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Multiple-step geomagnetic storms and their interplanetary drivers

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[1] While the classic picture of a geomagnetic storm is of a main phase eventually reaching maximum intensity, followed by a recovery, the profile can often be more complex. This has been recognized in past studies that have classified storms as having "one" or "two" "steps" during the main phase. However, the intense ($Dst \leq -100$ nT) storms studied during the LWS CDAW Workshop may be more complicated. We discuss the variety of interplanetary circumstances that gave rise to several storms of varying complexity. **Citation:** Richardson, I. G., and J. Zhang (2008), Multiple-step geomagnetic storms and their interplanetary drivers, *Geophys. Res. Lett.*, *35*, L06S07, doi:10.1029/2007GL032025.

1. Introduction

[2] The classic description of a geomagnetic storm (as measured for example by the *Dst* index) is that it undergoes a "main phase", eventually reaching maximum intensity, and then recovers to pre-storm levels. However, *Kamide et al.* [1998] recognized that a significant fraction of storms show more complicated structures. In particular, they concluded that there is a "distinct class of two-step main phase storms". To identify such storms, *Kamide et al.* [1998] used the criteria that the intervening recovery should not exceed 90% of the first peak (otherwise the peaks would be treated as separate storms), and that the peaks should be separated by >3 hours (to remove dips due to what they consider may be "substorm effects"), while recognizing that some storms with closer-spaced peaks will not be identified by this scheme. They concluded that ~67% of intense storms ($Dst \leq -100$ nT) in their sample developed in a two-step fashion, characterized by a second, usually larger, decrease in *Dst*, compared with ~29% with simple (one-step) growth in *Dst*. Remarkably, only ~4% could not be classified as either one- or two-step. They suggested that the superposition of two moderate storms may give rise to an intense storm.

[3] In examining the intense storms studied by the LWS CDAW workshop [*Richardson et al.*, 2006; *Zhang et al.*, 2007] (see also http://cdaw.gsfc.nasa.gov/geomag_cdaw/), we treated peaks in (negative) *Dst* separated by more than 24 hours as individual storms. Examination of these storms indicates that they may have not only one or two but also larger numbers of steps. These steps are clearly associated with intermittent regions of enhanced southward magnetic field (and hence the cross-tail electric field E_y) in the driving solar wind, separated by less geoeffective solar wind. We suggest that the expectation that storms have predominantly either "one" or "two" steps is over simplistic, and misses some of the complexity in many events. We illustrate several storms with various numbers of steps from among the CDAW workshop events, and discuss briefly the variety of solar wind drivers that gave rise to these steps.

2. Observations

[4] Figure 1 shows the *Dst* index (top panel) and various near-Earth solar wind magnetic field and plasma parameters (from the 1- minute averaged OMNI database as described in Figure 1 caption) for an example of a clear two-step storm (March 20, 2001) that had a minimum $Dst = -149$ nT. The peak of the storm is driven by prolonged southward fields ($B_z < 0$) in a magnetic cloud (indicated by gray shading; note the characteristic enhanced magnetic field showing a slow rotation through a large angle, e.g., *Klein and Burlaga* [1982]) while the first dip ($Dst = -105$ nT) is associated with southward fields in the sheath upstream of the magnetic cloud and within the leading edge of the magnetic cloud. The leading edge of the sheath is bounded by a shock (solid green vertical line; there are data gaps in the vicinity of the shock). See, e.g., *O'Brien and McPherron* [2000], for discussion of the relationship between *Dst* and parameters of the solar wind encountering the Earth. The *Dst* steps and the corresponding intervals of southward magnetic field are indicated by arrows. This event illustrates one of the interplanetary situations discussed by *Kamide et al.* [1998] that might give rise to two-step storms, namely southward magnetic fields in the sheath followed by a later region of southward fields in a magnetic cloud.

