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What is a geomagnetic storm?

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Abstract. After a brief review of magnetospheric and interplanetary phenomena for intervals with enhanced solar wind-magnetosphere interaction, an attempt is made to define a geomagnetic storm as an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system, to an intensified ring current sufficiently strong to exceed some key threshold of the quantifying storm time *Dst* index. The associated storm/substorm relationship problem is also reviewed. Although the physics of this relationship does not seem to be fully understood at this time, basic and fairly well established mechanisms of this relationship are presented and discussed. Finally, toward the advancement of geomagnetic storm research, some recommendations are given concerning future improvements in monitoring existing geomagnetic indices as well as the solar wind near Earth.

1. Introduction

The importance of studying geomagnetic storms is basically twofold. One refers to their academic aspect of being considered a central part of geophysics. The other involves practical aspects that in some cases can represent a particular concern for mankind.

For 30 years or more magnetospheric scientists have been studying storms under the simple assumption (originally proposed by Sydney Chapman) that storms are simply a collection of substorms and that by understanding the "unit" of fundamental energy injection, one could understand the whole.

New interest in understanding such a classical assumption for the definition of the geomagnetic storm and of its relationship to substorms has been recently pursued [e.g., *Kamide,* 1992; *Feldstein,* 1992]. The main reason behind such an interest is our modern knowledge of magnetospheric physics using spacecraft, as compared to older epochs when most of that knowledge had to come from ground observations. In addition, past attempts to formulate definitions for storms were restricted only to the near-Earth environment, the ionosphere and magnetosphere. However, with the subsequent accumulation of information obtained in the interplanetary medium, critical aspects of these definitions now involve diverse findings related to the solar wind dynamics [e.g., *Burton et al.,* 1975; *Gonzalez and Tsurutani,* 1987; *Tsurutani and Gonzalez,* 1987].

Motivated by an interest in trying to find unifying concepts about the geomagnetic storm and the long-standing problem of storm/substorm relationship, the authors of this review paper met at the National Institute for Space Research of Brazil (INPE), at São José dos Campos, São Paulo, during the interval of November 5–8, 1991. The results obtained in this meeting, together with further elaboration, are presented in this paper in the following sequence.

Section 2 is devoted to historical aspects of geomagnetic storm research, as based on ionospheric and magnetospheric parameters. In section 3 the interplanetary origin of storms is addressed. A brief review follows on solar wind-magnetosphere coupling, particularly applied to storm intervals. Then, for completeness, the seasonal and solar cycle distribution of storms is briefly considered. Section 4 reviews basic aspects of the storm/substorm relationship problem. In section 5, a discussion about additional mechanisms that contribute to ring current intensification as well as about basic mechanisms for ring current decay is given. A brief review on the relationship of *Dst* to other geomagnetic indices follows. Section 6 gives summary concepts on geomagnetic storms and on their relationship to substorms. A definition for a geomagnetic storm is suggested. Finally, in section 7 recommendations con-

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cerning future improvements in monitoring existing geomagnetic indices as well as the solar wind near the Earth are provided.

2. Geomagnetic Storm

2.1. Historical Development and Critique of Existing Definitions

Episodes of extraordinary fluctuations in the Earth's magnetic field were denoted as storms in the mid-1800s. It was recognized that over the major part of Earth, the principal average feature of a magnetic storm is an unmistakable decrease of the horizontal intensity and its subsequent recovery [e.g., *Chapman and Bartels,* 1940]. This decrease in intensity is now known to be due to an enhancement of the trapped magnetospheric particle population. Drifts due to magnetic field gradient and curvature as well as to gyration orbit effects lead to the ions moving from midnight toward dusk and electrons from midnight toward dawn, giving an overall ring of current. A comprehensive analysis of storm morphology was undertaken by *Sugiura and Chapman* [1960], who assigned a numerical intensity index to individual storms by measuring the difference in daily mean values of the horizontal field at 26 mostly middle and low geomagnetic latitude observatories. On the basis of this index, they divided their collection of storms into three sets: weak, moderate, and great.

