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# How good is the relationship of solar and interplanetary plasma parameters with geomagnetic storms?

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[1] Since the work of Snyder et al. (1963), who showed a possible link between interplanetary solar wind speed *V* and geomagnetic index *Kp*, such a relationship has been examined by many workers and found to be rather loose. In the present communication this relationship is rechecked for all data during 1973–2003. It was noted that moderate or strong geomagnetic storms occurred only when solar wind speed *V* was above ~350 km/s. However, above this limit, the plots of *Dst* versus *V* showed a large scatter, and any value of *V* could be associated with any value of *Dst* in a wide range of a factor of ~2, or any *Dst* value could be associated with any value of *V* in a wide range of a factor of ~2, indicating a poor relationship between *V* and *Dst*. The scatter could be partly because not *V* but $VB_s$ (product of *V* and the southward component $B_s$ of interplanetary field *B*) is the appropriate variable relevant for *Dst* changes. This was checked. In the plot of *Dst* versus $VB_s$ it was noticed that the scatter was smaller and correlation better than that in the plot of *Dst* versus *V*. Since the relationship between *V* and *Dst* is poor, an estimate of *V* with some antecedence, as is done in a present-day prediction scheme ((Gonzalez et al., 2004) *V* estimated from the lateral extension speed of side halo coronal mass ejections (CMEs) and assuming $V^2$ proportional to *Dst* magnitudes) is not likely to give reliable estimates of *Dst* magnitudes. However, estimate of *V* could certainly be useful to estimate the time when the storm would hit the Earth but remembering that 15% of the halo CMEs may miss the Earth.

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## 1. Introduction

[2] Space weather and its terrestrial effects is a burning topic now. It all started when *Carrington* [1859] and *Hodgson* [1859] observed a brilliant spot on the solar disc (a solar flare) on 1 September 1859, which was followed by a geomagnetic storm ~18 hours later. They hesitated to claim that the two phenomena were related, but later, *Hale* [1931] claimed that such phenomena were really interrelated and *Chapman and Bartels* [1940] suggested that on some occasions like the eruptions of solar flares, the Sun probably emits corpuscular radiation (particles), which take a few hours (or days) to reach the Earth. *Biermann* [1951] noted that the comet tails were always pointing away from the Sun, probably indicating that the Sun was emitting material outward continuously. *Parker* [1959] showed theoretically that the Sun must be emitting material all the time, called by Parker as "solar wind." The early satellites sent by the United States and USSR detected in interplanetary space a thin plasma moving away from the Sun, with speeds of ~300–700 km/s (quiet and enhanced solar wind [*Gringauz et al.*, 1960; *Neugebauer and Snyder*, 1962]). The concept of space weather (counterpart to meteorology on the Earth [*Gold*, 1959]) was born.

[3] The solar wind compressed the terrestrial magnetic field and confined it into a "magnetosphere," which had a magnetopause ~10 Earth radii ($R_E$) away on the sunward side and a long tail away from the Sun. The solar wind could not normally penetrate the magnetosphere, but on certain occasions, particularly after solar flares, interplanetary structures with high number density and increased wind speed caused geomagnetic storms, but only when the magnetic field in the structure had a component $B_s$ antiparallel to geomagnetic field ("*s*" means southward). *Dungey* [1961] gave a theoretical explanation based on magnetic reconnection as follows. If the interplanetary magnetic fields are directed opposite to the Earth's field, there is magnetic erosion on the dayside magnetosphere by magnetic reconnection, and magnetic field accumulates in the nightside magnetotail region. The magnetic reconnection in the tail leads to plasma injection toward the Earth in the nightside. Low-energy particles precipitate in the high latitudes and cause aurora, while high-energy protons drift to the west, and electrons drift to the east, forming a "ring current" around the Earth, which causes a reduction in geomagnetic field (storm time disturbance field *Dst*). This is, of course, a simplified picture. Auroras are observed every day and get intensified during storms. Also, the


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observed $Dst$ can have contributions not only from the ring current located at 2–7 $R_E$ but also from magnetopause currents, induced currents in the solid Earth, and other sources not yet fully quantified (ionospheric, field-aligned, tail, etc. [*Gonzalez et al.*, 1994]).

[4] *Snyder et al.* [1963] showed that the geomagnetic activity index $Kp$ responds to solar wind speed $V$ rather than to $dV/dt$ but stated that the relationship of $V$ with $Kp$ was not precise and reliable and was only suggestive. Since then, many workers have noticed that the relationship of $V$ with $Kp$ or $Dst$ is loose. *Ballatore* [2002] points out that there is a "saturation effect" of fast solar wind on geomagnetic storms ($Dst$ not keeping up with larger solar wind speeds). Also, many combinations of interplanetary $V$ and the magnetic field component $B_s$ directed southward have been used as coupling functions for solar wind–magnetosphere interaction, but most of these are particular cases of general expressions of the electric field and the energy transfer at the magnetopause due to large-scale reconnection [*Gonzalez*, 1990]. In simple terms, the parameter related to geomagnetic $Dst$ would be the product $VB_s$.

[5] Large $Dst$ currents are known to cause severe perturbations in terrestrial environment. It is important to know the severity with which a storm may occur, so that possible preventive or remedial measures could be taken. Satellite observations of $V$ and $B_s$ as at present from the ACE satellite near L1 are of limited utility for predictions, as these are available only with an antecedence of <1 hour. To predict with more antecedence, relationship must be established with directly observed solar features, as these are seen tens of hours earlier. Since many storms are related to coronal mass ejections (CMEs), relationship of $Dst$ with some key observational parameter of CME could lead to a prediction scheme. Such a scheme (details given by *Gonzalez et al.* [2004]) has been formulated as follows:

[6] 1. $Dst$ is assumed to be proportional to the product $VB_s$. Thus $Dst \propto VB_s$. This is a key assumption ($V$ is the maximum solar wind speed observed by near-Earth satellites).

[7] 2. From the examination of several dozen magnetic clouds, *Gonzalez et al.* [1998] and *Dal Lago et al.* [2001] found that the peak values of the solar wind speed $V$ are related to the total magnetic field intensity $B$ of the magnetic clouds at 1 AU (near Earth). Thus $V \propto B$.

[8] 3. When $B_s$ is high, the total field $B$ is also high, by ~30%. Thus $B_s \propto B$ (note that the reverse may not be true; on many occasions when $B_s$ is almost zero or even positive, $B$ could be high because of high values of the $B_x$ and $B_y$ components).

[9] 4. Combining all these relationships, $Dst \propto V^2$.

[10] 5. Halo CMEs have a lateral expansion speed $V_e$, which can be measured. *Schwenn et al.* [2001] and *Dal Lago et al.* [2002] found for some selected CME events that $V \propto V_e$. Thus $Dst \propto (V_e)^2 \propto (V)^2$. Hence a value of $Ve$, obtained several hours before a geomagnetic storm, could give an estimate of the $Dst$ magnitude to be expected by this prediction scheme.

[11] It may be noted that all the necessary relationships are obtained from regression analyses of a small group of selected events (for example, 54 magnetic clouds during 1965–1997 by *Dal Lago et al.* [2001]), and the regression coefficients have standard errors. When results of one are plugged into the other, the errors increase. Hence the estimates of $V$ values will have large uncertainties. Also, the proportionality of $V$ and $V_e$ mentioned in (5) above is valid only for halo CMEs associated with magnetic clouds with a rotation across the ecliptic plane, a specialized set of events. The relationship may not hold for all types of events in general.

[12] The solar wind speed $V$ is used by different workers in different ways, for averages over different timescales. *Snyder et al.* [1963] used daily averages and 6-hour averages of $V$ measured by near-Earth satellites. Others like *Gonzalez et al.* [1998] and *Dal Lago et al.* [2001] use peak values during an event. Most of the recent works seem to be using hourly values to locate the peak values. If the solar event, e.g., a solar flare and/or a CME responsible for a geomagnetic event (e.g., a SSC), can be identified correctly, the time difference (transit time) yields an estimate of the "average" speed of travel [*Cliver et al.*, 1990]. For CMEs the numerical study of *González-Esparza et al.* [2003] indicates that from near the Sun to 1 AU, fast CMEs (speed exceeding 1000 km/s) have three phases: (1) an abrupt and strong deceleration just after their injection against the ambient wind which ceases before 0.1 AU, (2) a constant speed propagation from 0.1 AU up to ~0.45 AU, and (3) a gradual and small deceleration up to 1 AU and beyond. Since we are interested in the $Dst$ effects of solar wind, the relevant velocity $V$ used is that of solar wind obtained by near-Earth satellites. However, in some comparisons, it was noticed that the average velocity (obtained from the transit time) and the velocity observed by the satellite near Earth are roughly the same within ~10% of each other. In the present communication the $Dst$-$V$ and $Dst$-$VB_s$ relationships are reexamined for several events during 1973–2003, particularly to check whether prediction schemes based on $Dst$-$V$ relationship alone would yield fairly good, approximate, or unsatisfactory predictions.

