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Relationship between Dst(min) magnitudes and characteristics of ICMEs

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All interplanetary disturbances having shocks and directed towards the Earth are geoeffective, giving at least a storm sudden commencement (SSC) and giving Dst depressions [Dst(min)] in a wide range -10 to -500 nT, actual magnitudes roughly proportional to the magnitudes of negative Bz(min) of interplanetary magnetic field. During 1965-1996, the ejecta and shock events not accompanied with magnetic clouds (MCs) had only ~17% intense storms [Dst(min) ≤-200 nT] but ejecta and shocks accompanied with magnetic clouds (MCs) had ~40% intense storms. For solar cycle 23, ejecta and shocks without MCs had only ~3% intense storms; but ejecta and shocks accompanied by MCs had 11% intense storms. Thus, events accompanied with MCs gave larger percentage of intense storms. Events related to corotating interaction regions (CIRs) led to only weak and moderate storms [Dst(min): -20 nT to -140 nT]. For cycle 23, the plots of –Bz(min) *vs* –Dst(min) for ejecta and shocks without MCs showed a large scatter for the ranges Bz(min) -3 to -20 nT *vs* Dst(min) -5 to -170 nT. Thus, analysis in this region would give confusing and uncertain results. Concentrating on intense events [Dst (min) ≤ -200 nT], the Bz(min) *vs* Dst(min) plot showed a correlation of only +0.77±0.12, with considerable scatter in the Dst(min) range -200 to -300 nT [for the same value of Bz(min), Dst(min) would have an uncertainty of about ± 50 nT]. The correlation did not improve when Bz(min) was substituted by the product BzV, or by cumulative negative Bz from the start to the peak of negative Bz(min).

Keywords: Interplanetary disturbance, Magnetic clouds, Ejecta, Shocks, Intense storms, Corotating interaction region (CIR), Interplanetary coronal mass ejections (ICME), Dst, Interplanetary magnetic field

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1 Introduction

An increase in interplanetary number density, speed and magnetic field, etc. above the background solar wind level heralds interplanetary disturbance of various types (shock fronts, sheaths, etc.[1], which can cause a geomagnetic storm, provided there is a long duration southward magnetic field Bs (same as –Bz component of interplanetary magnetic field, IMF) which seems to control magnetospheric activity through magnetic reconnection processes[2-5]. Many of these disturbances are interplanetary coronal mass ejections (ICMEs) which have their origin in solar coronal mass ejections (CMEs). These were discovered by Tousey[6] and have been copiously studied since then and presently, the SOHO-LASCO catalogue (http:// cdaw.gsfc.nasa.gov/CME_list/) provides all characteristics of CMEs, past and present [ref. (7) and references therein]. However, CMEs near Sun suffer considerable evolutions during their transit from the Sun to the Earth´s orbit at 1 AU and the resulting ICMEs have internal structures very different from those of the original CMEs. Most of the CMEs are narrow and their Earth-directed ICMEs may still miss the Earth. But their subset, halo CMEs, are fairly wide and the chance of their Earth-directed ICMEs hitting the Earth is ~80%. The ICMEs are composed of shock with ejecta (i.e. driver) and are occasionally accompanied or followed by magnetic clouds (MCs), which are structures defined by Burlaga and co-workers as having enhanced (> 10 nT) magnetic fields that rotate smoothly through a large angle, low proton temperatures, and low plasma beta[8,9]. Besides ICMEs, there are also corotating interaction regions (CIRs) in interplanetary space, which are caused when high speed solar wind from coronal holes impinges on the slow ambient solar wind and causes shock fronts. These fronts participate in solar rotation and are sources of recurring geomagnetic storms.

Several studies have reported relationships between interplanetary magnetic structures and their geoeffectiveness[5,10-15]. Echer *et al.*[16] presented a statistical study of the geoeffectiveness of MCs, CIRs and interplanetary shocks for the entire period 1964-2003, where frequency distributions were obtained that gave the probability of Kp, AE, etc. of every interplanetary structure being followed by intense, moderate and weak geomagnetic activity levels. They reported that the percentage of intense magnetic activity was higher for MCs than for shocks or CIRs. Similar further work has been reported by Kim *et al.*[17,18] and Wu & Lepping[19]. Further, Alves *et al.*[20] fitted histograms to obtain theoretical continuous probability distribution functions.