Reorganizing low-latitude ground-based data to measure the intensity of the ring current, *Sugiura* [1964] published hourly values of the average global variation of the low-latitude *H* component (*H*, *D*, and *Z* are the vector components of the magnetic field at ground-based observatories: *H*, horizontal; *Z*, vertical; and *D*, the dip-angle between the field vector and *H*) for the International Geophysical Years. This index, called *Dst*, has been continued since then and is presently compiled by the World Data Center C for Geomagnetism in Kyoto, Japan. IAGA Bulletin 40 [*Sugiura and Kamei,* 1991] contains hourly and summary *Dst* values from 1957 to 1986. The *Dst* index for July 12–16, 1982, shows the largest storm during solar cycle 21. This is plotted in Figure 1, in which the relatively sharp decrease in the *H* component and the subsequent slow recovery are clearly seen. The principal characteristic of a geomagnetic storm-*Dst* representation is the "main phase" (see below), namely, the interval of large decrease of *Dst*.

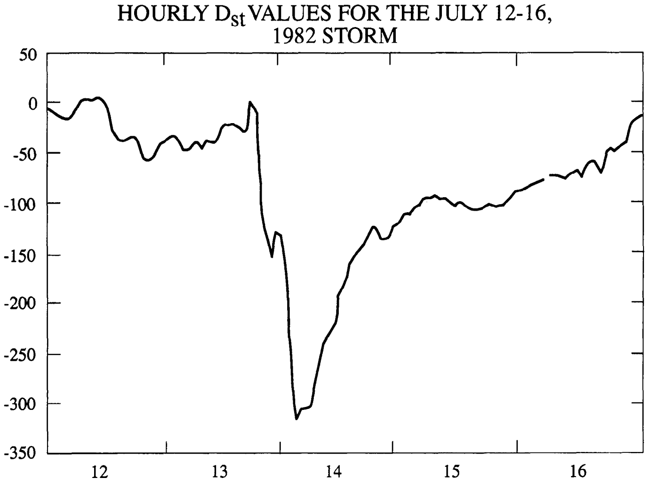

Figure 1. Great magnetic storm of July 12–16, 1982. The solar wind-pressure corrected Dst^* reached peak values around -440 nT.

Early studies of the ionosphere suggested that the level of disturbance of the geomagnetic field was a useful proxy for the level of disturbance of other geospace phenomena. For example, *Matsushita* [1959] studied ionospheric storms by selecting intervals of geomagnetic disturbance based on the *Ap* index (see below); if *Ap* was 50 or more, the geomagnetic storm was "strong." Similar but nonstandarized rules for identifying storms continue to the present. Geomagnetic activity is classified by size usually depending on a variety of summaries of the *K* index, a number between 0 and 9 scaled from the range of observed fluctuations that indicates the level of disturbance in a given 3-hour interval of the universal time day [e.g., *Rostoker,* 1972; *Menvielle and Berthelier,* 1991]. The *A* index is a 24-hour average of converted *K* index readings with a range from 0–400. A global composite of *K* and *A* indices, the *Kp* and *Ap* indices, have been made available since 1932 by the Institute of Geophysics in Gottingen, Germany, and are widely used for research and operational purposes. Other composites of global *K* indices, especially the *aa*, *An*, and *As* indices produced by the Centre De Rechearche en Physique de l'Environment-Centre National de la Recherche Scientifique of France, are also useful. (For a description of various geomagnetic indices, see, *Mayaud* [1980]). *K* index variations are difficult to interpret physically because they can be caused by any geophysical current system including magnetopause currents, field-aligned currents, and the auroral electrojets. Nevertheless, the *Kp* indices for the evaluation of activity have been more widely used than *Dst* because they are generally available in final form only a few weeks after the date of observation. *Dst* requires more analysis to produce and at times has been delayed by years. However, this time delay is not intrinsic to the index, and modern magnetometer observations and communication methods permit *Dst* to be evaluated in near real time.

Some geomagnetic storms, especially the largest ones, begin with a sudden impulse which signals the arrival of an interplanetary shock structure. This generally coincides with the onset of a period of increased ram pressure (the initial phase) that is followed by sustained southward interplanetary fields (the main phase) and then by a return to normal conditions (the recovery phase). Such sudden impulses preceding geomagnetic storms are called storm sudden commencements; these events are cataloged in Solar Geophysical Data (published monthly), and IAGA Bulletin 32. Lists of SSCs have been used as proxies for lists of geomagnetic storms. However, such usage is ill-advised because the criteria that determine whether a sudden impulse should be a storm sudden commencement is qualitative and vague. Lenient and inconsistent interpretations of the levels of geomagnetic activity prerequisite for storms have led to confusion in the literature and suggestions to standardize the terminology [*Joselyn and Tsurutani,* 1990; *Kamide and Joselyn,* 1991; *Gonzalez et al.,* 1992]. Because interplanetary shock structures are neither sufficient nor necessary for geomagnetic storm occurrence or development, their presence is not a prerequisite for defining geomagnetic storms.