## 2. Data and Plots

[13] *Cane et al.* [1996] examined data for 30 years (1964–1994) to identify cosmic ray decreases ≥4%, and for these events (termed by us as Cane events), they identified the nature of the associated interplanetary structures as class 1, shock plus ejecta; class 2, shock (ejecta missed the Earth); class 3, shock plus ejecta, less energetic than class 1; and class 4, complex events including a corotating high-speed stream. For some of these events we could obtain the maximum $Dst$ depressions and the maximum solar wind speeds $V$. Figure 1 shows a plot of $V$ versus $Dst$ values (hourly peak values of $V$, generally near $Dst$ hourly maximum depressions) for the Cane events of class 1 (small solid circles), class 2 (crosses), class 3 (triangles), class 4 (open circles), and many other events chosen by us during the further interval 1994–2003 (hatched circles). The $Dst$ range is large, right from ~20 to ~600 nT. The scatter is very large at all $Dst$ values for all classes of events, indicating that the $Dst$-$V$ relationship is rather poor. Correlations were calculated for different $Dst$ ranges (0–150, 50–200 nT, etc.) and are noted in Figure 1. There were two giant events in recent times (Halloween events A: 29 October 2003, $Dst$ −401 nT, and B: 20 November 2003, $Dst$ −472 nT, marked in Figure 1 as solid

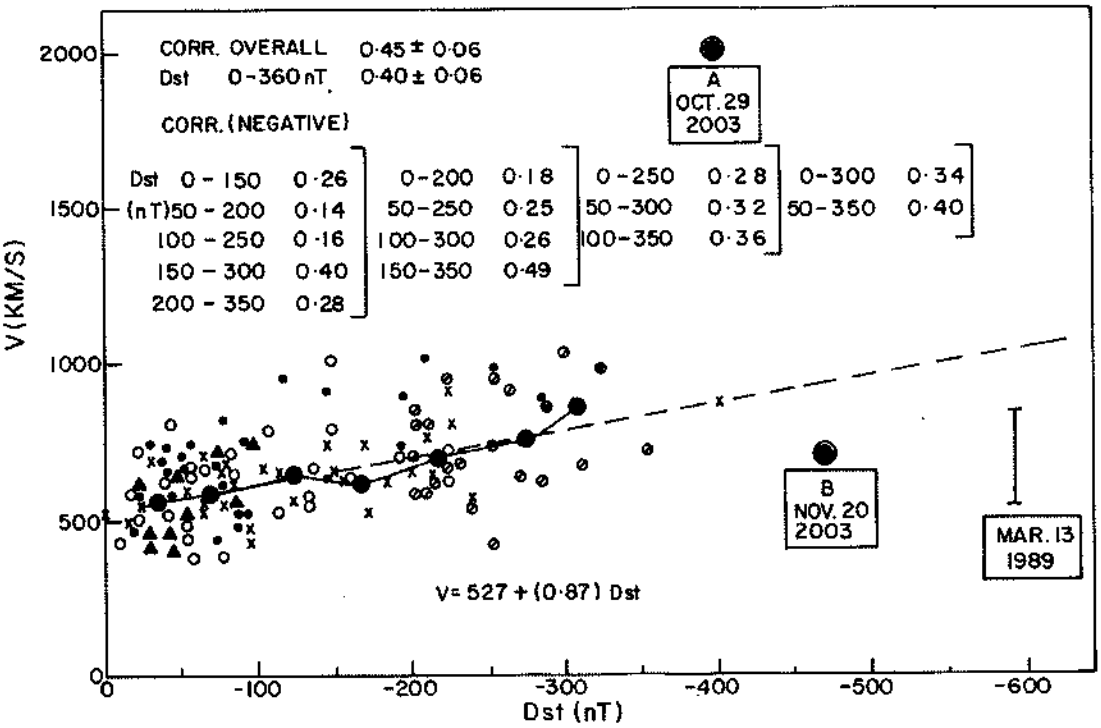


**Figure 1.** Plot of the maximum geomagnetic *Dst* depressions versus solar wind speed *V* (hourly peak values of *V*, generally near *Dst* hourly maximum depressions) for 162 pairs of interplanetary structures (Cane events during 1973–1994: small solid circles, shock plus ejecta; crosses, shock (ejecta missed the Earth); triangles, less energetic shock plus ejecta; open circles, complex events including a corotating high-speed stream; and hatched circles, other events of strong *Dst* during 1994–2003). Medium solid circles are averages over equal *Dst* intervals, and the big solid circles are the Halloween events of 29 October 2003 and 20 November 2003.

big circles) and the earlier largest event of 13 March 1989 (*Dst* −589 nT). The points for all of these three events seem to be well away from (down or above) the linear trend, indicated by the dashed line, representing the regression equation: $V = 527 + (0.87) * Dst$. The full circles are averages over equal *Dst* intervals and show roughly an increasing trend, but the correlation for all events was only 0.45 ± 0.06. If the three giant events are omitted, the correlation is 0.40. Correlations for selected ranges were all below 0.50, the largest being 0.49 for *Dst* −150−350 nT. Thus the relationship *Dst*-*V* is poor throughout (correlation 0.5 implies only 25% variance common and 75% independent or random).

[14] Confining attention to moderate and large *Dst* only (<−140 nT), Figure 2a shows a plot of $VB_s$ versus *Dst* (59 pairs of hourly peak values during 1973–2003). The scatter is still large, but the correlation has improved to 0.67. Thus not just *V* but the product $VB_s$ is a better representative of *Dst*, as expected. Figure 2b shows a plot of $VB_st$ versus *Dst* (only 16 pairs, as $B_s$ oscillates considerably, and determining "*t*" is subjective and often impossible) and shows a still better correlation, namely 0.71. Thus the duration (*t*) for which $B_s$ is negative is also important.

[15] Another data set is for 23 events from historical records during 1938–1989, given by *Cliver et al.* [1990]. They selected only those storms that were preceded by a major flare and calculated for each identified flare-storm pair the average speed ("transit speed") of the associated interplanetary shock from the interval between the flare onset and the sudden commencement of the geomagnetic storm. From these they inferred the maximum solar wind flow speed *V* from an empirical relationship between the shock transit speed and the peak flow velocity of the associated transient stream. From their 23 events (henceforth called Cliver events), 16 occurred during 1957–1989, and *Dst* values are available for all these. Since the authors have given the *Ap* star values also for all events, we plotted the *Dst* values versus *Ap* star values for 1957–1989 and found a linear relationship (except for some points which were way out and were omitted from consideration), which could be used for allotting *Dst* values for the seven events before 1957. Figure 3 shows a plot of the inferred *V* values versus *Dst* for the 23 Cliver events. (For the event of 13 March 1989 the Cliver values for *V* are 550 km/s. In the National Oceanic and Atmospheric Administration (NOAA) website, values of *V* are mostly missing, but *V* seems to be near 800 km/s at least for some hours soon after the storm. Hence this point is shown in a *V* range 550–800 km/s. The same is done in Figure 1 also). The overall correlation is very poor (−0.19). The regression line shown is similar to that given in Figure 1 for *V* versus *Dst*. The solid circles are for data where *Dst* values were available (1957–1989), and the open circles are for earlier data (1938–1956) for which *Dst* values were estimated. As can be seen, the scatter is very large, for both solid circles and open circles. Some points lie near the regression line, but for many others, large

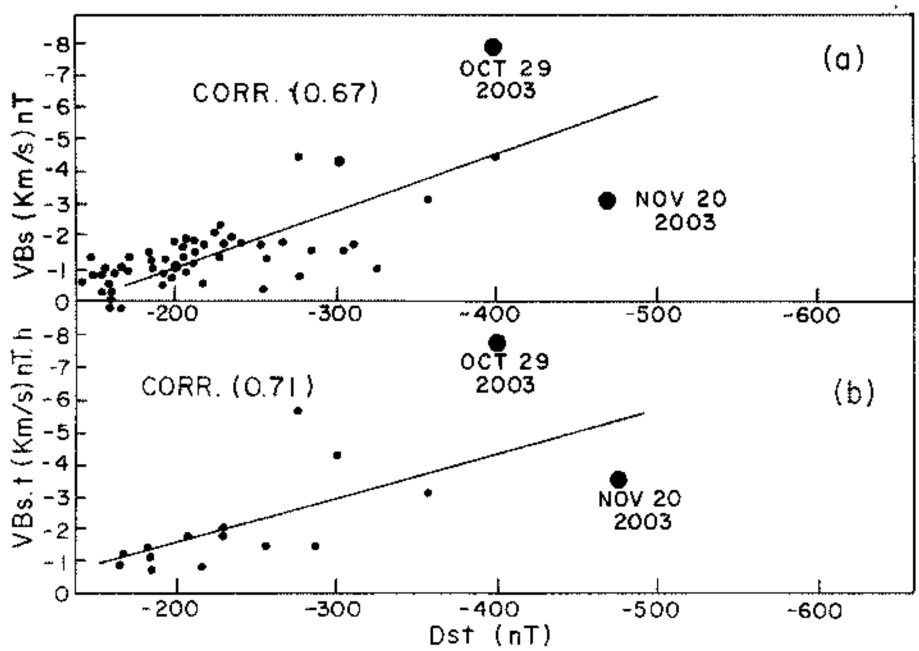


**Figure 2.** Plot of *Dst* versus (a) $VB_s$ and (b) $VB_st$ (hourly peak values), where $B_s$ is the southward component of interplanetary magnetic field and "$t$" is its duration.

