Asymmetric development of magnetospheric storms during magnetic clouds and sheath regions

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[1] This study examines how the asymmetry in the low-latitude geomagnetic field evolves during sheath and magnetic cloud domains of interplanetary coronal mass ejections using the *Dst*, *SYMH* and *ASYH* indices. For all investigated storms the station that contributed most to *Dst* was located in the dusk sector while the smallest disturbance field was concentrated around dawn. We found that sheath region storms are associated with larger morning/afternoon asymmetry than magnetic cloud storms. For sheath storms the station in the dusk sector contributed almost four times as much to *Dst* as the station in the dawn sector. Furthermore, the disturbance field is strongly variable during sheath storms. The results of this study suggest that for magnetic cloud storms the asymmetry arises mainly from ions drifting on open trajectories whereas in a case of a sheath driven storm the sudden intensifications of the substorm associated current systems add significantly to the asymmetry. **Citation:** Huttunen, K. E. J., H. E. J. Koskinen, A. Karinen, and K. Mursula (2006), Asymmetric development of magnetospheric storms during magnetic clouds and sheath regions, *Geophys. Res. Lett.*, *33*, L06107, doi:10.1029/2005GL024894.

1. Introduction

[2] The basic defining property of a magnetic storm is a global decrease in the horizontal (*H*) component of the geomagnetic field at low latitudes. The storm strength is usually quantified in terms of the hourly *Dst* index that is a weighted average of the deviation from the quiet level of the *H* component measured at four low-latitude magnetometer stations (Table 1). Originally the *Dst* index was aimed to measure the axially symmetric ring current source [*Sugiura*, 1964]. However, today it is well established that during magnetic storms the low-latitude geomagnetic field develops very differently at different local times [e.g., *Lui et al.*, 1987; *Grafe*, 1999; *Liemohn et al.*, 2001; *Takalo and Mursula*, 2001; *Shi et al.*, 2005].

[3] The main storm-time asymmetric field is formed by ions drifting on open trajectories around the dusk side of the Earth and out through the dayside magnetopause. In addition several other current systems, such as the tail current, the magnetospheric closure of the region 2 current and the substorm current wedge, contribute to the magnetic variations at low latitudes. Particularly, the current system that discharges the space charge that accumulates at the nightside and dayside boundaries of the polar cap and the auroral oval due to large conductivity gradient between these regions is greatly enhanced during substorms [e.g., *McPherron*, 1991].

[4] Solar wind structures that lead to the largest depressions of *Dst* are magnetic clouds and regions of compressed and heated solar wind plasma ahead of the CME ejecta (sheath). Magnetic clouds are a subset of CME ejecta that are recognized in the solar wind by enhanced magnetic field strength, low proton temperature and a large and smooth rotation of the interplanetary magnetic field (IMF) direction [*Burlaga et al.*, 1981; *Klein and Burlaga*, 1982]. Sheath regions and magnetic clouds are structurally quite different and lead to different response of the auroral and ring current systems [*Huttunen et al.*, 2002; *Huttunen and Koskinen*, 2004]. In general solar wind dynamic pressure is much larger in a sheath than in a magnetic cloud and within a cloud magnetic field direction changes smoothly whereas within a sheath the directional changes of the IMF are irregular [*Lu*, 2006, Figure 4]. Furthermore, the passages of sheath regions are short when compared to magnetic clouds. The average passage time of magnetic cloud sheath identified near 1 AU by *Huttunen et al.* [2005] was 11 hours while the average duration of magnetic clouds is 27 hours [*Lepping and Berdichevsky*, 2000]. In this paper we investigate the dependence of storm-time low-latitude geomagnetic perturbations on these different solar wind drivers.

[5] We examine 28 magnetic storms that had the *Dst* minimum between −100 and −150 nT, that is, intense magnetic storms, between the years 1997 and 2002. To have an equal amount of sheath and magnetic cloud associated storms over this seven year period two sheath storms with the *Dst* minimum of −98 nT were included. The *storm driver* is defined as a solar wind structure that is responsible for the main *Dst* decrease. We have also used *SYMH* and *ASYH* indices that present the longitudinally symmetric and asymmetric parts of the geomagnetic disturbance [*Iyemori*, 1990]. *SYMH* and *ASYH* values were obtained from Kyoto World Data Center. *SYMH* is essentially the 1-minute *Dst* index derived from a partly different set of six low-latitude stations and *ASYH* is the range between the maximum and minimum deviations from *SYMH*.