[5] Figure 2 shows a storm (April 18, 2002; minimum $Dst = -127$ nT) also associated with a magnetic cloud and the upstream sheath of compressed solar wind. Overall, the gross features of the storm in *Dst* may again be characterized as two-step. The first step ($Dst = -98$ nT) is driven by variable, though predominantly southward, magnetic fields in the sheath, the second by prolonged southward fields in the magnetic cloud. However, close inspection of B_z and *Dst* suggests that there are smaller scale variations in *Dst* that are apparently related to the properties of the solar wind driver. In particular, during the "first step", there are three dips and an interruption in the recovery of *Dst* (indicated by arrows) that appear to be associated (with a small time delay) with the four regions of southward field (also indicated by arrows) in the solar wind immediately upstream of the shock and in the sheath. Although these dips barely meet the >3 hour peak separation criterion of *Kamide et al.* [1998], they are nevertheless features of this storm

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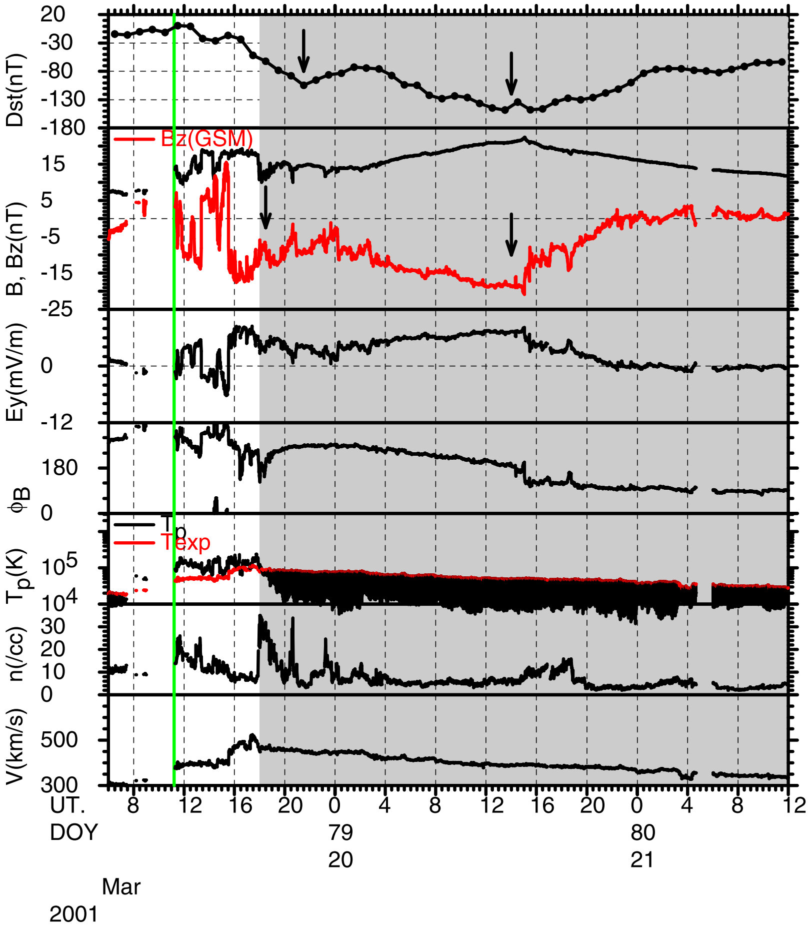

Figure 1. Interplanetary parameters associated with the geomagnetic storm of March 20, 2001, indicated by the *Dst* index in the top panel. Other panels show the magnetic field intensity and *Z* component (GSM coordinates), the *Y* component of the electric field, magnetic field azimuth (GSE coordinates), solar wind proton temperature (T_p), density, and speed. Over plotted on T_p is the expected value (T_{ex}) of T_p for normal solar wind [e.g., *Richardson and Cane*, 1995]. Black shaded regions indicate where $T_p < 0.5T_{ex}$, a typical indicator of the presence of interplanetary coronal mass ejections (ICMEs) including magnetic clouds (see *Zurbuchen and Richardson* [2006] for a recent review of the signatures of ICMEs and magnetic clouds). This two-step storm is associated with southward fields in the sheath (with a shock, indicated by solid green vertical line, at the leading edge) ahead of a magnetic cloud, and by southward fields in the magnetic cloud; gray shading indicates the magnetic cloud.

which arise from the properties of the solar wind driver. They are also comparable in size to the dips in the example events illustrated by *Kamide et al.* [1998]. There are also two brief dips around the peak of the storm, though there are no clearly-associated features in the solar wind parameters illustrated.

