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Geomagnetic response to magnetic clouds of different polarity

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Abstract. The polarity of a magnetic cloud refers to its changing magnetic field direction. It is classified as S-N polarity when the magnetic field rotates from southward to northward and N-S polarity when the field is initially northward and rotates southward. A study of 29 magnetic cloud events has found that 40-45% of magnetic clouds, independent of polarity, are followed by a fast solar wind stream which compresses the tail end of the cloud. The compression results in an increase in the solar wind plasma density and in 64% of the cases an increase in the magnetic field strength towards the latter part of the cloud. Such tail end compression can have a significant effect upon geomagnetic storm intensity if the magnetic cloud is of N-S polarity. This is because only in the N-S polarity case does the compression coincide with the southward IMF portion of the cloud. To test the "geoeffectiveness" of N-S versus S-N magnetic clouds three selected magnetic cloud events, two of S-N polarity and one of N-S polarity, are investigated in terms of their geomagnetic response through measured and estimated D_{st} values. It is found that there is an increased geoeffectiveness of N-S polarity clouds due to both an increased solar wind dynamic pressure and a compressed southward field associated with a following fast solar wind stream.

Introduction

A Magnetic cloud is a solar wind structure characterized by a strong, usually smooth magnetic field and a low plasma temperature and Beta. The magnetic field in a cloud often rotates through a large angle from strongly southward to northward (S-N) or vice-versa (N-S). Studies of their solar origin have shown close associations with coronal mass ejections (CMEs) and disappearing H-alpha filaments [*Bothmer and Rust*, 1997]. It is now well known that magnetic clouds in the interplanetary medium can produce large geomagnetic storms when they pass by the Earth [*Zhang and Burlaga*, 1988].

The polarity of magnetic clouds has been linked to the sun's global magnetic polarity and thus varies with the solar cycle [*Bothmer and Rust*, 1997]. S-N clouds occur most often during the period between even and odd solar maxima while N-S clouds occur most often between odd and even solar maxima. Currently, we are between even and odd solar maxima and so S-N clouds are presently the most common type. In recent observations of magnetic clouds such as the January 10-11, 1997 event it has been observed that a large trailing density enhancement near the end of the magnetic cloud is a relatively common feature. Such a large density could have a potential significant effect upon the magnetosphere particularly if it occurs simultaneously with a large southward IMF as it would in the case of a N-S cloud. In this paper we investigate a total of 29 magnetic cloud events to determine how common a large trailing density is and what causes it. We then look at three of these events in detail to see how a trailing density enhancement can affect the geomagnetic response of a magnetic cloud as a function of its polarity.

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Occurrence of Trailing Density Enhancement

To get a reasonable estimate of the occurrence frequency of the trailing density enhancement a large sample of magnetic clouds is required. *Bothmer and Rust* [1997] have investigated the field structure of 67 magnetic clouds (33 N-S and 34 S-N) for the years 1965-1993 using the OMNI-database. Our own investigation of these same events using the OMNI-database yielded only 27 events for which the plasma data was continuous enough to determine whether or not a trailing density enhancement existed. Within this set of 27 events, plus two additional recent events, there were 8 out of 18 S-N clouds and 5 out of 11 N-S clouds which had a large trailing density. Thus the occurrence rate of the trailing density enhancement is approximately 40-45%, independent of cloud polarity.

In all cases the enhanced trailing density was associated with a fast solar wind stream following the magnetic cloud. In addition 64% of those clouds with a trailing density enhancement also showed an increase in magnetic field strength at the same time. On the other hand, those clouds with no trailing density enhancement also had no following fast stream and exhibited a decreasing magnetic field in the latter part of the cloud. Thus the amount of plasma and magnetic field compression at the end of a magnetic cloud depends upon the structure of the background solar wind stream within which the cloud is embedded. Large Variations in flow speed are characteristic of the solar wind stream structure when the solar magnetic dipole is tilted relative to the solar rotation axis [*Gosling*, 1996] bringing polar coronal hole flows to low latitudes. Substantial quadrupole contributions to the solar field can also produce this effect.