The main purpose of this paper is not to ascertain the best Dst-Bz relationship, but to examine the Cane *et al.*[21] list with its classification, and see what conclusions can be drawn and how do they compare with results of cycle 23 reported by many researchers. In the present paper, frequency distributions of geomagnetic disturbance index Dst (ref. 22) for different interplanetary structures classified by Cane *et al.*[21], namely, ejecta (driver) with shocks but without MCs, shocks without MCs and ejecta and shock with MCs are presented (32 years data, 1965-1996) and results compared with those of data for cycle 23 (1996-2006). For earlier data, the classification given by Cane *et al.*[21] is somewhat ambiguous and a more rigorous classification is given by Gopalswamy[13], so the results of the study for this early sample (1996 and earlier) are to be considered only as rough indications. Regarding shocks only, it had been an enigma as to how one could produce shocks without a driver[23]. Recently, Gopalswamy *et al.*[7] have explained these, mentioning that these shocks are also CME driven but the driver does not arrive at the observer because of the observer´s location with respect to the nose of the CME. The classification in the Cane *et al.*[21] paper is somewhat convoluted (some categories mixed up) but these are retained as the purpose is to see what results these categories give as they are.

2 Events during 1965-1996 (32 years)

Cane *et al.*[21] have given a list of interplanetary structures. Only those events are considered by them, which were associated with cosmic ray (CR) Forbush decrease exceeding 4%. There could be errors in identification and the sample may not be complete, as some large Dst events might be omitted where CR Forbush decrease was smaller than 4%. Nevertheless, their sample is considered large enough to yield statistically significant results and good enough to compare with results of further data (cycle 23), though some correlations may be insignificant and results may be somewhat ambiguous. Figure 1(a) shows the frequency of occurrence of 80 events of ejecta only. As can be seen, the occurrence is largest for Dst(min) (hourly values) in the range -30 to -130 nT, but later, the frequency is spread over a very large range of Dst(min) extending beyond -400 nT. Figure 1(b) shows the distribution for shocks. The 53 events are confined to Dst(min) up to -220 nT and there are no severe storms. Figure 1(c) superposes (a) and (b) and the distribution is now more like a Poisson distribution, but still large Dst(min) are more than expected. There are 111 events in Dst(min) range -50 to -199 nT and 22 events beyond Dst(min) -200 nT, a ratio of 83 to 17%. Figure 1(d) shows distribution for ejecta and shock with MCs. Here, the proportion is very different. Out of 20 total events, 12 are in the Dst(min) range -50 to -199 nT while 8 are beyond -200 nT, a ratio of 60 to 40%. Thus, presence of MCs seems to encourage large storms. It may be noted, however, that the number of events with MCs is quite small, 133 ejecta without MCs, 20 ejecta with MCs.

All the distributions are flat, so the very high Dst may not be significantly different. Some Dst are very high indeed. For these, statistics should not be used. These are individually violent events, and should be treated as such, each giving some different information. For example, the relationship with interplanetary V is not consistent. There is no point in collecting more (weaker) events and try to deduce consistency.

Figure 2 shows the distribution for CIRs. There were only 15 events and the Dst(min) was confined to -50 to -100 nT. Thus, CIRs do not yield intense storms.

