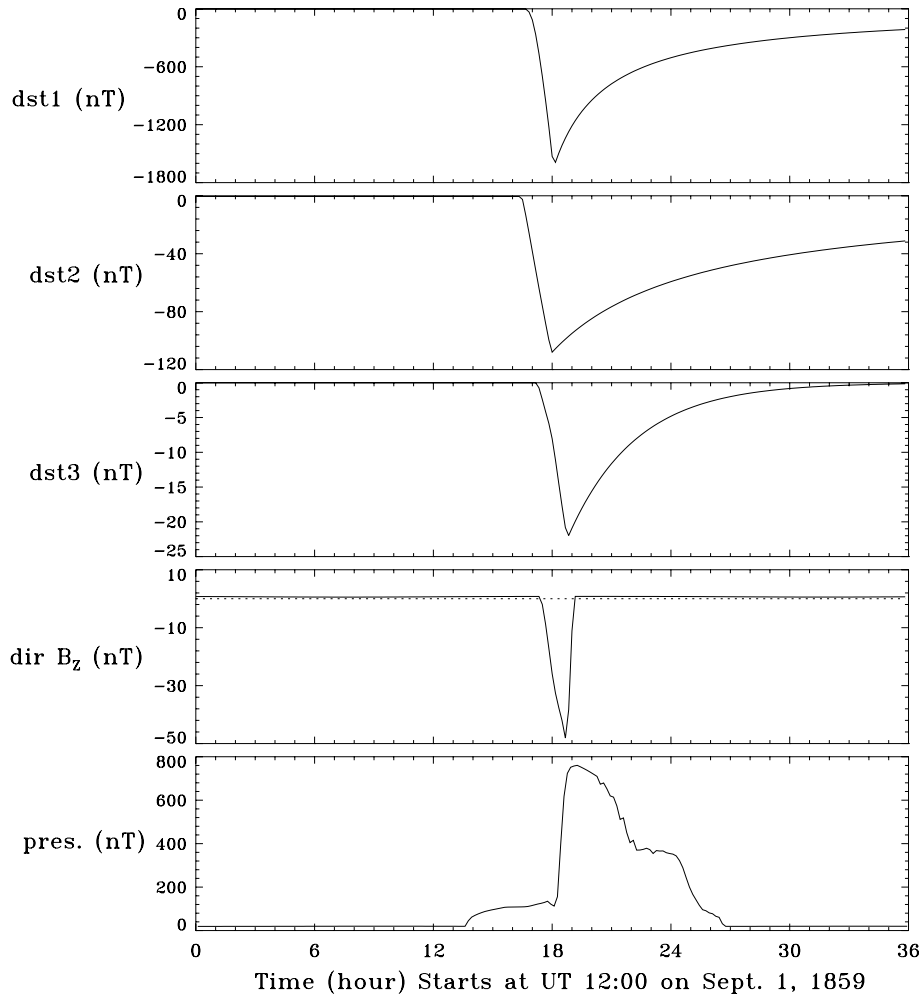

Fig. 2. The contribution from the different terms: *dst1*, *dst2*, *dst3*, direct IMF B_z term, and pressure term, which make up the final modeled Dst. The contribution from the 'offset term' is ignorable over such a short time period. See text for decay times for *dst1*, *dst2*, and *dst3*.

in a different direction and the minimum value of the modeled Dst as a function of the angle of the IMF away from the purely southward direction. To produce the results we rotated the southward IMF (but not the northward IMF) shown in Fig. 1 by the specified angle and calculated the minimum Dst value.

Furthermore, using the model, we can also show that if the same solar event had occurred on a different day of the year or at a different time on the same day, the results would have been different.

Fig. 4 shows how the minimum Dst would have varied in our model had the solar event occurred on a different day but at the same universal time (UT). It is clear that there is both an annual variation and semi-annual variation in the response of the magnetosphere to the solar wind.

Fig. 5 shows how Dst would have varied in our model had the solar event occurred at a different universal time but on the same day. The minimum Dst occurs near 12:00 UT when the Earth's dipole axis is most perpendicular to the solar wind velocity.