2. Statistical Results

[6] To investigate the local time evolution of the geomagnetic field during the 28 selected storms we compared the normalized values of the disturbance field components (*D*) at individual *Dst* stations. The disturbance fields were

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Table 1. Geographical and Geomagnetic Coordinates of the *Dst* Stations[a]

Station	Geographic Longitude, deg	Latitude, deg	Geomagnetic Longitude, deg	Latitude, deg	MLTMN
San Juan	18.1	293.2	28.6	5.1	4 h 14 min
Hermanus	−34.4	19.2	−33.9	83.6	23 h 0 min
Kakioka	36.2	140.2	27.1	208.5	14 h 41 min
Honolulu	21.3	202.0	21.6	269.4	10 h 37 min

[a]The last column gives the local magnetic midnight time at each station.

calculated according to newly reconstructed values by *Karinen and Mursula* [2005] following the original *Dst* recipe by *Sugiura* [1964]. The secular variations of the Earth's magnetic field as well as the solar quiet daily variation (regular diurnal variations associated with the ionospheric tidal currents) have been subtracted from the measured values at each station.

[7] Figures 1a and 1b show the magnetic local time (MLT) distribution of the stations that gave the largest contribution to *Dst* (D_{max}) for sheath (Figure 1a) and magnetic cloud (1b) associated storms. For both driver types D_{max} is measured at the station that was located in the evening sector. Figures 2c and 2d demonstrate that the smallest disturbance field (D_{min}) is concentrated around dawn.

[8] As presented on histograms of Figure 2 the afternoon/morning asymmetry is larger for sheath associated storms (Figures 2a and 2c) than for magnetic cloud associated storms (Figures 2b and 2d). On average D_{max} accounts for 39% of the total *Dst* for sheath storms and 34% for magnetic cloud storms while D_{min} contributes on average 11% and 16% respectively. For example, in a case of a sheath driven storm for the $|Dst|$ of 100 nT, the disturbance field at the dusk sector is 156 nT whereas at the dawn sector the disturbance field is only 44 nT. For magnetic cloud associated storms the corresponding values are 136 nT and 64 nT. Furthermore, as presented by Figure 2 the spread of the D_{max} values is considerably larger for sheath storms than for magnetic cloud storms. The standard deviation is 3.7% for magnetic cloud storms and 7.0% for sheath storms.

[9] As demonstrated in Figure 1 the geomagnetic field has its maximum in the evening sector and the minimum in the dawn sector regardless of the associated solar wind driver. The investigation of the high-resolution *ASYH* and *SYMH* indices brings out clear differences between the response to sheath regions and magnetic clouds.

[10] We evaluated the ratio $R = |ASYH|/|SYMH|$ during the 4 hour time interval before the *Dst* minimum for each storm (Figure 3). *ASYH* and *SYMH* indices were averaged over 15 minutes. Figure 3 shows that the R values are evidently organized according to the solar wind driver. The majority (83%) of magnetic cloud associated storms correspond $R < 1$ while sheath storms have a tendency to have $R > 1$ (68%). In addition, Figure 3. shows that all largest R values correspond sheath storms and that the standard deviation is considerably larger for sheath storms than for magnetic cloud storms.

[11] Figure 4 (left) shows the IMF north-south component (B_Z) and solar wind dynamic pressure measured by ACE as well as magnetic indices during a sheath driven magnetic storm on August 17–18, 2001. At this time ACE was located about 240 R_E upstream of the Earth. We have sifted the data by 50 minutes to present conditions at the magnetopause using the average solar wind speed 510 km/s during the event. The strong interplanetary shock hit the magnetopause on August 17, at 11:06 UT. The B_Z displayed irregular behavior downstream of the shock and solar wind dynamic pressure reached values as high as 40 nPa. The auroral activity (4d) became intense immediately after the shock arrival at the magnetopause and remained at high levels for 10 hours. During the main phase of this storm *ASYH* developed with deep excursions that are associated with strong auroral activity.