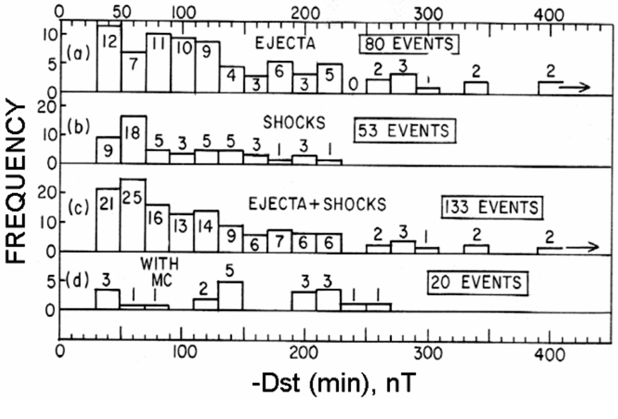

Fig. 1 — Occurrence frequency of geomagnetic storms, [Dst(min) range -50 to -500 nT] for: (a) 80 ejecta events, (b) 53 shock events, (c) 133 ejecta and shock events, and (d) ejecta and shocks with magnetic clouds MCs, during 1965-1996

3 Events in solar cycle 23 (1996-2007)

For cycle 23, Fig. 3(a) shows the frequency distribution for 184 ejecta events (including shocks but no MCs). The frequency is very large for very small Dst(min), but spreads in small numbers up to -360 nT, but with only 5 events from -200 nT beyond. The mean value is -66 nT. The ratio for events before -200 nT and beyond is 97 to 3%.

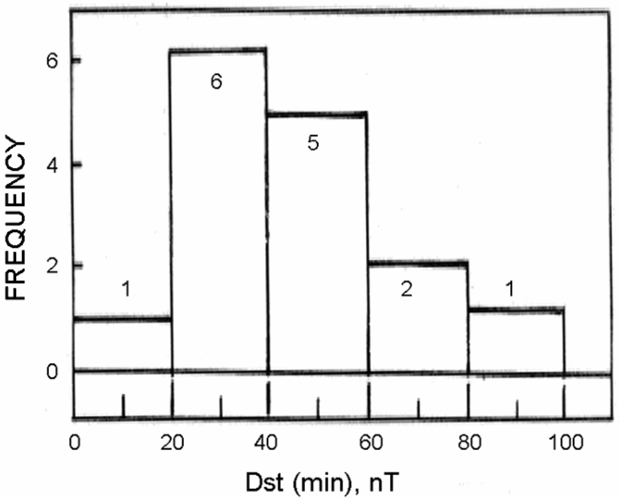

Fig. 2 — Occurrence frequency of geomagnetic storms, [Dst(min) range -50 to -100 nT], for corotating interaction regions (CIRs) during 1965-1996

Figure 3(b) shows the distribution for 100 ejecta events with MCs. The distribution is spread more towards larger Dst(min) and there are 11 events from -200 nT beyond. The mean value is -105 nT. The ratio for events before -200 nT and beyond is 89 to 11%.Thus, MCs definitely favor stronger storms.

In Fig. 1, the ejecta were 133 and shocks 20, a ratio of 87 to 13%. In Fig. 3, the numbers are 184 and 100, a ratio of 65 to 35%. Thus, there were more MCs in cycle 23. This could be because of differences in solar cycles or because of incomplete listing, probably in earlier samples before cycle 23.

During 1995-2003 (data courtesy Dr. E. Echer, INPE), the Dst(min) distribution for CIRs was 87, 111, 62, 20 12, 3, 1 for Dst(min) centered at -20, -40, -60, -80, -100, -120, -140 nT, respectively. Thus, the distribution was overwhelming in the low Dst(min) range -20 to -60 nT and there were only weak and moderate storms [Dst(min) -20 to -50 nT; -50 to -140 nT] and no intense storms [(Dst(min) ≤ -200 nT].