2.2. *Dst* Index and Magnetospheric Parameters

The principal defining property of a magnetic storm is the creation of an enhanced ring current, formed by ions (most notably by protons and oxygen ions) and electrons in the 10–300 keV energy range, located usually between 2 to 7 R_E and producing a magnetic field disturbance which, at the equator, is opposite in direction to the Earth's dipole field. The strength of this disturbance field is (approximately) given by the Dessler-Parker-Sckopke relationship [*Dessler and Parker,* 1959; *Sckopke,* 1966]:

$$Dst^*(t)/B_0 = 2E(t)/3E_m \qquad (1)$$

where Dst^* is the field decrease due to the ring current, B_0 is the average equatorial surface field, $E(t)$ is the total energy of the ring current particles, and E_m ($= 8 \times 10^{24}$ ergs) is the total magnetic energy of the geomagnetic field outside the Earth. (For a complete review, see *Carovillano and Siscoe* [1973]).

Dst^* is the measured *Dst* value after a correction due to magnetopause currents is made. *Dst* needs to incorporate also a correction factor due to induced currents in the solid earth [e.g., *Langel and Estes,* 1983; *Stern,* 1984]. Other possible contributions to *Dst* from additional (ionospheric, field-aligned, tail, etc.) currents have not been quantified as yet.

With the correction due to magnetopause currents the relation between *Dst* and Dst^* is usually written [e.g., *Burton et al.,* 1975; *Gonzalez et al.,* 1989; *Feldstein,* 1992] as

$$Dst^* = Dst - bp^{1/2} + c,$$

where p is the storm time solar wind ram pressure, obtained as nm^+V^2 (n and V being the solar wind density and speed, respectively, and m^+ the proton mass), b is a proportionality factor, and c is the quiet time solar wind ram pressure contribution. Typically, $b = 0.2$ nT $/(\text{eV cm}^{-3})^{1/2}$ and $c = 20$ nT. During large pressure variations, Dst^* can be considerably different from *Dst*. *Gonzalez* [1992] and *Tsurutani et al.* [1992a] have reported the existence of storm events with more than a 100% difference between Dst^* and *Dst*.

As we can note from equation (1), the field decrease is linearly related to the total energy of the ring current particles. Thus the planetary Dst^* index is used as a practical measure of the total particle energy injected into the inner magnetosphere and hence the intensity of the magnetic storm.

The general relationship of energy balance for the ring current is given by

$$\frac{dE(t)}{dt} = U(t) - E(t)/\tau, \qquad (2)$$

where $U(t)$ is the rate of energy input into the ring current and τ is the decay time. As discussed in section 5, τ is a complex function of several types of loss processes. Using equation (1), equation (2) can be written in terms of Dst^* as

$$\frac{dDst^*(t)}{dt} = Q(t) - Dst^*(t)/\tau \qquad (3)$$

with $Q(t) = 2.5 \times 10^{21} U(t)$ in Gaussian units.

When there is no energy input, as during the (ideal) recovery phase of the storm, equation (2) has the following simple solution:

$$E(t) = E_0 e^{-(t-t_0)/\tau}, \qquad (4)$$

from which one can obtain reasonably accurate values for the decay time τ.

A formal solution for equation (2), or equation (3), can be written as

$$Dst^*(t) = e^{-t/\tau}\left[Dst^*(0) + \int_0^t Q(z) e^{z/\tau} dz\right]. \qquad (5)$$

This solution is particularly useful when the input function Q is known analytically. Otherwise, equation (2) has to be solved numerically as has been done by several authors [e.g., *Burton et al.,* 1975; *Gonzalez et al.,* 1989; *Pisarskij et al.,* 1989]. These authors have assumed that the energy input function can be identified with the magnetospheric energy input as obtained from reconnection at the frontside magnetopause, also known as the "coupling function." A brief review on coupling functions is given in section 3.