*V* values are associated with a large range of *Dst* values. Two possibilities are indicated, namely, there is no meaningful relationship between *V* and *Dst*, and/or the inferred values of *V* given by *Cliver et al.* [1990] are erroneous (wrong identification of the solar flares involved). There is also the possibility that the model used by *Cliver et al.* [1990] to estimate the peak speed *V* has inaccuracies. They do not show enough cases with both predicted and measured speeds to estimate the errors in their procedure.

[16] Recently, *Tsurutani et al.* [2003] presented a detailed study of the magnetic storm of 1–2 September 1859, which was the most intense in recorded history. They estimated several parameters of this storm (*Dst*, interplanetary electric field, ejecta velocities, etc.). They also gave a list of large magnetic storms in the past, based on the earlier presentations of *Ellis* [1900], *Moos* [1910], and finally, *Chapman and Bartels* [1940]. Here in Table 1 we list the remarkable events of the past. The first 11 events are controversial and

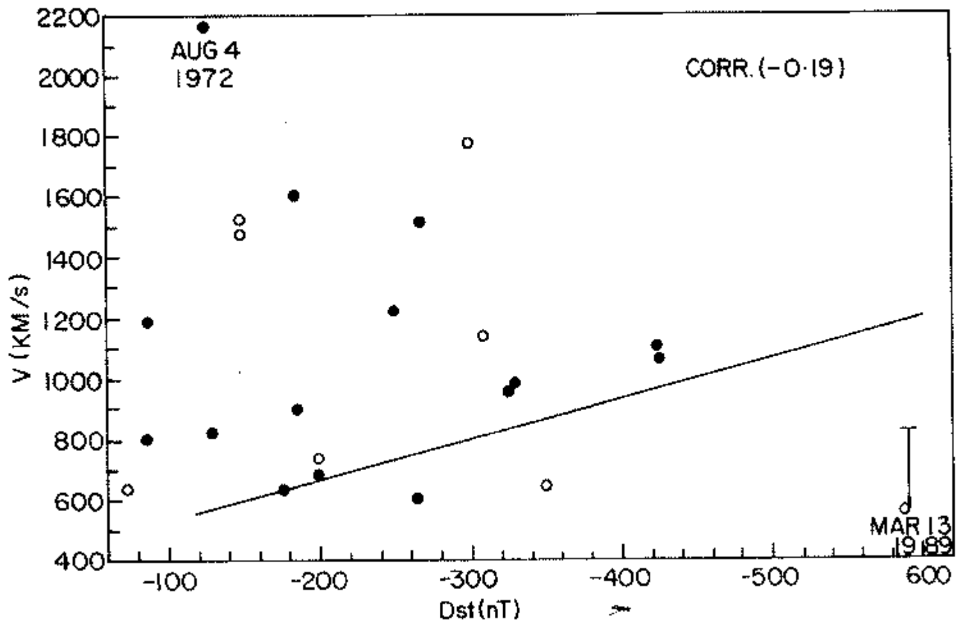


**Figure 3.** Plot of *Dst* versus *V* for the 23 Cliver events [*Cliver et al.*, 1990].

**Table 1.** Details of Remarkable and Many Other Geomagnetic Storm Events

| Storm | Date[a] | $H$ Range, nT | $Dst$, −nT | $V$, km/s | $B_s$, −nT | $VB_s$, (km/s)nT | $t$, hours | $VB_st$ |
|---|---|---|---|---|---|---|---|---|
| 1[b] | 16.04.1938 | 530–1,900 | | 1,480 | | | | |
| 2 | 01.09.1859 | 1,760 | 1,760 | 2,000 | 80 | 160,000 | | |
| 3 | 25.09.1909 | 1,500 | 1,500 | 1,500 | | | | |
| 4 | 17.11.1882 | 450–1,090 | 450 | 1,500 | | | | |
| 5 | 13.05.1921 | 700 1,060 | 700 | 1,500 | | | | |
| 6 | 04.02.1872 | 1,020 | 1,020 | 1,500 | | | | |
| 7 | 12.10.1859 | 980 | 980 | 1,500 | | | | |
| 8 | 31.10.1903 | 820 950 | 820 | 1,500 | | | | |
| 9 | 07.07.1928 | 780 | 780 | 1,500 | | | | |
| 10 | 11.02.1958 | 660 | 426 | | | | | |
| 11[b] | 13.03.1989 | 640 | 589 | 550 | | | | |
| 12 | 13.09.1957 | 580 | 427 | | | | | |
| 13 | 20.11.2003 | | 472 | 700 | 46 | 32,200 | 11 | 354,200 |
| 14[b] | 15.07.1959 | | 429 | 1,090 | | | | |
| 15 | 13.09.1957 | | 427 | | | | | |
| 16[b] | 11.02.1958 | | 426 | 1,100 | | | | |
| 17 | 29.10.2003 | | 401 | 2,000 | 40 | 80,000 | 10 | 800,000 |
| 18 | 26.05.1967 | | 387 | | | | | |
| 19 | 31.03.2001 | | 358 | 712 | 44 | 31,328 | 10 | 313,280 |
| 20 | 09.11.1991 | | 354 | | | | | |
| 21[b] | 29.03.1940 | | 350 | 650 | | | | |
| 22 | 13.11.1960 | | 339 | | | | | |
| 23[b] | 08.07.1958 | | 330 | 980 | | | | |
| 24 | 01.04.1960 | | 327 | | | | | |
| 25 | 14.07.1982 | | 325 | 1,360 | 50 | 68,000 | | |
| 26 | 30.04.1960 | | 325 | | | | | |
| 27 | 05.09.1957 | | 324 | | | | | |
| 28 | 13.04.1981 | | 311 | 669 | 26 | 17,394 | | |
| 29[b] | 26.07.1946 | | 310 | 1,130 | | | | |
| 30 | 09.02.1986 | | 307 | 852 | 19 | 16,188 | | |
| 31 | 23.09.1957 | | 303 | | | | | |
| 32 | 04.09.1958 | | 302 | | | | | |
| 33 | 15.07.2000 | | 301 | 1,040 | 43 | 44,720 | 10 | 447,200 |
| 34[b] | 07.02.1946 | | 300 | 1,770 | | | | |
| 35 | 06.04.2000 | | 288 | 620 | 25 | 15,500 | 10 | 155,000 |
| 36 | 06.11.2001 | | 277 | 663 | 68 | 45,084 | 13 | 586,092 |
| 37[b] | 20.10.1989 | | 268 | 1,510 | 20 | 30,200 | | |
| 38[b] | 17.11.1989 | | 266 | 600 | | | | |
| 39 | 11.04.2001 | | 256 | 740 | 18 | 13,320 | 11 | 146,520 |
| 40[b] | 21.01.1957 | | 250 | 1,210 | | | | |
| 41 | 12.08.2000 | | 235 | 666 | 30 | 19,980 | 10 | 199,800 |
| 42 | 22.10.1999 | | 231 | 690 | 28 | 19,320 | 10 | 193,200 |
| 43 | 25.09.1998 | | 207 | 830 | 17 | 14,110 | 6 | 84,660 |
| 44 | 04.05.1998 | | 205 | 835 | 22 | 18,370 | 10 | 183,700 |
| 45[b] | 24.01.1949 | | 200 | 740 | | | | |
| 46[b] | 31.10.1972 | | 199 | 620 | | | | |
| 47[b] | 17.07.1959 | | 183 | 1,610 | | | | |
| 48[b] | 04.02.1983 | | 183 | 900 | | | | |
| 49 | 01.10.2002 | | 183 | 414 | 14 | 5,796 | 12 | 69,552 |
| 50 | 03.10.2001 | | 182 | 579 | 22 | 12,738 | 10 | 127,380 |
| 51 | 04.10.2000 | | 182 | 537 | 24 | 12,888 | 10 | 128,880 |
| 52[b] | 04.09.1957 | | 179 | 630 | | | | |
| 53 | 07.09.2002 | | 170 | 555 | 22 | 12,210 | 10 | 122,100 |
| 54 | 22.10.2001 | | 166 | 668 | 17 | 11,356 | 12 | 136,272 |
| 55 | 22.09.1999 | | 164 | 604 | 19 | 11,476 | 8 | 91,808 |
| 56[b] | 16.04.1938 | | 150 | 1,480 | | | | |
| 57[b] | 01.03.1942 | | 150 | 1,540 | | | | |
| 58[b] | 08.05.1960 | | 129 | 810 | | | | |
| 59[b] | 04.08.1972 | | 125 | 2,170 | 80 | 173,600 | | |
| 60[b] | 11.05.1959 | | 88 | 1,180 | | | | |
| 61[b] | 10.06.1968 | | 88 | 820 | | | | |
| 62[b] | 25.02.1956 | | 75 | 640 | | | | |