[12] Figure 4 (right) gives the corresponding observations for a magnetic cloud associated storm on October 31 – November 1, 2001. Now ACE was located 215 R_E from the Earth and the solar wind speed was 380 km/s yielding the time delay of 60 minutes. The shock arrived at the magnetopause at 13:55 UT on October 31 and the front boundary of the magnetic cloud reached the magnetopause at 21:20 UT. In the sheath (the region bounded by dashed and solid lines in the left part of Figure 4) IMF was only slightly southward, and thus for this event no significant geomagnetic activity occurred during the sheath region. IMF turned strongly southward at the front boundary of the magnetic cloud and remained southward for about a day. As a consequence *Dst* was depressed for several hours. During the main phase the disturbance field was less variable than during the sheath storm and the symmetric component dominated. For this storm the *Dst* minimum was about the same as for the August 2001 storm (−105 nT and −106 nT respectively), but the comparison of 4d and 4h show that the auroral activity

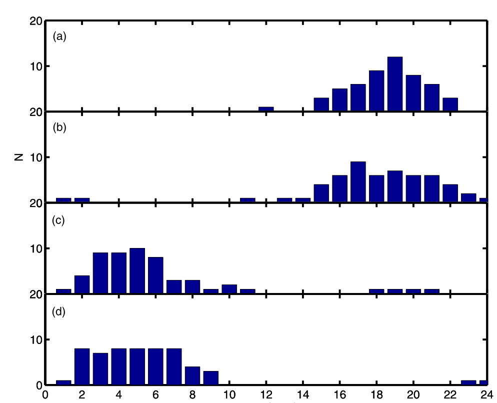

Figure 1. Magnetic local time of the station that gave the (a, b) largest and (c, d) smallest contribution to the *Dst* index. Figures 1a and 1c describe the sheath-associated storms, Figures 1b and 1d the magnetic cloud-associated storms. A four hour time interval before the *Dst* minimum for each storm has been considered.

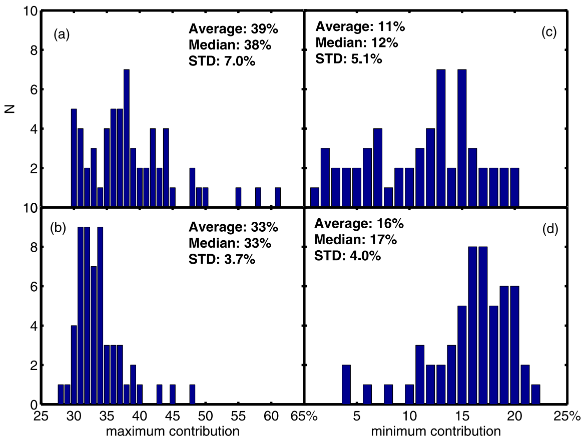

Figure 2. The contribution (a, b) from D_{max} and (c, d) from D_{min} to the *Dst* index. Figures 2a and 2c describe the sheath-associated storms, Figures 2b and 2d the magnetic cloud-associated storms. A four hour time interval before the *Dst* minimum for each storm has been considered. Average, median and standard deviation (STD) are given in each plot.

was considerably more intense during the sheath storm than the magnetic cloud storm.

3. Discussion and Conclusions

[13] In this study we have investigated the evolution of the low-latitude geomagnetic field during the main phases of 28 intense magnetic storms whose solar wind driver was either a sheath region or a magnetic cloud.

[14] By comparing the measurements at the individual *Dst* stations we found that the intensity of the low-latitude disturbance field clearly depends on local time. The largest contribution to *Dst* comes from the station that is located in the dusk sector while the smallest disturbance field is centered around dawn. This result is consistent with previous simulation studies and direct satellite measurements [e.g., *Lui et al.*, 1987; *Takalo and Mursula*, 2001; *Kozyra et al.*, 2002; *Le et al.*, 2004]. Although the low-latitude geomagnetic field evidently developed differently at different local times during all investigated storms, sheath regions were associated with larger afternoon/morning asymmetry than magnetic clouds. On the average, for sheath storms the station in the evening sector contributed to *Dst* almost four times as much as the station in the morning sector. For magnetic cloud associated storms the disturbance field on the dusk was on average only about twice as large as the disturbance field in the dawn.

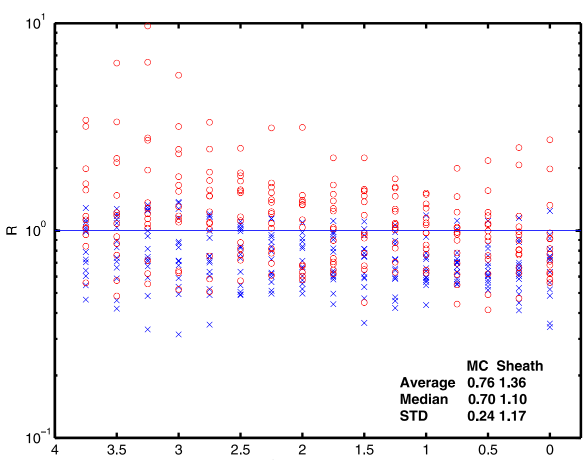

Figure 3. |ASYH|/|SYMH| during 14 sheath (red circles) and 14 magnetic cloud (blue crosses) driven storms (plotted logarithmically). Average, median and standard deviation (STD) for magnetic cloud (MC) and sheath data sets are given in the lower right hand corner.