One particularly difficult problem that remains unsettled with respect to the solution of equation (3) is that the loss rate parameter τ is as yet poorly known. The ring current particle loss rate depends upon the particle species, energy, pitch angle, and L. The loss rate parameter τ is therefore an average over the whole ring. Clearly, the value of τ is changing continuously during the magnetic storm. However, it has been necessary to attempt to derive an average value for analytical purposes. Some authors [e.g., *Burton et al.,* 1975; *Feldstein et al.*, 1984] have assumed a constant τ for all possible values of *Dst*. More recently, *Vasyliunas* [1987], *Gonzalez et al.* [1989], and *Prigancova and Feldstein* [1992] have suggested that a variable τ needs to be incorporated (note that equations (4) and (5) assume τ constant). Typical τ values of 5 to 10 hours that are common during the recovery phase have been shown not to be appropriate at earlier times, particularly at the peak of the main phase of intense storms for which much shorter decay times, of about 1 hour, need to be adopted. However, decay times as short as 0.5

hour or less do not seem to be appropriate unless the storm is very intense [*Gonzalez et al.*, 1989; *Prigancova and Feldstein,* 1992].

2.3. Classification of Storms by Intensity: The Question of Threshold

By virtue of the name, storms are expected to be extraordinary disturbances. At what level does a disturbance become extraordinary? The range of observed *Dst* is approximately +100 nT to −600 nT. Quiet time (undisturbed) conditions are represented by a *Dst* index of 0, but this is not typical. For example, for the years 1976–1986, the median *Dst* was between −20 nT and −10 nT. The Magsat field analysis, based on quiet days in 1979, suggested a baseline value of about −20 nT. Thus an "enhanced" ring current (negative values of *Dst*) is ordinary and does not necessarily represent storm-level conditions. The distribution of observed hourly values offers some guidance. During 1976–1986, approximately 25% of all values were more negative than −30 nT, approximately 8% were more negative than −50 nT, and approximately 1% were more negative than −100 nT. These convenient breakpoints can be used to place given disturbances in relative context. Following the terminology of Sugiura and Chapman, great (or intense) storms are those with peak *Dst* of −100 nT or less, moderate storms fall between −50 nT and −100 nT, and weak storms are those between −30 nT and −50 nT. For comparison, less than 1% of the *Kp* values were 7 or larger, and less than 10% were 5 or larger.

3. Role of the Interplanetary Medium in the Origin of Storms: The IMF B_S Component

The primary causes of geomagnetic storms at Earth are strong dawn-to-dusk electric fields associated with the passage of southward directed interplanetary magnetic fields, B_S, past the Earth for sufficiently long intervals of time. The solar wind energy transfer mechanism is magnetic reconnection between the IMF and the Earth's magnetic field. The energy transfer efficiency is of the order of 10% during intense magnetic storms [*Gonzalez et al.,* 1989]. Viscous interaction, the other prime energy transfer mechanism proposed, has been shown to be only < 1% efficient during intense northward directed IMFs [*Tsurutani et al.*, 1992a].

The electric field is composed of two factors: the solar wind velocity V and the southward IMF. It has been empirically shown [*Gonzalez and Tsurutani,* 1987] that intense storms with peak $Dst \leq -100$ nT are primarily caused by large $B_S \geq 10$ nT fields with duration greater than 3 hours. Although such high fields are considerably greater than typical field magnitudes in the quiet solar wind (5 nT), [*King,* 1986] and are therefore often associated with greater than average solar wind velocities (high-speed streams), it has been demonstrated that it is the extraordinarily high B_S rather the than high V that is the dominant part of the electric field [*Tsurutani et al.,* 1992b]. As mentioned below, the electric field seems to be modulated by the solar wind ram pressure when such pressure changes become important. Since this pressure term depends on the solar wind density ρ, it has been reported that, besides B_S and V, the factor ρ also plays an important role in the ring current intensification [*Smith et al.*, 1986].

A general relationship between the intensity of the B_S field and its duration, ΔT, as a function of storm intensity, *Dst*, has not been found to date. However, *Gonzalez and Tsurutani* [1987] referring to intense storms with peak $Dst \leq -100$ nT for the interval of 1978–1979, have suggested threshold values of $B_S \geq 10$ nT and $\Delta T \geq 3$ hours. Also, preliminary studies of moderate storms with −100 nT < peak $Dst \leq -50$ nT (for the same interval of 1978–1979), confirm earlier suggestions made by *Russell et al.* [1974] for associated threshold values of $B_S \geq 5$ nT and $\Delta T \geq 2$ hours. Table 1 shows these threshold values at an 80% occurrence level. As stated in this table, the threshold conditions for small storms are equivalent to those expected for typical substorms.