Given the occurrence rate of fast solar wind streams following magnetic clouds it is very important to determine what effect the tail end compression has upon the geomagnetic response. To this end three magnetic cloud events, shown in Figures 1, 2 and 3, have been selected and analyzed in terms of their D_{st} response. Figure 1 and Figure 2 are of S-N polarity while Figure 3 is of N-S polarity. The three events were chosen for their ideal magnetic cloud sig-

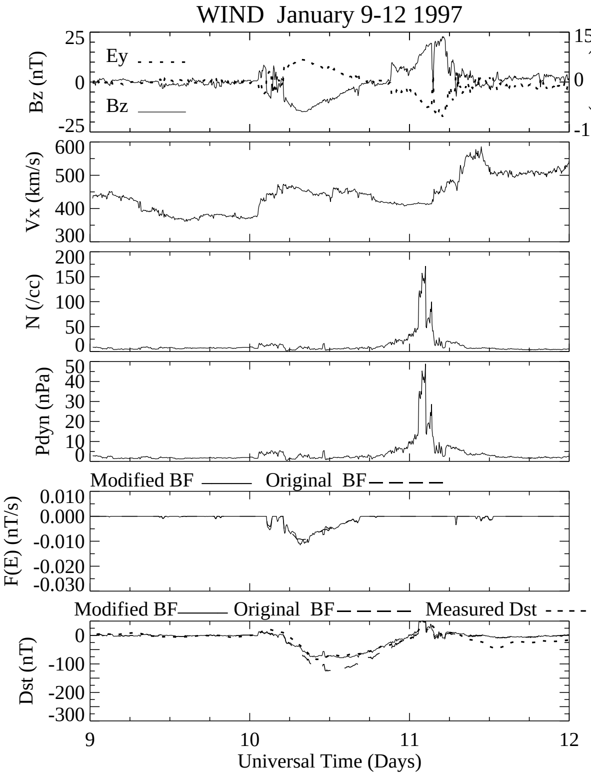

Figure 1. Solar wind and D_{st} parameters for the January 9-11, 1997 magnetic cloud event. Both the original and modified versions of the Burton Formula (BF) ring current injection rate, *F(E)*, and D_{st} estimate are shown.

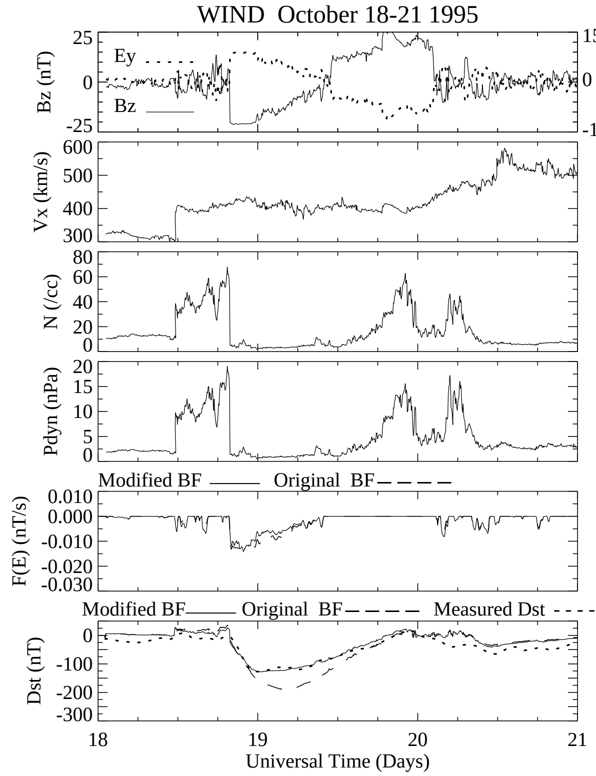

Figure 2. Solar wind and D_{st} parameters for the October 18-21, 1995 magnetic cloud event. Both the original and modified versions of the Burton Formula (BF) ring current injection rate, *F(E)*, and D_{st} estimate are shown.

natures which include slow, steady magnetic field rotation preceded by a forward shock region of high pressure. All three magnetic cloud events are followed by a fast solar wind stream and thus exhibit the trailing density and magnetic field enhancements.