[6] A more complicated storm (October 5, 2000), with more than two main steps, is shown in Figure 3. This storm is associated with a shock (on October 5) plowing into the trailing edge of a magnetic cloud that passed the Earth on October 3–5 (gray shaded region). There are at least 3 main dips in *Dst* (indicated by arrows). The first of these dips, which at *Dst* = −143 nT exceeds the intense storm threshold in its own right, is associated with southward-directed fields in the trailing edge of the magnetic cloud. As the shock compresses the magnetic cloud trailing edge, southward fields are intensified. The next dip in *Dst* (to −175 nT) is the result, and this is followed by a rapid recovery as the sheath fields turn strongly northward. Finally, storm maximum (*Dst* = −182 nT) is associated with another region of southward fields that is probably also in the sheath. Thus again, this storm consists of a series of elements that reflect specific features in the solar wind driver; it is not adequate to classify the storm as only one or two step. We also note that this ensemble of solar wind structures produced an earlier dip in *Dst*, on October 3, that is associated with weak southward fields in the shocked plasma ahead of the magnetic cloud. However, this decrease does not attain the *Dst* = −100 nT threshold required for an intense storm.

[7] Figure 4 shows a similar interplanetary situation–a shock plowing into the trailing edge of a magnetic cloud–that in contrast leads only to a single-step storm (on June 26, 1998). The magnetic cloud (shaded gray) passed the Earth on June 24–25, 1998. At about 16 UT on June 25, a shock is evident propagating through the magnetic cloud. In this case, however, the magnetic field inside the trailing edge of the magnetic cloud is pointing strongly northward, and compression of this field by the shock only intensifies the

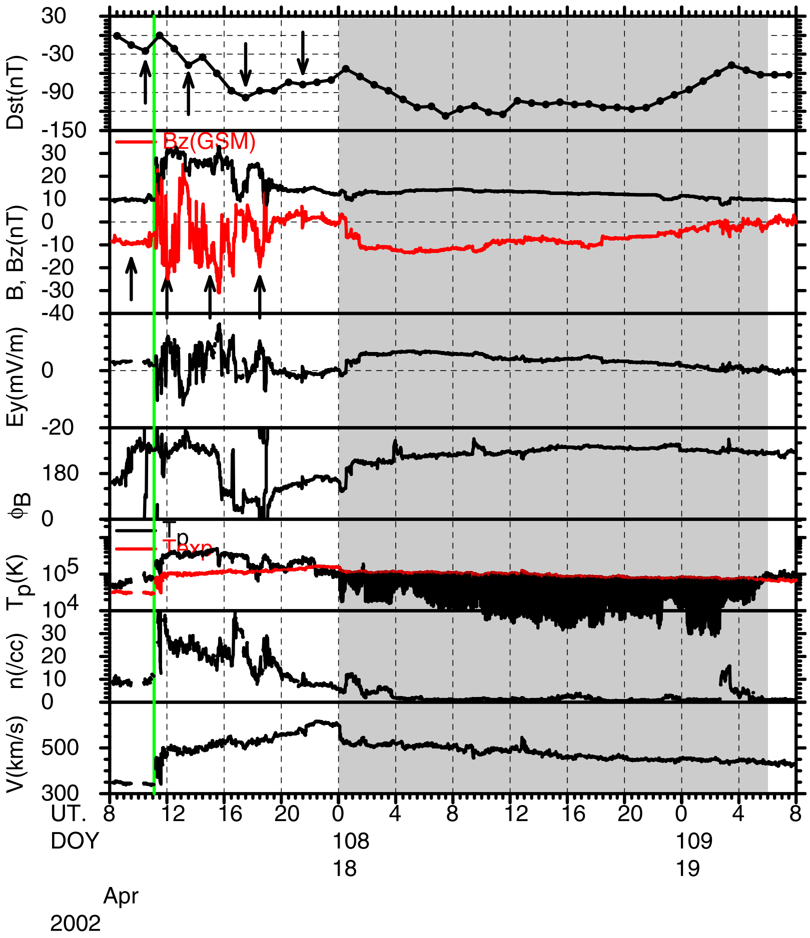

Figure 2. Interplanetary parameters associated with the geomagnetic storm of April 18, 2002. This storm is associated with an extended interval of southward fields in the leading edge a magnetic cloud (gray shading) and variable but predominantly strong southward fields in the upstream sheath with a shock at the leading edge. Arrows indicate small dips in *Dst* and the corresponding intervals of strong southward fields.

northward field. Hence, there is no storm activity associated with this particular shock-magnetic cloud interaction. The storm results from a single region of enhanced southward field following the shock. We suggest that this southward field region is probably inside the ICME driving this shock, although the boundary between the ICME and the upstream sheath (composed of shocked magnetic cloud material) is difficult to decern.