Table 1. (B_z, ΔT) Thresholds for Storms at 80% Occurrence Level (ISEE 3 Interval: August 1978 to December 1979)

	Dst, nT	B_z, nT	ΔT, hours
Intense	−100	−10	3
Moderate	−50	−5	2
Small (typical substorm)	−30	−3	1

3.1. Origins of B_S

The intense interplanetary magnetic fields can be thought of as being associated with essentially two parts of a high-speed stream, the intrinsic fields, and plasma associated with the coronal ejecta (called driver gas fields), and the shocked and compressed fields and plasma due to the collision of the high-speed stream with the slower solar wind preceding it. In the latter case, the compression is related to the strength of the shock and thus to the speed of the high-speed stream relative to the upstream (slow) solar wind. The higher the relative velocity, the stronger the shock and the field compression. If the shock runs into a trailing portion of a high-speed stream, preceding it, exceptionally high magnetic fields may result. So far very few storms from interplanetary events of this type have been reported [*Zhao,* 1992].

Within the driver gas there are sometimes strong N–S magnetic field components. This occurs primarily in the low β plasma region, where the magnetic fields are relatively free of discontinuities and waves and angular changes occur slowly [*Zwickl et al.,* 1983 *Tsurutani et al.,* 1988]. *Choe et al.* [1992] found a beta range of 0.03 to 0.8 with ~ 0.1 typical. This region of space is often characterized by bidirectional electron or proton streaming [*Gosling et al.*, 1987]. It is thought that this field region is only a portion of the driver gas. There may be other regions of the coronal ejecta that have not been identified yet (see *Choe et al.* [1992] concerning an outer He^{++} shell). Only about 10% of driver gases have these large N–S directional variations.

These regions of large N–S field variations are called magnetic clouds, after *Klein and Burlaga* [1982]. A schematic representing this original idea is shown in Figure 2e. Clouds are found not only within high-speed streams but also in the quiet solar wind. A more recent field configuration of magnetic clouds has been proposed by *Marubashi* [1986] and others. This latest idea is that the field configuration is a giant flux rope, with the force-free fields generated by currents flowing along the magnetic axis. The magnetic configuration for the other driver gas events is not known at this time. It is possible that they could have magnetic tongue configurations, that is, long extended fields that are still attached to the Sun, as proposed by *Gold* [1962].

There are a variety of causes of southward IMFs in the high-speed stream sheath region. These are also schematically illustrated in Figure 2. First, if there is a preexisting southward component upstream of the shock, shock compression will intensify this component (Figure 2a). As these fields convect toward the driver gas region, the draping effect will intensify the fields further (Figure 2d) as discussed by *Zwan and Wolf* [1976] for the Earth's magnetosheath fields. This draping will occur whether there is shock compression or not. Another type of field draping, proposed by *McComas et al.,* [1989], creates northward and southward sheath components even though the quiet solar wind field is near the (solar magnetospheric) equatorial plane. As illustrated, the fields above and below the midpoint of the CME have opposite N–S components. If the heliospheric current sheath is swept up by the shock, distortions are postulated to lead to strong N–S components (Figure 2b). This was the case for one of the CDAW 6 substorm events [*Tsurutani et al.,* 1984]. Turbulent waves and discontinuities can also be associated with strong northward and southward IMFs (Figure 2c).

The types of B_S fields illustrated in Figure 2 have been inferred from studies of intense storms during the ISEE 3 interval of August 1978 to December 1979. Figure 3 shows an example of an intense storm (August 28, 1978) which has a southward field of a magnetic cloud type in the B_y direction and an associated large B_S excursion. Figure 3 also shows one of the high-intensity, long-duration, continuous AE activity (HILDCAA) events (indicated by the horizontal bar on the AE panel) studied by *Tsurutani and Gonzalez* [1987] for the same ISEE 3 interval. These events are characterized by substorm events with similar amplitudes as those that tend to occur during intense storms, although with shorter durations. Another interesting characteristic is that in this case, substorms, although intense, do not seem to contribute much to the ring current buildup as they do during intense storms. (Probably the finding of this different type of frequent and intense substorms, during HILDCAA events, was one of the main motivations for trying to reformulate the questions of what is a geomagnetic storm and what is the storm/substorm relationship).