[a]Date is in day, month, year format. Read 16.04.1938 as 16 April 1938.
[b]These events are Cliver events.

are listed at random. The rest are listed in the order of their descending $Dst$ values (or estimates) with values of other parameters like $V$, $B_s$, and $VB_s$. Events 1–34 are with $Dst < -299$ nT, and eight of these are Cliver events (see footnote b). Events 35–62 are the rest of the 15 Cliver events, plus some other large $Dst$ events mostly in cycle 23. All the $V$ values are approximate with a possible uncertainty of ~10% ($V$ values are peak values and may differ from the $V$ values at $Dst$ maximum depression by roughly 10% or less). The values are plotted as $V$ versus $Dst$ (hourly values) in Figure 4. The following may be noted from Figure 4 and Table 1:

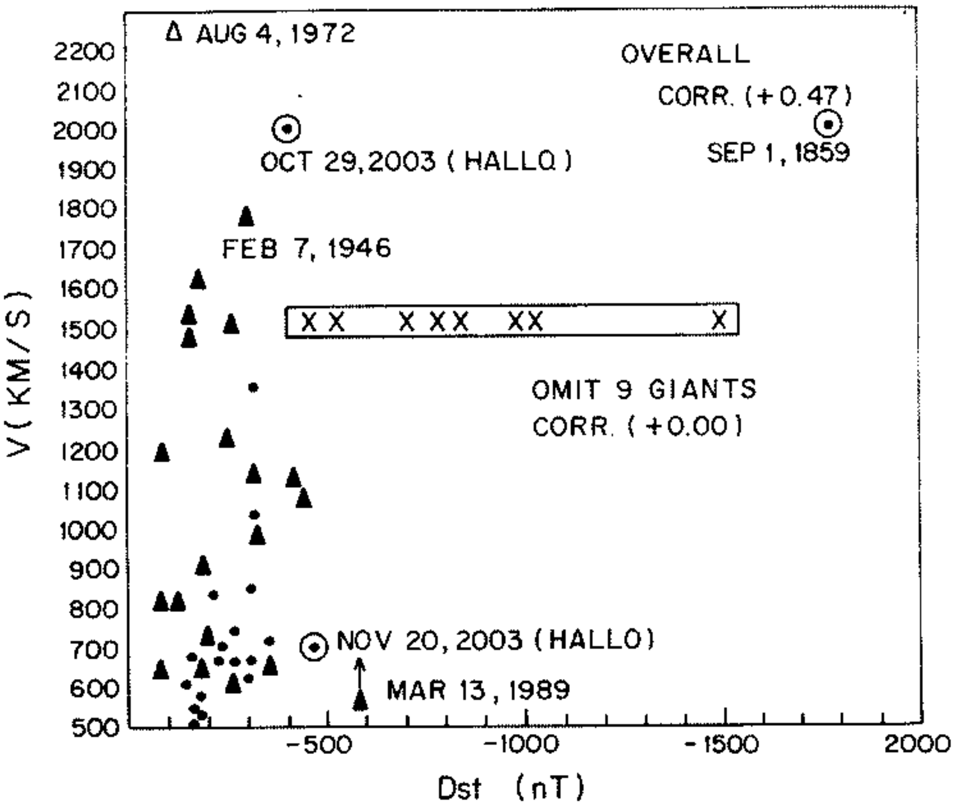


**Figure 4.** Plot of *Dst* versus *V* for all major *Dst* events. Crosses represent historical major events for which *V* is allotted arbitrarily as ∼1500 km/s. Triangles represent 23 Cliver events.

[17] 1. For some historical storms, there were no *Dst* values as such, and only ranges of the *H* (horizontal) component of the geomagnetic field (defined as the difference between the maximum and minimum value of *H* during the storm event) are available [*Tsurutani et al.*, 2003]. These were recorded at one or two low- and middle-latitude locations, and hence for pairs, two values are indicated in Table 1. *H* values at a single station will have a contribution not only from *Dst* but also from *DS* (storm-time LT effect) and ionospheric effects. When values at two locations are available for the same event, the lower value is likely to be nearer to the correct *Dst* value, and the lower value is used for the plot of that event in Figure 4. The solar flares associated with these events are not known, and hence the transit speeds or *V* values are not known, though these were most probably very high. For the 1 September 1859 event the values given by *Tsurutani et al.* [2003] are used. For the other events the *V* values are set (arbitrarily) at 1500 km/s. In Figure 4 the crosses enclosed in a rectangle represent eight such remarkable events. The Cliver events (same as in Figure 3) are all here and are marked with solid triangles.

[18] 2. Correlation calculated for all the 51 pairs of *V* and *Dst* (9 remarkable events, 23 Cliver events, and 19 other events) was moderate (+0.47 ± 0.11). However, if the nine remarkable events (crosses and the 1 September 1859 event) are omitted, the correlation is zero, indicating very poor relationship between *V* and *Dst* for not very intense storms. This is obvious from Figure 4 where a very large *V* range is associated with a small *Dst* range: 300–400 nT. The correlation is low partly because the 4 August 1972 event (top left corner) had a very high *V* value (exceeding 2100 km/s) and a very low *Dst* (−125 nT), while the 13 March 1989 event had a low *V* (550–800 km/s) and a high *Dst* (−589 nT). Note that the two Halloween events 29 October 2003 and 20 November 2003 marked with circles are far away from each other, though their *Dst* values are similar.

[19] 3. For 23 pairs of $VB_s$ versus *Dst*, Figure 5a shows the plot. The overall correlation was +0.58 ± 0.13, but this was mainly because of the large value of $VB_s$ for the single event of 1 September 1859 (top right corner). If this event is omitted, the correlation becomes 0.03, but this low value is also partly because of the 4 August 1972 event (top left corner) of high *V* and low *Dst*. If this event is omitted, the correlation increases to 0.66 ± 0.11. Thus the correlation of *Dst* with $VB_s$ is reasonably high but in restricted low ranges of *Dst* and *V*. Figure 5b shows a plot for $VB_st$ versus *Dst* (17 events). The correlation (+0.71 ± 0.12) is better than that in Figure 5a, indicating that the duration "*t*" of $B_s$ is also important. However, this analysis of ours is rather crude, with only peak hourly values used even if there was a dephasing between the peaks. Some of the scatter in Figures 5a and 5b may be due to our choosing $VB_s$ as a simple product of hourly peak values. *Wang et al.* [2003] have made a more rigorous analysis using the average values of the product $VB_s$ for simultaneous values of *V* and $B_s$ over short time intervals (few minutes) for magnetic cloud events, and they get a very good correlation, which

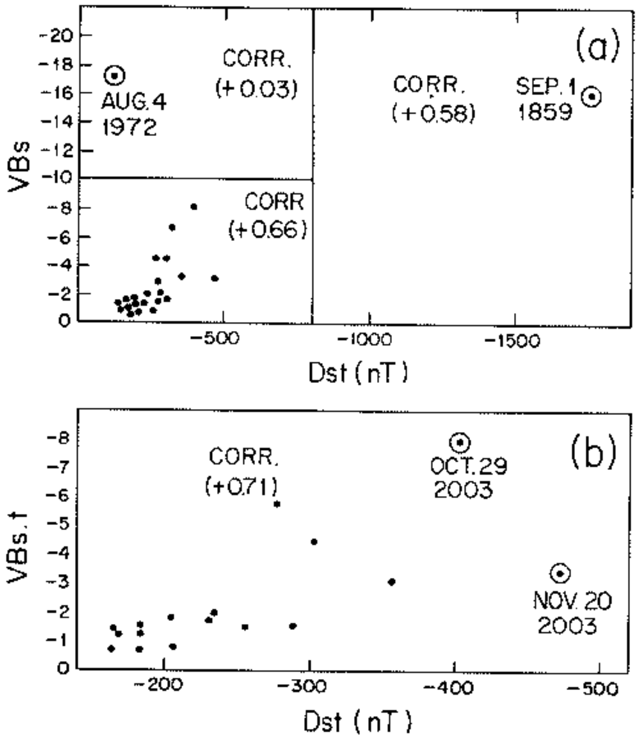


**Figure 5.** *Dst* versus (a) $VB_s$ and (b) $VB_st$, for major *Dst* events.

improves still more when the duration ($t$) of large $VB_s$ is also taken into consideration.