3. Summary and Discussion

[8] The intense geomagnetic storms during 1996–2005 studied during the LWS CDAW workshop show a wide range of levels of complexity in the *Dst*-time profiles. We conclude that:

[9] (1) While *Kamide et al.* [1998] concluded that the vast majority of storms may be divided into one or two step storms, more complicated cases do occur, as also recognized by *Gonzalez et al.* [2002] who show examples from previous solar cycles. Because *Kamide et al.* [1998] set no criteria for a minimum size, estimating the numbers of steps or dips in each event is somewhat subjective. Considering the workshop storms, we estimate that around 59% may be classified as having predominantly one step, a significantly larger fraction than the 29% found by *Kamide et al.* [1998]. However, estimation of the number of steps depends on whether modest dips (as in one of the examples of two-step storms illustrated by *Kamide et al.* [1998]) are taken into consideration, or whether only the overall "envelope" of the storm is considered. Interpretation of the *Dst* profile alongside the profile of B_s or E_y in the concurrent solar wind data may help to infer the number of dips that are present.

[10] (2) Minor, often closely spaced in time, steps in *Dst* are clearly related to multiple intervals of southward magnetic field separated by less geoeffective conditions in the solar wind driver. They do not appear to be generated by magnetospheric processes following a single element storm driver, a possibility raised by *Kamide et al.* [1998].

[11] (3) It is important to emphasize that the number of peaks in *Dst* is not necessarily directly related to the number of interplanetary transients that are involved in generating the storm. For example, the double-peak storm in Figure 1 arises from a single magnetic cloud including southward magnetic fields and the related upstream sheath that also contains southward fields; only one transient is involved in producing this storm. The storm in Figure 4 occurs in the vicinity of the interaction of a shock with a preceding