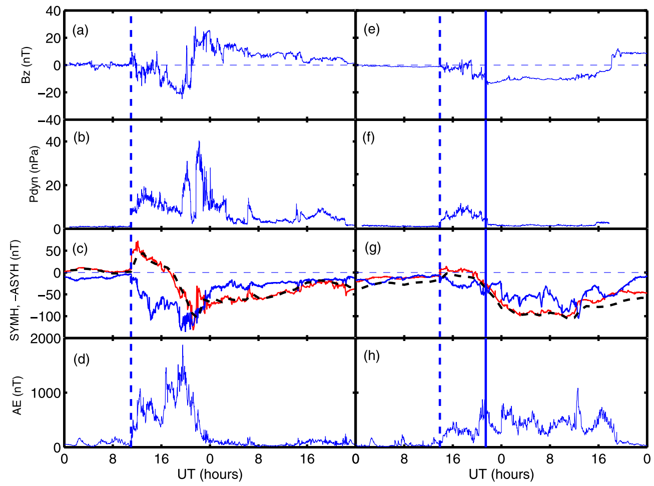

Figure 4. Examples of (left) a sheath storm on August 17–18, 2001 and (right) a magnetic cloud storm on October 31 - Nov 1, 2001. The plots show (a, e) the IMF *Z*-component in the GSM coordinate system, (b, f) solar wind dynamic pressure measured by ACE: *SYMH* (red), -*ASYH* (blue), (c, g) the *Dst* index (black dash-dotted line), and (d, h) the *AE* index from Kyoto World Data Center. The dashed (solid) line indicates the arrival time of the shock (magnetic cloud) at the magnetopause.

[15] The evolution of *SYMH* and *ASYH* indices during the selected storms showed clear differences between magnetic cloud storms and sheath storms. When a sheath drives a storm the asymmetric component (*ASYH*) dominates the symmetric component (*SYMH*) while for most magnetic cloud storms it is vice versa. In addition, throughout the main phase of a sheath storm the asymmetry of the disturbance field is strongly variable, as *ASYH* develops with large excursions related with the auroral activity.

[16] The magnetosphere can respond in several different ways to solar wind driving depending in the first place on how the interplanetary magnetic field changes in time. The prolonged periods of southward magnetic fields within a cloud cause intervals of continuous dissipation of the solar wind energy without remarkable configurational changes in the magnetosphere [*Tanskanen et al.*, 2005]. In fact, a lack of substorm expansion phases for long time periods during several magnetic cloud-driven storms has been reported [*Tsurutani et al.*, 2004]. As a consequence, in the main phase of a magnetic cloud driven storm the asymmetry is mainly attributed to the plasma sheet ions drifting under a steady convection electric field around the dusk side of the Earth and out through the dayside magnetopause.

[17] A rapidly varying magnetic field direction and high dynamic pressure in a sheath lead to very different magnetospheric dynamics than a slowly varying magnetic field and low dynamic pressure within a cloud. In a sheath magnetic field typically fluctuates several times from the south to the north that effectively triggers substorm expansion phases. In addition to ions on open drift paths the sudden intensifications of the substorm associated current systems play an important role in producing the observed afternoon/morning asymmetry. The characteristic timescales of the substorm current systems are short when compared to the timescale of a global convection electric field provided by a magnetic cloud. The sudden enhancements of these current systems would explain the observed strong variation in the low-latitude geomagnetic field during sheath storms.

[18] Our study demonstrates that the dominant sources producing the asymmetric low-latitude disturbance field are different during magnetic cloud storms and sheath storms. This is important to keep in mind when using *Dst* as a measure of magnetic activity. The *Dst* index aims to display the ring current intensity, but particularly during sheath storms the contribution from other current systems to *Dst* may be significant. Studying the *Dst* index only is likely to give an incorrect picture of the magnetospheric response to solar wind drivers.

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