3. Discussion

Our results show that our model can easily achieve the extremely negative Dst values inferred from the Colaba Observatory magnetometer using solar wind speed scaled from the observed shock speed and an assumed IMF. Our Dst model accurately predicts (and specifically does not over predict) the largest magnetic storms of the 1995–2002 period. Perhaps more problematic, however, is the very fast recovery of the H-component registered at the Colaba Observatory magnetometer. It rises over 1200 nT in 20 min following its maximum negative excursion. The '*dst1*' term does not decay that fast even though it has a non-linear decay 'constant'. To explain the rise we need to introduce an extremely large solar wind density enhancement of almost 2000 particles/cm^3, moving at about 1500 km/s, to produce the dynamic pressure necessary to explain this rise. Such a large dynamic pressure is unknown in the record of Dst for the last 46 years. However, solar wind density enhancements of smaller magnitude are not unheard

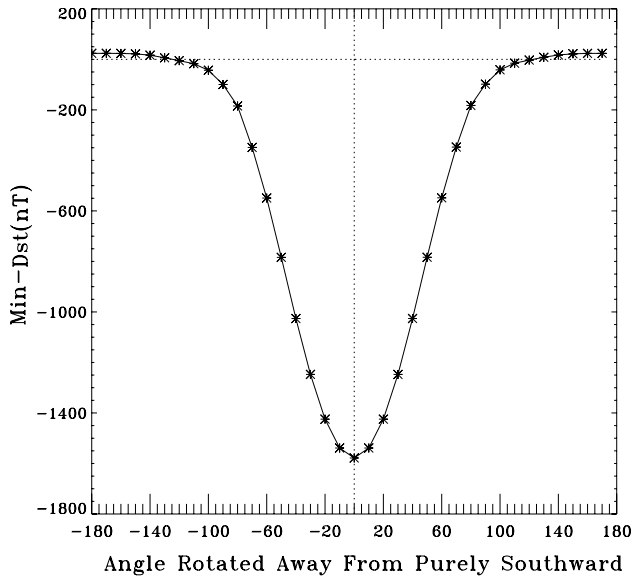

Fig. 3. The minimum values of the modeled Dst if the direction of IMF had been rotated away from purely southward 10° a time, other solar wind parameters kept the same.

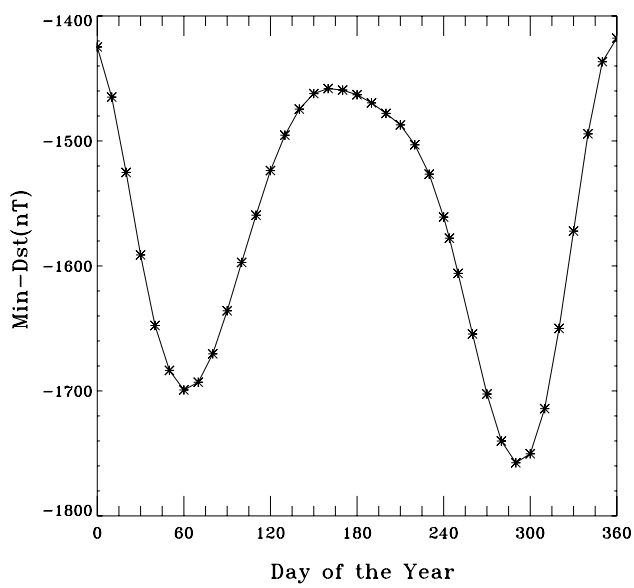

Fig. 4. The minimum values of the modeled Dst if the solar event had occurred on a different day but at the same universal time.

of during a coronal mass ejection (CME). A typical CME, as identified by coronagraph observations has three parts: bright outer loops, a dark region, and a filament nearest the Sun (Hundhausen, private comm. 1996). It has been argued by Tsurutani and Gonzalez (1997) and Farrugia et al. (1997) that the dark region is the (Klein and Burlaga (1982)) magnetic cloud. Recently, Burlaga et al. (1998) made the first observation of the high density filament at 1 AU associated with the January 10–11, 1997 event. This filament/plasma plug followed the magnetic cloud, as expected. Perhaps