Geomagnetic Response

The interaction of a magnetic cloud with the Earth can produce a large geomagnetic storm, the size of which can be measured by the change in the D_{st} index. The D_{st} index is a measure of the average horizontal component of the geomagnetic field measured at mid-latitude and equatorial stations around the world. Negative changes to the D_{st} are caused by an enhanced ring current, and therefore larger negative D_{st} values indicate a more intense magnetic storm. The measured D_{st} for each of the events is shown in the bottom panel of Figures 1-3. Also shown are estimates of the D_{st} measurements. These estimates are made using both the original and a modified version of the formula derived by *Burton et al.* [1975]. Burton et al. found that the D_{st} could be predicted quite successfully using the following formula.

$$\frac{d(D^*_{st})}{dt} = F(E) - aD^*_{st} \qquad (1)$$

where

$$D^*_{st} = D_{st} - b\sqrt{P_{dyn}} + c \qquad (2)$$

and

$$F(E) = 0, \qquad E_y < 0.5\ mV/m \qquad (3)$$

$$F(E) = d(E_y - 0.5), \quad E_y > 0.5\ mV/m \qquad (4)$$

with

$$a = 3.6 \times 10^{-5}\ \ s^{-1}$$

$$b = .20\ \ nT/\sqrt{eV/cm^3}$$

$$c = 20\ \ nT$$

$$d = -1.5 \times 10^{-3}\ \ nT/(smV/m)$$

In the above equation D^*_{st} is the change to D_{st} from only the injected ring current. The constant b is a measure of the D_{st} response to solar wind dynamic pressure (P_{dyn}), while c is a measure of the quiet time ring current. *F(E)* is the ring current injection rate and only depends upon the dawn to dusk solar wind electric field, E_y, which is given by $-(\mathbf{VxB})_y$, $\mathbf{V}$ being the solar wind velocity and $\mathbf{B}$ the solar wind magnetic field. The constant d is a measure of the response of the injection rate to E_y which is assumed to be linear, and the parameter a is a measure of ring current decay, the value of which corresponds to an e-folding time of 7.7 hours.

To obtain better D_{st} estimates two modifications to the above formula are made. First, the injection function *F(E)* is modified to be dependent upon the solar wind dynamic pressure as well as E_y. This modification is based upon the study done by *Murayama* [1982] which found better correlation between estimated and measured D_{st} when the injection