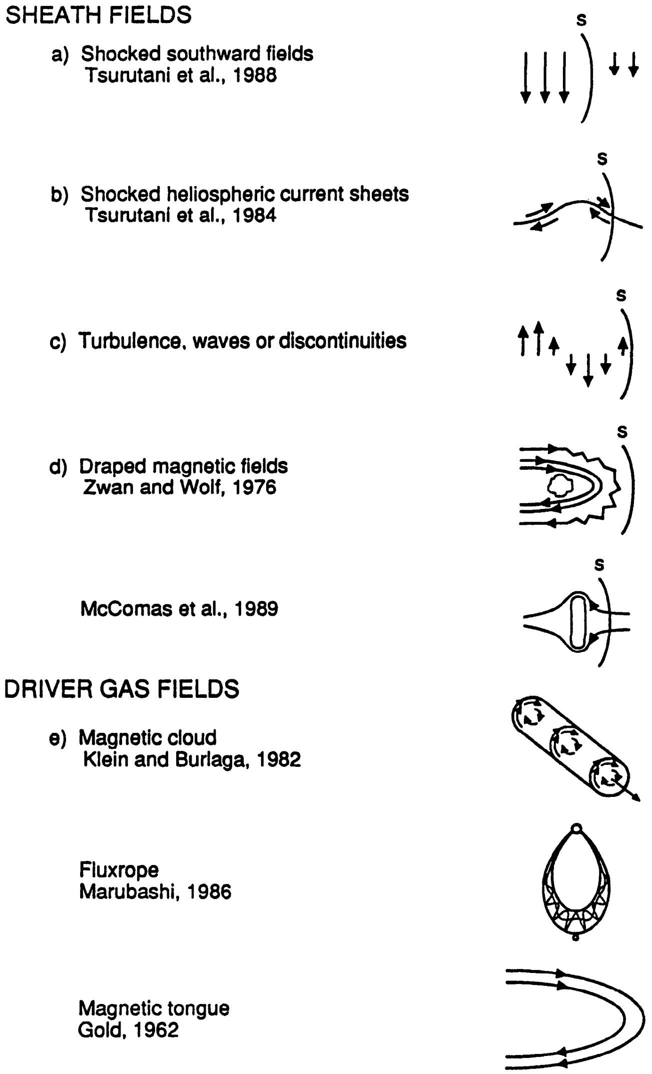

Figure 2. The various interplanetary features that were associated with large-amplitude (< -10 nT), long-duration ($>$ 3h) B_z fields for the 10 intense storms (peak Dst < -100 nT) of the August 1978 to December 1979 ISEE 3 interval. They are grouped in two broad categories: Sheath fields and Driver gas fields.

To date, the interplanetary causes of storms of all intensities are not understood. *Gonzalez and Tsurutani* [1987] and *Gosling et al.* [1991] have shown that for intense storms (e.g., with intensities of peak $Dst \leq -100$ nT) about 90% are caused by southward magnetic fields within high-speed streams led by shocks. *Tsurutani et al.* [1988] have shown that half the cases are caused by driver gas fields and half by sheath fields. As the storm intensity threshold is decreased, high-speed streams become less important. They are only involved in about 45% of storms with -100 nT $<$ peak $Dst \leq -50$ nT and in about 23% of storms with