## 3. Frequency of Occurrence of Intense Storms

[20] During 1957–2003 (47 years after International Geophysical Year (IGY)) the frequency distribution of maximum *Dst* depressions in the severe storms (*Dst* < −150 nT, in bins of 10 nT) was as shown in Figure 6. For example, there was just one storm of *Dst* in the range −581 to −590 nT (the storm of 13 March 1989), only two storms of *Dst* in the range −351 to −360 nT, etc. NOAA has given a "Space Weather Scale" for geomagnetic storms as follows: G1 (minor, *Kp* ~ 5), G2 (moderate, *Kp* ~ 6), G3 (strong, *Kp* ~ 7), G4 (severe, *Kp* ~ 8), and G5 (extreme, *Kp* ~ 9). The scale was developed for communication with the public and is oversimplified, for example, using only *Kp*. Details are available at the Web site http://www.sec.noaa.gov/NOAAscales/EosNewScales.html. Even moderate storms (G2) start affecting terrestrial power grids, and more intense storms (notably G5) can have disastrous effects. In inset in Figure 6 (top right), *Dst* values are plotted versus *Kp* values for various storms in 1957. As can be seen, there is a lot of scatter, and a *Kp* value of ~6 corresponds to a wide range of *Dst* (−50 to −125 nT). So all the storms considered in the present paper (*Dst* < −160 nT) probably had at least small damaging effects but probably did not make news. Storms with *Dst* < −300 will certainly be noticed prominently, and the remarkable events like those in Table 2 would attract worldwide attention. A *Kp* of ~9 would cause G5 (extreme) storms, with *Dst* < −250 nT. Figure 7 shows the occurrence frequency of different storm levels during the last five solar cycles. The very extreme storms (*Dst* < −300 nT) are shown in black and occur mostly near solar maxima and soon after, but occasionally slightly before sunspot maximum (1967), or well after sunspot maximum (2003), or even very near sunspot minimum (1986). Figure 8 shows at what phases of the solar cycles the historical, remarkable (severest) events occurred. They seem to have occurred mostly near solar maxima, but two occurred later and one earlier. There are nine events during 80 years (1859 1938), a frequency much, much larger than the one very severe event (*Dst* −589) of 13 March 1989 or

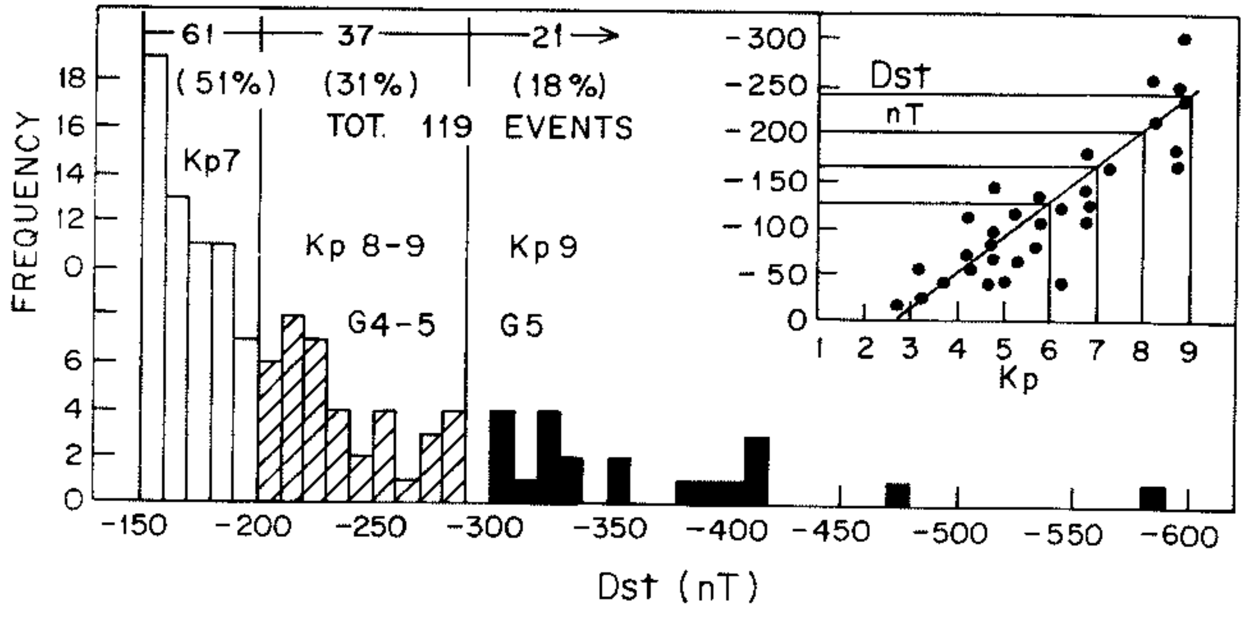


**Figure 6.** Histogram of events of different *Dst* ranges in 47 years (1957–2003). Inset is a plot of *Dst* versus *Kp* during 1957.

Table 2. Characteristics of the Halloween Events and a Few Other Events

| Event Parameter | 28–29 Oct. 2003 | 4 Nov. 2003 | 20 Nov. 2003 | 13 March 1989 | 4 Aug. 1972 |
|---|---|---|---|---|---|
| N/cm$^3$ | 10–20 | 20 | 20 | ~15 | ~23 |
| Transit hours | 20 | 25 | 47 | 47 | 14.6 |
| Transit *V*, km/s | 2070 | 1660 | 880 | 880 | 2850 |
| Observed *V*, km/s | >2000 | 800 | 700 | 550–800 | >2000 |
| Dal Lago *V* | 1220 | | 824 | | |
| $B_s$, nT | −40, −68 | −25 | −46 | no data | mostly north |
| Observed *Dst*, nT | −400 | −71 | −472 | −589 | −125 |
| Wang *Dst* | −363 | | −426 | | |

five severe events (*Dst* < −400 nT) in 47 recent years. So one may conclude either that geomagnetic activity is declining with time (Gleissburg cycle of ~80 years, [*Feynman and Gabriel*, 1990]), or all those historical events have their magnitudes highly overestimated. It seems (W. D. Gonzalez, private communication, 2004) that *Tsurutani et al.* [2003] are having a second look at their estimates of *Dst* of −1760 nT for the 1 September 1859 storm, and at least in one scenario, they find that the *Dst* estimate may come down below 1000 nT.

## 4. Halloween Events as a Test Case

[21] Most of the regression equations studied so far by previous workers have been obtained for magnetic clouds, and the maximum *Dst* range considered was near about −300 nT. Correlations of ~0.80 have been reported, but some points deviate considerably from the regression lines. Thus the validity of these equations for stronger *Dst* events is not certain. On the other hand, the stronger *Dst* events are the most damaging. In the last 47 years the largest *Dst* event was of 13 March 1989 and is reported to have caused considerable damage [*Allen et al.*, 1989]. However, the next two largest *Dst* events occurred very recently and in quick succession (29 October 2003 and 20 November 2003, an interval of only ~20 days). These offer a good opportunity to test for these giant events the previous relationships obtained for less intense events.