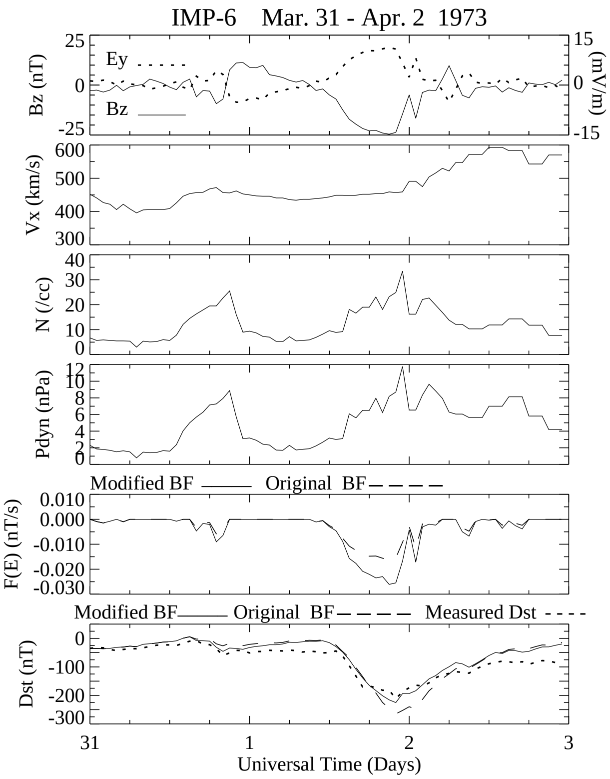

Figure 3. Solar wind and D_{st} parameters for the March 31 - April 2, 1973 magnetic cloud event. Both the original and modified versions of the Burton Formula (BF) ring current injection rate, *F(E)*, and D_{st} estimate are shown.

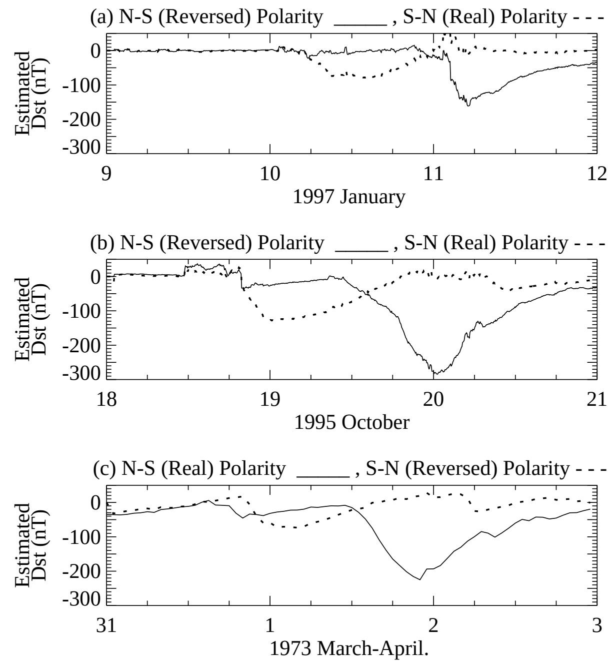

Figure 4. Modified Burton Formula D_{st} estimates corresponding to real and reversed polarity magnetic clouds during (a) the January 1997 event, (b) the October, 1995 event, and (c) the March-April, 1973 event. The reversed polarity estimates are determined by reversing the sign of Bz and recalculating the D_{st} estimate. For each event the N-S polarity D_{st} estimate is plotted as a solid line and the S-N polarity estimate is plotted as a short dashed line.

function was of the form $E_y(P_{dyn})^{1/3}$. Thus the injection function used is

$$F(E) = d'(P_{dyn})^{1/3}(Ey - 0.5), \qquad (5)$$

where $d' = -1.2 \times 10^{-3}\ nT/(smV/m)$ is chosen such that $d'(P_{dyn})^{1/3}$ is consistent with Burton et al.'s d value for the case where P_{dyn} is a typical 2 nPa.

The second modification is in the ring current decay parameter, a. *Feldstein* [1992] presented a summary of numerous studies of ring current decay and found that variations in a during a single storm must be taken into account. The value of a depends upon geocentric distance, ion composition and ion energy of the ring current which can vary substantially between the main phase and the recovery phase of the storm. Numerous authors [*eg. Feldstein et al.*, 1984] found improved D_{st} estimates by using faster decay rates during the main phase of storms. Thus for the modified Burton formula we use a decay rate corresponding to an e-folding time of 3 or 5 hours (whichever produced the best fit) during the main phase of the storm when E_y is greater than 4 mV/m and an e-folding time of 7.7 hours for the remainder of the event.

In the last panel of Figures 1-3 the modified Burton Formula provides a much better estimate of the D_{st} than the original Burton Formula. This indicates that during storms the ring current decay is indeed bi-exponential and also that the ring current injection rate increases during periods of enhanced solar wind dynamic pressure.