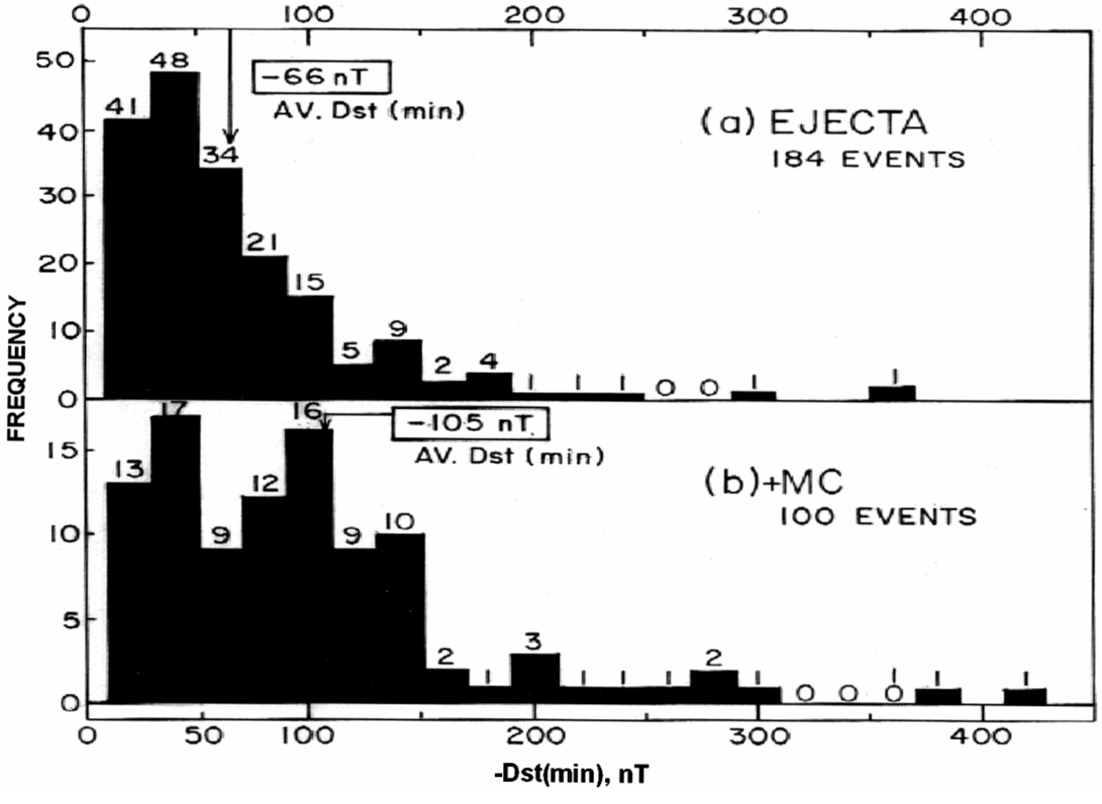

Fig. 3 — Occurrence frequency of geomagnetic storms, [Dst(min) range -50 to -500 nT], for: (a) 184 ejecta events, and (b) 100 MC events, during 1996-2007

4 Role of southward interplanetary magnetic field component [-Bz(min)]

For the same type of interplanetary structure, there is a wide range of Dst(min) magnitudes. Obviously, some additional factor is involved. This factor is known to be mainly the negative Bz(min), which acts as a valve for solar wind entry into the magnetosphere (the other factors are comparatively less important; the number density is not of much consequence and even large B may be ineffective unless its negative Bz component is large)..

Figure 4 shows a plot of -Bz(min) *vs* -Dst(min) for: (a) ejecta and shocks only; and (b) ejecta and shocks with MCs. In Fig. 4(a), the range -50 to -100 nT has a lot of scatter. For storms, Gonzalez *et al.*[1] mentioned a threshold of 5 nT for Bz(min). But it seems that any value of Dst(min) from -50 to -100 nT could be related to any value of Bz(min) from -3 to -17 nT. Many researchers have used samples in this region and the results are often contradictory, probably because of this inherent scatter. The correlation is only +0.34. Even in the next range Dst(min) -100 to -170 nT, the correlation is only moderate (+0.58). The overall correlation for Dst(min) -50 to -170 nT is moderate (+0.54±0.07). If average Bz(min) is calculated for successive Dst(min) ranges 20 nT apart, the full dots show a slow increase of Bz(min) from -8 to -12 nT for the Dst range -60 to -120 nT. The right hand of Fig. 4(a) has only 4 events so not much can be said,

In Fig. 4 (b) for ejecta with MCs also, the correlations are low, though the overall correlation for Dst(min) -50 to -170 nT is slightly better (+0.66±0.06), though not significantly better as compared to (+0.54±0.07) of Fig. 4(a). Overall, the Dst(min) values in the range -50 to-170 nT and the Bz(min) values in the range -3 to -20 nT have uncertain relationship (low correlation). The right hand side has very few data points. Also, for the Halloween events, the data points for high -Bz are very different from the low -Bz hourly values given in website. Thus, results for the Halloween events are unreliable.