[22] Figure 9 shows a plot for these events. Figure 9a shows a plot of the 6-hourly values for the 28-day interval 27 October to 23 November 2003, where the *Kp* values exceeded 6 during 29–30 October 2003 and 21 days later on 20 November 2003. The *Dst* values reached about −330 and −435 nT, respectively (6-hourly values). Figure 9b shows a plot of the hourly values for the 11-day interval 28 October to 7 November 2003. There was very strong solar flare activity (indicated by solid triangles above the zero line for *Dst* in Figure 9b) on 28 October and later on 2–4 November 2003. The corresponding values of interplanetary parameters, namely, number density *N*, wind

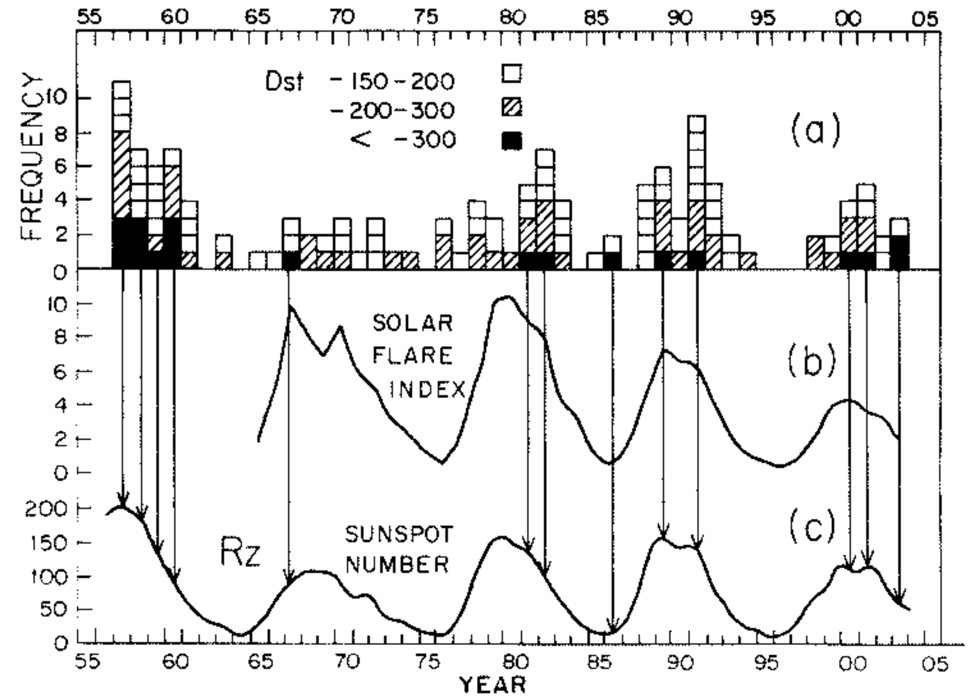


**Figure 7.** (a) Occurrence frequency of events of different *Dst* ranges (−150–200, −200–300, <−300 nT), (b) solar flare index, and (c) sunspot number $R_z$, for every year during 1957–2003. Vertical bars indicate at what phase of the solar cycle (mostly near the maximum) the major events (*Dst* < −300 nT) occurred.

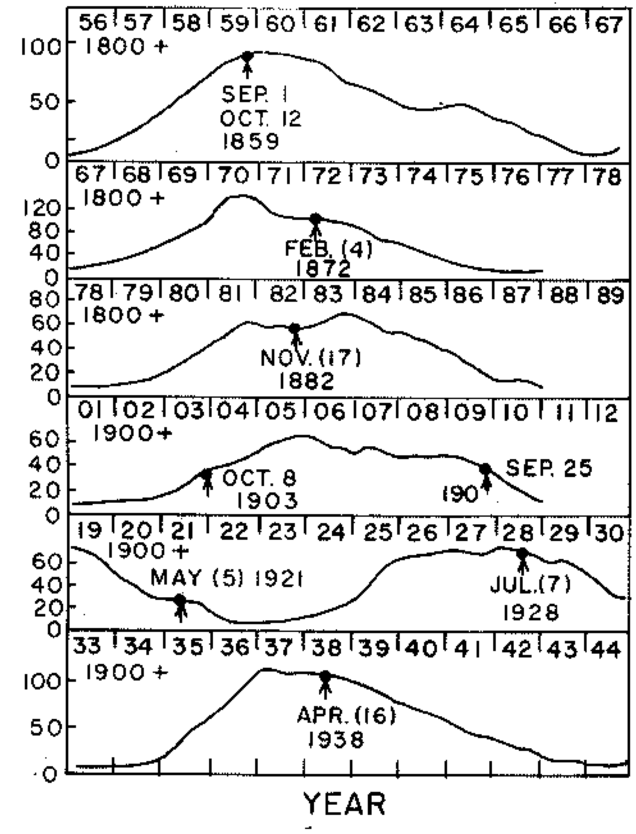


**Figure 8.** Historical 11-year sunspot cycles and the phases where the historical storm events occurred (shown by arrows).

speed $V$, and magnetic components $B_s$ and $B$ are also shown. The NOAA website shows interplanetary data missing for this interval, but *Skoug et al.* [2004] have mentioned some values and have sent these to us (R. M. Skoug, private communication, 2004). As can be seen, the interval 29–30 October shows an enormous storm (two swings of −363 and −401 nT in hourly values, $Kp$ = 9, $Ap$ = 400). The $V$ value was almost 2000 km/s. Later, there was a small storm ($Dst$ −71 nT) on 4 November 2003, which was also preceded (2–3 November 2003) by mild solar flare activity. On 4 November itself, there was a tremendously large flare, biggest so far in recorded history, but it had no geomagnetic effects, as the flare was close to the west limb, and the related CME was not directed toward the Earth. Figure 9c shows the plots of hourly values for 19–23 November 2003. There was a medium-sized solar flare on 18 November, and a $Dst$ storm occurred on 20 November 2003. The storm was very severe ($Dst$ −472 nT, $Kp$ = 9, $Ap$ = 300), because the $B_s$ component was large. Just for comparison, Figure 9d shows plots of hourly values for the giant event of 13 March 1989, with largest $Dst$ (−589 nT) in the last 50 years. However, interplanetary data are missing during the main phase, and only some values are available for early hours of 15 March 1989. The $V$ values are near ~800 km/s and could have been larger in earlier interval, but this is only a speculation. No observations are available. The $Kp$ value was 9, and $Ap$ value was 400.

[23] Table 2 lists the characteristics of the October–November 2003 Halloween events, and the 13 March 1989 and 4 August 1972 events. The following may be noted:

[24] 1. The 28–29 October 2003 event was ~3 times faster ($V \sim 2000$ km/s) as compared to the 20 November 2003 event ($V \sim 700$ km/s). Thus, based on $V$ values alone, since the prediction scheme [*Gonzalez et al.*, 2004] envisages a ($V^2$) dependence, the $Dst$ values for the 28–29 October event should have been ~9 times larger than that for the 20 November event. Actually, the values were almost similar (401 and 472 nT), indicating that the use of $V$ alone may give grossly erroneous estimates of $Dst$.

[25] 2. Obviously, more vital is the information about $B_s$ and its duration. *Wang et al.* [2003] presented a statistical study of 105 geomagnetic storms during 1998–2001 and found that the average value of $VB_s$ during the time interval, starting of negative $B_z$ to the minimum of $Dst$ depression, was very well correlated with the $Dst$ of intense storms. For the October–November 2003 storms their expected $Dst$ values were −363 and −426 nT (Y. Wang, private communication, 2004), a reasonably good matching with the observed values −401 and −472 nT. Thus the magnitude of $B_z$ (i.e., $B_s$) and its duration have a very important role to play. *Temerin and Li* [2002] have added a new dimension to the $Dst$-$V$ problem by showing that, besides other things, the dipole tilt (angle of the Earth's dipole with respect to the solar wind velocity) has an important effect on the coupling efficiency of the magnetosphere with the solar wind.

[26] 3. However, this is matching, not prediction. Interplanetary measurements are now available by the Advanced Composition Explorer (ACE) satellite, which orbits the L1 libration point which is a point of Earth-Sun gravitational equilibrium ~1.5 million km from Earth and 148.5 million km from the Sun. When reporting space weather, ACE can provide an advance warning, but only with ~1 hour or less of antecedence. For prediction with much more antecedence the lateral expansion speed of the relevant CME and the value of $V$ estimated from it is the only parameter available for use. For the October–November 2003 events a prediction with antecedence could have been made, but, as far as we know, no prediction was given. The members of the *Dal Lago et al.* [2004] group are presently engaged in a detailed analysis, but some preliminary calculations carried out by them (A. Dal Lago, private communication, 2004) indicate lateral expansion speeds of ~4000 and 2200 km/s for the two events, leading to values of $V \sim 1200$ km/s for the 28–29 October event (far below the observed value of ~2000 km/s) and ~820 km/s for the 20 November event (almost the same as the observed value of ~700 km/s). Since these are in the ratio of ~1.5/1.0, the $Dst$ values based on $V^2$ dependence would be more than a factor of 2 in magnitude for the first event as compared to the second event. Actually, the $Dst$ values were almost similar, if not slightly larger, for the second event. Thus this prediction methodology as it stands, relying completely on estimated $V$ values, gives grossly erroneous predictions of $Dst$ for the Halloween events. Presently, there is no way to assess the magnitudes of the $B_s$ component, and hence, reliable estimates of the $Dst$ magnitudes, which depend upon $VB_s$ rather than $V$ alone, cannot be obtained. On the other hand, if $V$ is predicted reasonably well, it will give a fairly good