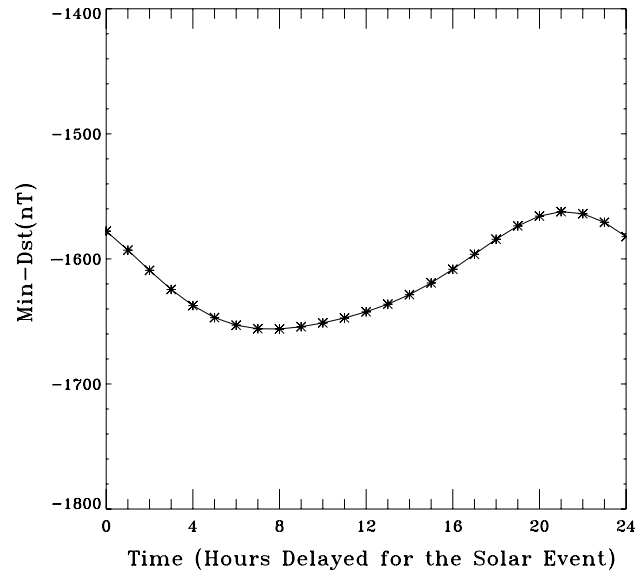

Fig. 5. The minimum values of the modeled Dst if the solar event had occurred at a different universal time but on the same day. The minimum Dst would have occurred 7–8 h delayed, which corresponds to around 12:00 UT (since the solar wind with negative B_z arrived at Earth around 4–5 UT on 2 September 1859, see Fig. 1).

a similar high density plasma plug could explain the values that we have used to model the 1859 CME/magnetic storm. In this recent event, a very dense of cold solar wind plasma, ~180 ions/cm^3 Larson et al. (2000), enveloped the Earth during the recovery phase of the storm and produced a positive excursion from the somewhat depressed storm with a Dst value of about −80 nT. The velocity of the flow was about 450 km/s. The required dynamic pressure and kinetic energy density in the flow of the 1859 event is thus assumed to be one hundred times larger than that of the January 1977 event, which had one of the largest solar wind dynamic pressures of the current solar cycle.

There has been a controversy simmering between those who believe that the Colaba Observatory measurement represented the Dst or the magnetospheric currents and those who suggest that significant portion of the measurements was due to ionospheric currents. Green and Boardsen (this issue) report, based on auroral records for this storm and the extrapolated Holzworth–Meng model (Holzworth and Meng, 1975), that red auroras came within 8° of the magnetometer observation in Mumbai. They suggest that currents in the auroral electrojet may contribute significantly to the magnetometer measurements in Mumbai. However, the fact that ionospheric currents associated with red auroras could have produced such a large magnitude of magnetic field excursion at such a low latitude is also unheard of. In addition, the timing of sighting the aurora north of Mumbai and the magnetometer measurements at Mumbai cannot be confirmed.

3.1. Difference between the Temerin–Li model and Burton model

The updated Temerin–Li Dst model can achieve the extremely large negative Dst values inferred from the Colaba Observatory, whereas the Burton model (1975) cannot, mainly because of the velocity dependence of the driver term in the *dst1* term of the updated model. The driver term in *dst1* determines the negative rate of change in *dst1* and is proportional to $B_z^{0.971} \times V_x^{2.09} \times n^{0.543} \times$ (a function of the magnetic clock angle) $\times$ (other terms) instead of $B_z \times V_x$ (i.e., E_y) in the Burton formulation, where n is the density of the solar wind. Because of the large velocity of this event, our driver term is much larger than the Burton driver. Because B_y was set to zero in the simulation shown in Fig. 1, the magnetic clock angle term was one for negative B_z and zero for positive B_z. The exponents in the driver terms were found by fitting eight years of solar wind and Dst data. (We continue to improve the model and these exponents are subject to small adjustments in the future.) It is worth noting that the driver term for the *dst1* term is approximately proportional to E_y (the Burton driver) times the square root of the dynamic pressure ($n \times V^2$). It is also necessary to note that the model was determined from data for the eight years, 1995–2002, and Dst never dropped below −400 nT during this time and thus any extrapolation of the model to the solar wind conditions inferred for the 1859 storm is highly speculative.