There are no events in the range Dst(min) -170 to -198 nT. (There is a gap in data). Concentrating on Dst(min) storms from -199 nT onwards as intense storms, Fig. 5(a) shows a plot of -Bz(min) nT *vs* –Dst(min) nT, for 4 non-MC storms (small dots) and 9 MC storms (full big circles) (In these, the full squares represent the two Halloween storms of 29-30 October 2003. For these, the values of Bz(min) are

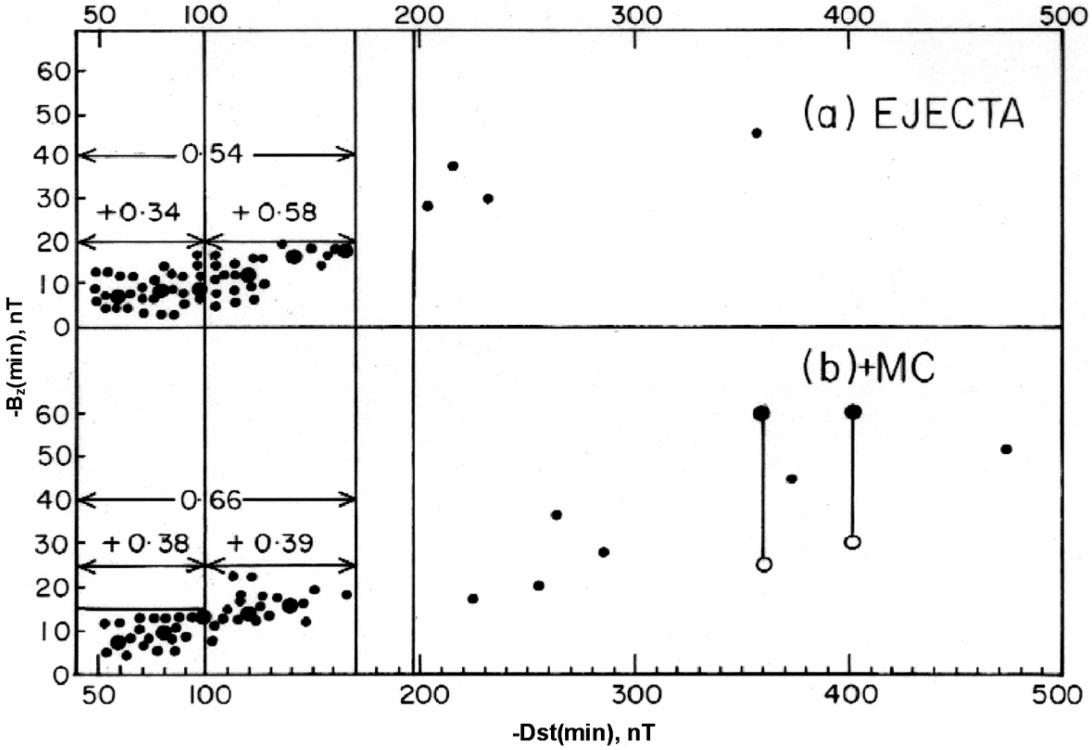

Fig. 4 — Plot of –Bz(min) *vs* –Dst(min) during cycle 23 (1996-2007) for: (a) ejecta, and (b) magnetic clouds MC. In the left half, the big full dots indicate average values of –Bz(min) for -Dst (min) 60, 80. 100, 120, 140 nT. In the right half in (b), the Halloween events of 29-30 October 2003 are shown as 1-minute values (full dots) and hourly values (open circles), connected by vertical lines

uncertain. Skoug *et al.*[24] mentioned ~60 nT as 1-min values, while the NOAA SPIDR website mentions 25 and 29 nT as hourly values. In the figure, full squares have been shown as ~60 nT and the blank squares connected by vertical lines as 25 and 29 nT. The correlation is +0.77±0.12 and there is considerable scatter in the lower Dst(min) region (for the same value of Bz(min), Dst(min) can be ascertained only with an uncertainty of about ± 50 nT). If the Halloween points are omitted, the correlation is +0.74±0.12.