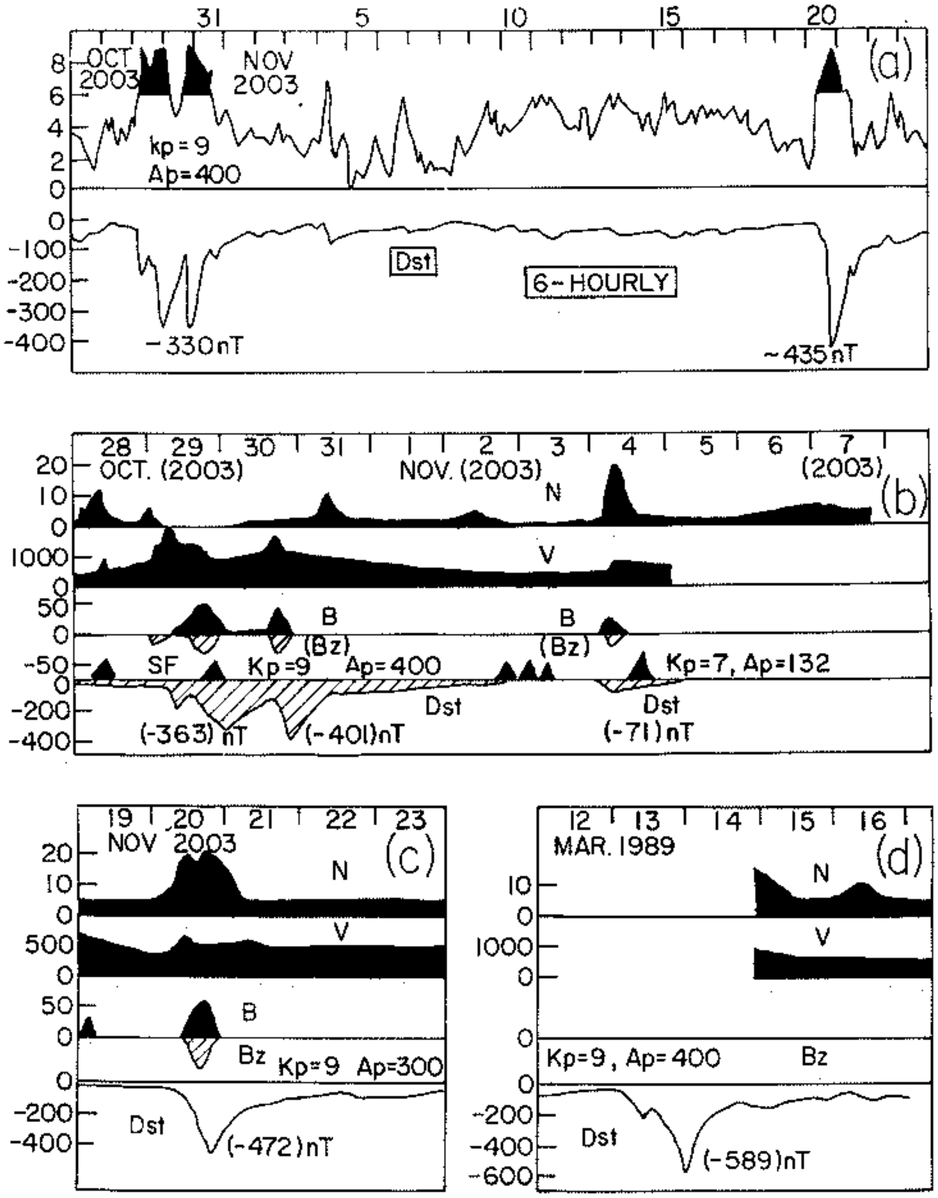


**Figure 9.** Plots of (a) 6-hourly values of *Kp* and *Dst* for the 28-day interval 27 October to 23 November 2003, showing the giant Halloween events of 29 October 2003 and 20 November 2003. Further, plots of hourly values of *Dst* and interplanetary parameters *N, V, B,* and $B_z$ for (b) the 11-day interval 28 October to 7 November 2003, (c) the 5-day interval 19–23 November 2003, and (d) the 5-day interval 12–16 March 1989 are shown.

dea about the transit time, and one can at least say with in antecedence of a few tens of hours when the storm is ikely to hit the Earth. Such an estimate was not given with antecedence for the Halloween events. However, such nformation would certainly be useful for taking remedial action.

[27] 4. On 4 November 2003 the largest solar flare in ecorded history was witnessed. The coronal ejection temorarily blinded the machines taking the images. Using the amount of time that the satellites were out of commission, cientists are now estimating a flare magnitude anywhere rom X27 to X40+. However, this flare produced no geomagnetic disturbance, because though the associated CME had a high lateral expansion speed (~4500 km/s, A. Dal Lago, private communication, 2004), it was a limb CME, not directed toward the Earth (its flanks probably scrapped the Earth on 7 November and gave a structure with total field *B* about 15 nT, but $B_y$ negligibly small, and hence no *Dst* storm). The small *Dst* (−71 nT) storm on 4 November itself was triggered by the solar flare activity on 2–3 November 2003, and the CME on 2 November was also a near-limb CME, producing only a small *Dst*.

[28] 5. For the event of 13 March 1989, no interplanetary data are available, but the large geomagnetic indices $Dst = -589$ nT, $Kp = 9$, $Ap = 400$ were probably due to the very strong (X45) flare which occurred at ~1800 UT

on 10 March 1989 (~48 hours before the *Dst* storm commencement), implying a transit speed of ~880 km/s. *Cliver et al.* [1990] estimate the speed as only 550 km/s, indicating that there are considerable uncertainties in the estimates by the Cliver technique. The satellite observations were absent during the event, but when these started soon after, the $V$ values were ~800 km/s. So the $V$ during this event could have been of this order. This is not a very high speed, but the *Dst* depression (−589 nT) was the largest ever since IGY.

[29] 6. For the event of 4 August 1972, *Tsurutani et al.* [1992, 2003] have provided some estimates. This was the fastest ever event (14.6 hours transit time corresponding to a speed of 2800 km/s) and could have created the most violent *Dst* storm, but this did not happen because the $B_s$ component was mostly northward. Thus very high $V$ by itself does not guarantee abnormal geomagnetic activity.

## 5. Possible Role of Helicity

[30] Geomagnetic effects are related specifically to the east-west electric field, and hence geomagnetic *Dst* is expected to be directly related to the product $VB_s$, rather than to $V$ alone. In recent years, another parameter, namely the helicity of magnetic clouds, has received considerable attention. Large geomagnetic storms are caused by encounters with either magnetic clouds or "compound streams" (interacting CMEs, clouds, and/or high-speed streams), [*Burlaga et al.*, 1987]. A magnetic cloud is characterized by high magnetic field magnitudes, low plasma beta (ratio of plasma pressure to magnetic pressure, or low proton temperature) and smooth rotation of the magnetic field vector within a day [*Burlaga et al.*, 1981]. The polarity of the magnetic clouds is linked to the global (solar) magnetic polarity, and the helicity (rotation positive, right-handed, clockwise; rotation negative, left-handed, counterclockwise) is the same as that of the solar source region [*Kumar and Rust*, 1996; *Bothmer and Rust*, 1997]. *Fenrich and Luhmann* [1998] showed that when the polarity rotated from northward to southward, there was increased geoeffectiveness, fitting *Dungey* [1961] mechanism. Thus the helicity might be playing some role, which needs to be explored.

[31] *Georgieva et al.* [2005] examined the differential terrestrial effects of right-handed (R) and left-handed (L) helicity. They gave a list of 90 magnetic clouds, 40 right-handed, 50 left-handed, during 1992–2002, and mentioned that geomagnetic *Kp* and *Dst* were higher for L events. For the recent few years 1996–2002, there were 31 right-handed and 42 left-handed helicity events.

[32] We examined the general list of *Georgieva et al.* [2005] and found that the larger geoeffectiveness of L events was true, but only of borderline significance. Many of those events were geomagnetically weak. Choosing only intense *Dst* depressions (100 nT or more), mean *Dst* values for L (−167 nT) were considerably higher than those for R (−127 nT), indicating that for strong storms, helicity L is more favorable. However, a test of this finding could be made for the two Halloween events of October–November 2003. The helicity details for these events are not given by *Skoug et al.* [2004], but one of those authors (Q. Hu, private communication, 2004) mentions that the cloud of 29 October 2003 was L, while the cloud on 20 November 2003 was R. Now, the *Dst* values for L are expected to be higher than those for R, but in these events, 29 October 2003 (L) had *Dst* 401 nT, while 20 November 2003 (R) had *Dst* 472 nT. Thus the helicity hypothesis seems to be invalid for these giant events.