3.2. The equinoctial effect

The differences in the minimum Dst shown in Figs. 4 and 5 are mainly due to the dependence of the driver term (part of the 'other term' mentioned above) on the equinoctial angle, the angle between solar wind velocity and the dipole axis. The driver term is largest when this angle is 90° (Temerin and Li, 2002) and is, no doubt, due to the dependence of the efficiency of reconnection on this angle. This dependence produces a semi-annual and diurnal variation in the response of the magnetosphere to solar wind conditions (Cliver et al., 2000; Li et al., 2001; O'Brien and McPherron, 2002). This equinoctial effect is different from the Russell–McPherron effect (Russell and McPherron, 1973), which is due to the typically larger z-component of the IMF near the equinoxes in GSM coordinates. The Russell–McPherron effect is not involved in Figs. 4 and 5 because we have assumed a fixed IMF orientation in GSM coordinate. Cliver et al. (2000) argued that the equinoctial effect is the dominant cause of the semi-annual variation in geomagnetic activity.

In addition, we find that Dst has a small annual variation. This is included, in part, as an annual variation of the *dst1* term (rather than as annual variation of the driver of the *dst1* term). We do not have a physical explanation for the annual variation and it may be due to the fact that three northern hemisphere magnetometers are included in the calculation of Dst while only one from the southern hemisphere is used.

3.3. The rarity of the 1–2 September 1859 storm

The 1859 equatorial magnetometer reading, if it is representative of magnetospheric conditions, is not just unusual because of its large magnitude but also because of its rapid decay and recovery. In fact, because the normal Dst index is an hourly average and because of this rapid change, the Dst index for this event would be only about −700 nT if the Colaba Observatory were representative of all the Dst observatories (hourly averaged). Siscoe and Cooker (this issue) used the Burton et al. equation as modified by O'Brien and McPherron (2000) to calculate Dst and obtained values close to the hourly-averaged Mumbai magnetogram.

Tsurutani et al. (2003) have argued that perhaps the 1859 storm, though the biggest in the historical record, may not be so unusual. They pointed out that the velocity of the interplanetary shock after the large flare on August 1972 was even larger and that no such large magnetic storm occurred maybe only because the direction of the IMF was northward. This would be consistent with our model results: if the magnetic cloud B_z had been southward for the August 1972 event, the storm Dst intensity would have been even more negative (<-1600 nT).

However, to explain the magnetometer data in the updated Temerin–Li model, we also need a very large pressure enhancement. Such a pressure enhancement, had it occurred in the absence of a pre-existing main phase depression, would have produced a positive Dst of about 800 nT. No such enhancement was seen in August 1972 or at any other time. This argues that the 1859 event was indeed extremely unusual.

4. Summary and conclusions

Using an updated model from Temerin and Li (2002) for predicting Dst on the basis of solar wind conditions we were able to reproduce the 1859 Carrington event magnetometer record. The negative depression in the magnetometer record could be explained by assumptions as to the condition of the solar wind that do not seem too unusual given the known average speed of the interplanetary shock for this event. The extremely fast recovery of the magnetometer record, however, required that the dynamic pressure of the solar wind be substantially larger than

has ever been observed. Without this fast enhanced dynamic pressure of the solar wind, the negative depression of the magnetic field near the equator would have been much more severe and lasted longer. We also show how the strength of the magnetic storm would have depended on the season and time of day. For given solar wind conditions, the largest magnetic storms occur around the fall equinox during the year and 12:00 UT, during the day when the dipole axis is most perpendicular to the solar wind velocity. Based on our model prediction of Dst, a very fast solar wind with a very large negative IMF B_z can produce a super magnetic storm with minimum Dst less than −1600 nT and thus such a storm is likely to occur again. For the event of 1–2 September 1859, however, the extremely fast recovery of the Dst requires an extremely large pressure enhancement following the shock. Though a plug of cold high-density solar wind during a CME has been observed, the sheer magnitude of the required density enhancement (as shown in Fig. 1) for the 1–2 September 1859 event suggests that this particular event was extremely unusual.

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