One possibility for the scatter may be that Bz (min) is only a valve and not an energy input function. The simplest energy input function is BzV, where, V, is the solar wind velocity[1]. Using V for the hour when Bz(min) occurred, the product BzV has been calculated for all the 13 intense storms. Figure 5 (b) shows the plot of the product BzV (arbitrary units) *vs* Dst(min) nT. The Halloween events are way out because they have velocities exceeding 2000 kms^{-1}, while others have velocities in a range 500-900 kms^{-1}. If the Halloween events are omitted, the correlation is very poor (-0.07) which is very surprising and discouraging, because the product BzV is often reported as giving good results.

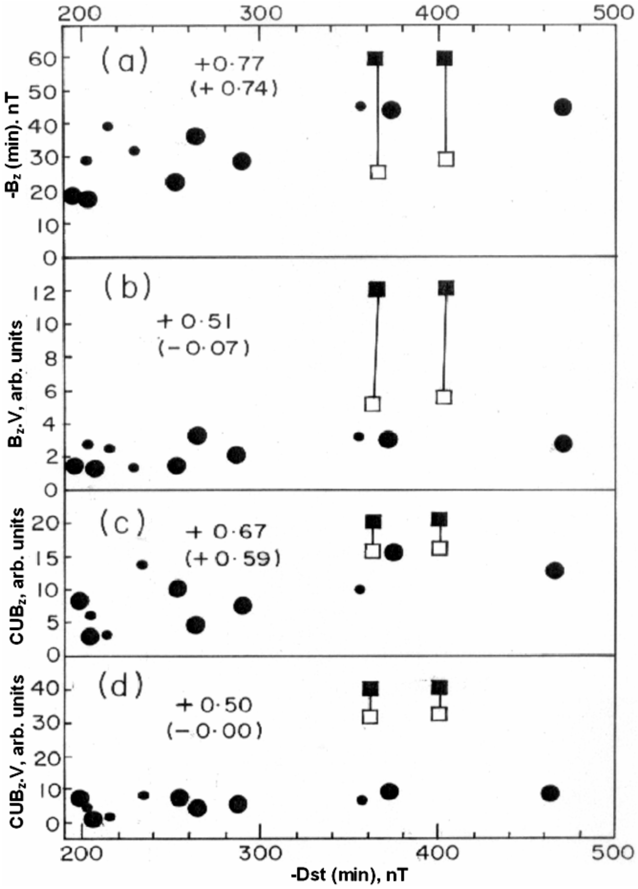

Fig. 5 — Plot for 13 intense storms (4 small dots for ejecta alone, 9 big full circles for ejecta with magnetic clouds) during cycle 23 (1996-2007) for: (a) –Bz(min) *vs* –Dst(min) in units nT, and (b) product BzV *vs* –Dst(min), (c) Cumulative negative Bz, CuBz *vs* –Dst(min), (d) Product CuBzV *vs* –Dst(min) in arbitrary units.. For Halloween events of 29-30 October 2003, the full squares represent 1-minute values and the open squares connected by vertical lines represent hourly values. Two correlations are shown in each panel, the upper one for all the 13 intense storms and the lower one for 11 intense storms (Halloween events omitted)

It is often mentioned that not –Bz(min) but its cumulative effect (duration) is important. The cumulative Bz, (CuBz), i.e. sum of hourly values of negative Bz starting from the hour when Bz started becoming negative, to the hour of maximum negative Bz(min) has been calculated. Figure 5 (c) shows the plot of CuBz *vs* –Dst(min). The correlations are almost the same as (slightly lower than) those in Fig. 5(a), indicating that the time over which Bz was negative is not of importance, because in the present cases, the time was almost the same for all events. Figure 5(d) shows the plot of the product CuBz and velocity V, (CuBzV) *vs* –Dst(min) and the correlations are similar to those in Fig. 5(b).