For all magnetic cloud events (Figures 1-3) the measured D_{st} exhibits a significant decrease only during the extended periods of southward IMF. Thus the large trailing densities in the two S-N cases (Figures 1 and 2) have little effect upon the storm in terms of the D_{st} response. However, the trailing density enhancement does appear to have a significant effect in the 1973 N-S cloud event (Figure 3) which is indicated by the larger ring current injection rate, *F(E)*, determined using the modified Burton Formula.

The differences in geomagnetic response between the three magnetic cloud events can be seen by comparing the minimum measured D_{st} value in each of the three events, taking into account the strength and duration of solar wind positive E_y in each case. The best comparison is between the 1995 S-N cloud (Figure 2) and the 1973 N-S cloud (Figure 3). Both of these events have approximately the same strength and duration of positive E_y and yet the D_{st} excursion of the S-N cloud, -127 nT, is much less than that of the N-S cloud, -211 nT. The 1997 S-N cloud (Figure 1) is expected to have a smaller D_{st} excursion, -84 nT, due to a weaker E_y. However, the difference in D_{st} between this S-N cloud and the 1973 N-S cloud (Figure 3) is greater than can be attributed to just the difference in E_y. Since the simultaneous occurrence of a trailing density enhancement with the southward IMF period is the only significant difference between the 1973 event (Figure 3) and the other two events, the above comparisons support the conclusion that a density enhancement at the tail end of a N-S cloud can increase the geomagnetic storm intensity.

Figure 4 presents another means of illustrating the potential difference in storm intensity between S-N and N-S clouds. For each of the three magnetic cloud events the figure plots both the D_{st} estimate corresponding to the real polarity and the D_{st} estimate corresponding to the opposite polarity for that particular cloud. Both estimates are calculated using the modified Burton Formula. The D_{st} for the opposite polarity is determined simply by reversing the sign of Bz and recalculating the estimate. In all three cases, the D_{st} depression is not only delayed by approximately one day but is significantly larger for the N-S estimate by as much as a factor of 2 to 3. The large increase in the storm intensity for the N-S polarity estimates is due to two factors: (1) the simultaneous occurrence of increased solar wind dynamic pressure during the southward IMF portion of the magnetic cloud, and (2) a compressed and therefore stronger southward magnetic field towards the end of the cloud. Both of these factors are a result of a fast solar wind stream following the cloud.

Conclusions

A combination of magnetic cloud polarity and solar wind stream structure within which a cloud is embedded can dramatically affect a cloud's geomagnetic response. When a magnetic cloud is followed by a fast solar wind stream the tail end of the cloud becomes compressed resulting in an enhanced plasma density at the end of the cloud and often an increase in magnetic field strength as well. Based upon a set of 29 magnetic cloud events it is found that tail end compression associated with a fast stream occurs in about 40-45% of all clouds, independent of polarity. If a cloud is of S-N polarity the compression is coincident with the northward IMF portion of the cloud and will have little effect in terms of the D_{st} response. However, if the cloud is of N-S polarity the compression is coincident with the southward IMF portion of the cloud and therefore can have a significant effect upon the D_{st} response. An examination of three magnetic cloud events trailed by a fast stream shows that clouds of N-S polarity can generate magnetic storms up to 2 or 3 times more intense than similar S-N clouds. This enhanced geomagnetic response to clouds of N-S polarity is due to both the increase in solar wind dynamic pressure and the larger southward field associated with the tail end compression. For cases where there is no following fast stream and thus no tail end compression, there is no significant difference in the geomagnetic response between N-S and S-N polarity clouds.

The results presented here have very important implications for space weather prediction. A N-S polarity magnetic cloud in combination with a strong, high speed stream structure may be considered a condition with particularly high potential "geoeffectiveness". N-S polarity clouds occur most often between odd and even solar maxima. We should therefore be on the lookout for such an effect after the next solar maximum.

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