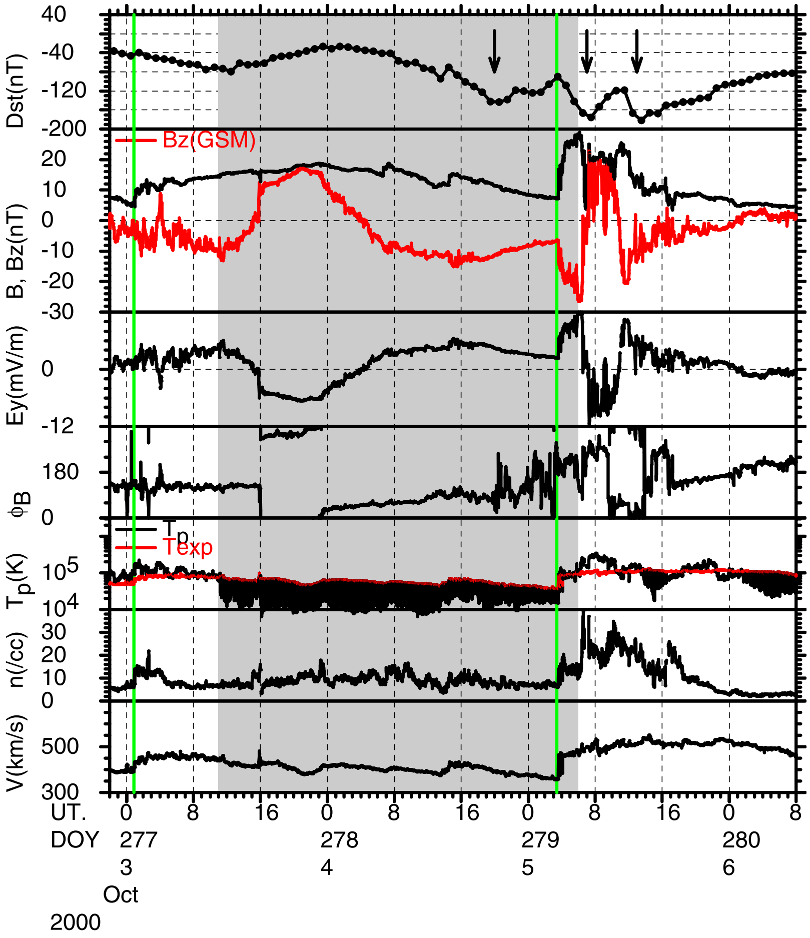

Figure 3. Observations for the geomagnetic storm of October 5, 2000. This storm, associated with a shock running into the trailing edge of a preceding magnetic cloud, has at least three distinct dips, associated with the magnetic cloud, shock compressed magnetic cloud, and southward fields in the post-shock sheath.

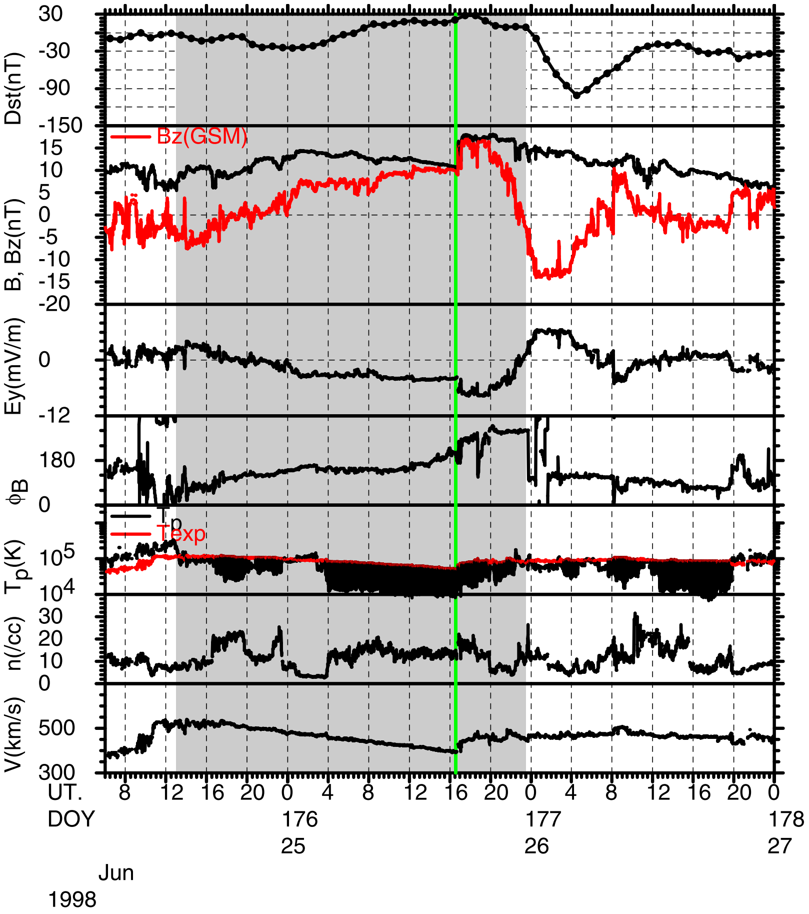

Figure 4. Observations for the geomagnetic storm of June 26, 1998. As in Figure 3, a shock runs into the trailing edge of a preceding magnetic cloud, but in this case, the field is northward and not geoeffective. The storm is associated with southward fields that are probably within the ICME driving the shock.

magnetic cloud (i.e., two transients are involved), but only a single-step storm results. In contrast, the storm in Figure 3 occurs in a similar situation, but this time, the storm includes at least 3 dips.

[12] In conclusion, we suggest that the one- or two- step classification of *Kamide et al.* [1998], while recognizing the complexity of many geomagnetic storms, does not adequately summarize the even more complex profiles of some intense storms in cycle 23. In a paper in preparation, we will make a statistical study of the profiles and related interplanetary drivers for all the CDAW Workshop storms.

[13] **Acknowledgments.** We acknowledge the use of data from the OMNI solar wind data base, compiled by the Space Physics Data Facility at the Goddard Space Flight Center (http://omniweb.gsfc.nasa.gov/).

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