The consideration of number density ‘n’ showed no improvement of correlations, probably because often n varies very differently from V and Bz. So results using ‘n’ are not mentioned in this paper.

5 Conclusions and Discussion

From the present analysis, the following conclusions can be drawn:

(a) All interplanetary disturbances directed towards the Earth are geo-effective giving at least a storm sudden commencement (SSC) and if the disturbance has a negative Bz component, Dst depressions [Dst(min)] in a wide range are produced, the magnitudes depending upon the strength of negative Bz.

(b) During 1965-1996, the 133 ejecta and shock events not accompanied with magnetic clouds (MCs) show a very wide Dst(min) distribution (0 to -400 nT) but peaking at about -60 nT and having 22 events (~17%) at -200 nT and beyond. For 20 ejecta and shock events accompanied by MCs, the distribution is broad, with peak near -140 nT and having 8 events (~40%) at -200 nT and beyond. Thus, events with MCs give larger percentage of intense storm events (Dst ≤-200 nT).

(c) During solar cycle 23, the 184 events with ejecta and shocks without MCs had a peak near -40 nT and a mean value -66 nT, with only 5 intense events (~3%) at -200 nT and beyond. The 100 events with ejecta and shocks and MCs had two peaks near -40 and -100 nT, with a mean value -105 nT and 11 intense events (11%) at -200 nT and beyond. Thus, events with MCs gave larger percentage of intense storm events [Dst(min) ≤-200 nT].

(d) The plots of –Bz(min) *vs* –Dst(min) for ejecta and shocks without MCs showed a large scatter for the ranges Bz(min) -3 to -20 nT *vs* Dst(min) -5 to -170 nT. Thus analysis in this region could give confusing and uncertain results.

(e) Concentrating on intense events [Dst (min) ≤ -200 nT], the Bz(min) *vs* Dst(min) plot showed a correlation of only +0.77±0.12, with considerable scatter in the Dst(min) range -200 to -300 nT [for the same value of Bz(min), Dst(min) would have an uncertainty of about ± 50 nT]. The correlation did not improve when Bz(min) was substituted by the product BzV or by cumulative negative Bz from the start to the peak of negative Bz(min).

(f) Although the incompleteness of the older data (1965-1996) mean that the results from that era cannot be used quantitatively, those measurements are also consistent with the conclusion that ICMEs with magnetic clouds are more likely to cause large excursions of Dst.

Thus, the relationship of Dst(min) with negative Bz seems to be complicated[25]. Two more possibilities exist. The negative Bz valve supplies energy to the equatorial ring current. The current effect is represented mostly by observed Dst, but it can be polluted by magnetospheric ram pressure current effects. These are proportional to NV^2, where N and V are interplanetary number densities and velocity. When the ram effect was calculated for the 13 intense storms, it was substantial (~70 nT) only for the Halloween events when velocity reached 2000 kms^{-1}. In all other events, the effect was only ~25 nT or less. Thus, if Dst(min) is replaced by Dst* [Dst(min) plus ram effect], all the points in Fig. 5 will be shifted to the right by ~25 nT, which is very small compared to the Dst(min) absolute values, all exceeding 200 nT. Dst* gave almost the same correlations as Dst(min) (0.77 became 0.76).

Another possibility is that the input energy goes not only to the ring current but to auroral electrojet currents also, represented by indices AU and AL. If this distribution changes from event to event, the ring current will receive anything in the range 70-100% of the input energy, percentage changing from event to event, and producing a scatter. In that case, only a multivariate correlation of Bz(min) with Dst(min), AU, AL could improve the correlation. Presently, this possibility is being explored. Preliminary results indicate some success.

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