## 6. Conclusions and Discussion

[33] Historically, since the work of *Snyder et al.* [1963], who showed a possible link between interplanetary solar wind speed $V$ and geomagnetic index *Kp*, such a relationship has been examined by many workers and found to be rather loose. Geomagnetic storms can occur due to several interplanetary features, including magnetic clouds, but it is only when the magnetic field of the interplanetary feature engulfing the Earth has a strong southward component $B_s$ that a good relationship is obtained between *Dst* and the product $VB_s$ [*Wang et al.*, 2003]. In the present communication, events during 1973–2003 were examined to check how good their relationships were with interplanetary $V$ and the product $VB_s$. The following was noted:

[34] 1. Moderate or strong geomagnetic storms occurred only when $V$ was above ~350 km/s (e.g., 26 September 1989, $V$ 374, *Dst* −151 and 10 January 1976, $V$ 393, *Dst* −156).

[35] 2. However, above this limit any value of $V$ could be associated with any value of *Dst*. For example, for a very small *Dst* range (−150–160 nT), $V$ values (km/s) were 451, 503, 549, 621, 639, 760, 778, and 811 (a wide range of a factor of ~2). For the small *Dst* range (−200 210 nT), $V$ values were 595, 707, 800, 835, and 1021 (largest $V$ value during 1973–2003, again, a wide range of a factor of ~2).

[36] 3. For $V$ values of ~700 km/s the *Dst* values had a wide range 160–400 nT.

[37] 4. The largest *Dst* value was −589 nT on 13 March 1989 with $V$ only ~550–800 km/s. The next largest *Dst* values were near −400 nT, but their $V$ values were vastly different (Halloween events, 29 October 2003, *Dst* −401 nT, $V \sim 2000$ km/s and 20 November 2003, *Dst* −472 nT, $V \sim 700$ km/s).

[38] 5. The scatter in the $V$ values could be partly because not $V$ but $VB_s$ is the appropriate variable relevant for *Dst* changes. This was checked. In the plot of *Dst* versus $VB_s$ it was noticed that the scatter was smaller and correlation better than that in the plots of *Dst* versus $V$ values.

[39] In conclusion, since the relationship between $V$ and *Dst* is poor, an estimate of $V$ with any antecedence, though academically very gratifying and certainly useful to estimate the storm arrival time at the Earth, may not be of much use to estimate the *Dst* magnitudes as such.

[40] In the prediction scheme outlined by *Gonzalez et al.* [2004], side halo CMEs are selected to measure their lateral expansion speeds $V_e$, which can be used as proxies of the Sun-Earth line speeds [*Schwenn et al.*, 2001] and have a linear relationship with $V$ [*Dal Lago et al.*, 2002]. Then, because of other relationships ($V$ with $B$, $B$ with $B_s$, etc.), *Dst* can be estimated, basically from $V^2$. Of course, this is a tricky procedure. The Gonzalez et al. derivation of *Dst* proportional to $V^2$ involves a large number of assumptions. All the necessary relationships are obtained from regression analysis of a small group of selected events (for example,

54 magnetic clouds during 1965–1997 by *Dal Lago et al.* [2001]). Each proportionality factor used involved two quantities, which were related with a correlation coefficient of 0.7 or so, and stacking several of these up can of course lead to a lot of scatter. Hence the estimates of $V$ values will have considerable uncertainties. However, even if $V$ values are estimated correctly, their use for estimating *Dst* does not seem to be very certain. *Dst*-$V$ correlations obtained in the present communication are low, and predictions based on the same are likely to be way out. The effects of large *Dst* are harmful, no matter what were the sources (ejecta, shocks, corotating streams, etc.) of the *Dst* variations.

[41] As matters stand, the continuous patrolling of solar flares and CMEs can be used for safe prediction only as follows. As soon as a strong flare is seen or a side halo CME is seen (which may not be often) and its lateral expansion speed is measured, a general alert may be given that something might happen in the next few tens of hours (commensurate with the lateral expansion speed). Then, keep fingers crossed, because anything may happen, including nothing. This is not speculation. It happened before. The 4 August 1972 event was the fastest one in recorded history, with a speed of ~2800 km/s, and could have resulted in a monstrous storm. However, as noted by *Tsurutani et al.* [1992, 2003], the magnetic field was mostly northward, and the resulting *Dst* was a paltry −125 nT. Alternatively, the magnetic cloud may get compressed causing an enormous $B_s$, which could result in a giant *Dst* event, causing a lot of damage to communication channels, power grids, computers, satellite systems, etc. If the speed is not indicated as high, the event may occur much more than 30 40 hours later, and the storm may not be very intense, causing virtually no harm, but even this is not for sure. The storm of 13 March 1989 had a transit time of 47 hours corresponding to a speed of ~880 km/s, and yet it resulted into an enormous storm of *Dst* −589 nT. Thus no reasonable estimate of the *Dst* magnitude is possible, as the matters stand today.

[42] It is embarrassing to note that this level of prediction is not very much superior to what *Chapman and Bartels* [1940] could have done more than 60 years back, except that they could not have predicted the transit time, while presently, a measurement of the lateral expansion speed of a CME (if possible) may give some idea of the time when the storm may hit the Earth. However, not all CMEs are geoeffective; only the halo CMEs are. *Schwenn et al.* [2004] mention that for an isolated, undisturbed frontside halo CME, their empirical formula allows us to predict the shock/interplanetary coronal mass ejection (ICME) arrival time at the Earth, and there is a 95% probability that the shock will arrive within one day around the predicted time (almost a 24-hour uncertainty, rather a poor precision), except if it is one of the 15% of ICMEs that never hit the Earth (false alarms, missing alarms).

[43] However, regarding the uncertainty of the *Dst* magnitudes, there is a redeeming factor as follows. Storms with *Kp* 9 are already dangerous and correspond to *Dst* < −300 nT. Hence, once the *Dst* has reached this level, the damage starts, and then it hardly matters whether *Dst* intensifies further or not. In fact, what matters then is how long *Dst* would remain at or below the −300-nT level. The information about higher *Dst* magnitudes would have been useful had the *Dst* magnitude been proportional to the duration, but it is not so. There are plenty of examples when on one hand, *Dst* decreased very much and very rapidly but recovered also rapidly within a few hours, or on the other hand, *Dst* near −300 nT dragged on and on for several hours before finally recovering. Hence the lack of a methodology of predicting very high *Dst* magnitudes is not of much consequence. One would have liked to know how long the high *Dst* values would continue, but that depends upon the storm-time $B_s$ values, which generally oscillate between zero (or even positive) and large negative values in an irregular, presently unpredictable way. It is hoped that in the future it will be possible to get with antecedence some telltale signs of such a near-Earth $B_s$ pattern in some solar phenomena.

[44] Regarding terrestrial effects including damages during intense storms, newspaper reports are available for several storms. Communication systems including those in airplanes can go haywire, and power grids can go down. The most outstanding example is of the 13 March 1989 event when the Hydro-Quebec (Canada) power grid went down for more than 9 hours, and the eastern U.S. seaboard power grid was almost put down [*Allen et al.*, 1989; *Tsurutani et al.*, 2003]. For the October–November 2003 Halloween events, "NASA, Solar System Exploration: News and Events, July 8, 2004, News Archive, Space Storm Tracking" mentioned that the effects on Earth were severe enough to cause the rerouting of aircraft, affect satellite operations, and precipitate a power failure in Malmoe, Sweden. Long-distance radio communications were disrupted because of the effects on the ionosphere, and northern lights (aurora borealis) were seen as far south as Florida.No NASA satellites near Earth were severely damaged by the storms. The International Space Station astronauts curtailed some of their activities and took shelter in the Russian- supplied Service Module several times during the storm.

[45] What measures, if any, have been taken to avoid or mitigate such damaging effects? *Beland* [2004] mentions that for Hydro-Quebec (HQ) in the province of Quebec in Canada, there are now two measurement systems (one primary and one backup) monitoring ground-induced current (GIC) effects on the grid in real time. To be informed in advance of a probable GIC occurrence, HQ now relies on a specialized organization providing geomagnetic activity alert and forecast. Following an alert or the detection of GIC effects on the network exceeding a minimal threshold, special operation rules become in effect for ensuring maximum stability and safety margin. Also, series capacitors are introduced on several 735-kV lines, which increase network stability and also block GIC circulation. Other installations might be using other methods. In some cases, operations are stopped (if possible) until the storm continues.

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