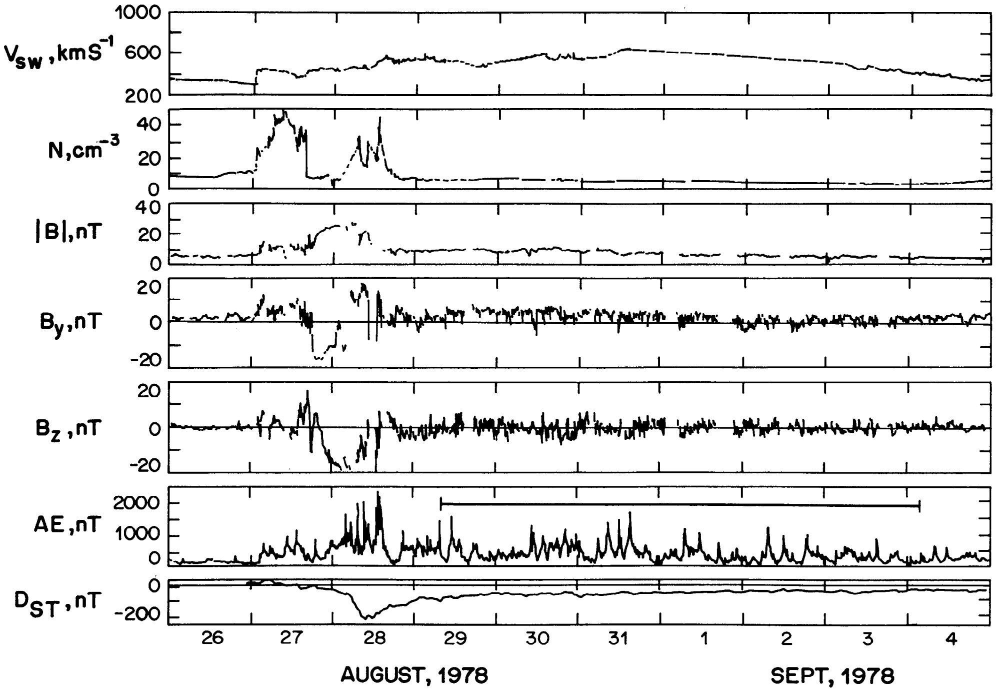

Figure 3. Example of an intense magnetic storm (August 28), with *peak Dst* < -100 nT, and of a HILDCAA event (August 29, 1978 to September 4, 1978), as indicated by a horizontal bar in the *AE* panel. On the top five panels, some of the interplanetary parameters measured by the ISEE 3 satellite are shown. The intense storm is associated with the arrival of a large magnetic cloud, whereas the HILDCAA event is associated with large-amplitude interplanetary Alfvénic fluctuations.

-50 nT $<$ peak $Dst \leq -30$ nT [*Gonzalez et al.,* 1992]. Further research is needed to investigate the interplanetary causes of these lower-intensity storms.

Concerning solar minimum intervals, *Akasofu* [1981a] has presented some examples showing that B_S fields at this epoch tend to be associated with the heliospheric current sheet (HCS) crossings at Earth. However, the nature of the HSC interaction with the recurrent high-speed streams, while are common in this epoch of the solar cycle, still needs to be investigated in order to understand the resulting type of B_S structures.

Finally, there has been recent progress in trying to understand the solar and interplanetary origins of the above mentioned B_S structures using MHD simulation techniques [*Detman et al.,* 1991; *Dryer et al.,* 1992; *Wu et al.,* 1992]. Although these studies have reproduced basic B_S features related for instance to the draping mechanism and to the shock interaction with the HCS, additional work still needs to be done before one can try to compare the obtained simulational results with the corresponding observations at 1 AU.

3.2. Solar Wind-Magnetosphere Interaction During Magnetic Storms

Figure 4 illustrates the overall features involved in the solar-interplanetary-magnetosphere coupling during solar maximum, indicating the main magnetospheric dissipation mechanisms, storms and substorms, as well as the basic role of the "magnetospheric dynamo" in magnetospheric energization.

The basic energy transfer process in the Earth's magnetosphere is the conversion of directed mechanical energy from the flow of the solar wind into magnetic energy stored in the magnetotail, followed by its reconversion into primarily thermal mechanical energy in the plasma sheet, auroral particles, ring current, and Joule heating of the ionosphere. Extraction of energy from solar wind flow requires a net force between the solar wind and the Earth, with force times solar wind speed giving the energy input rate. This is a more general way of looking to the magnetospheric dynamo illustrated in Figure 4. The resulting magnetosheath flow rate through the interaction region, large enough to supply the mechanical energy, can be shown to be a significant fraction of the solar wind flow through an area equal to the projected cross section of the magnetosphere (see *Vasyliunas* [1987], for a derivation from an equivalent stress argument). For energy going into the magnetosphere, the associated force is that between the Earth and the magnetotail (the 1 order-of-magnitude larger Chapman-Ferraro force is connected with the irreversible heating at the bow shock). The largest consumer of energy in the magnetosphere is the buildup of the storm time ring current, typically exceeding the dissipation in the aurora and the heating of the ionosphere. The alternative suggestion by *Weiss et al.* [1992] that substorm processes can consume more energy than the ring current was obtained under the assumption of fairly large values of the ring current decay time. During large storms, such values can be considerably reduced [e.g.,

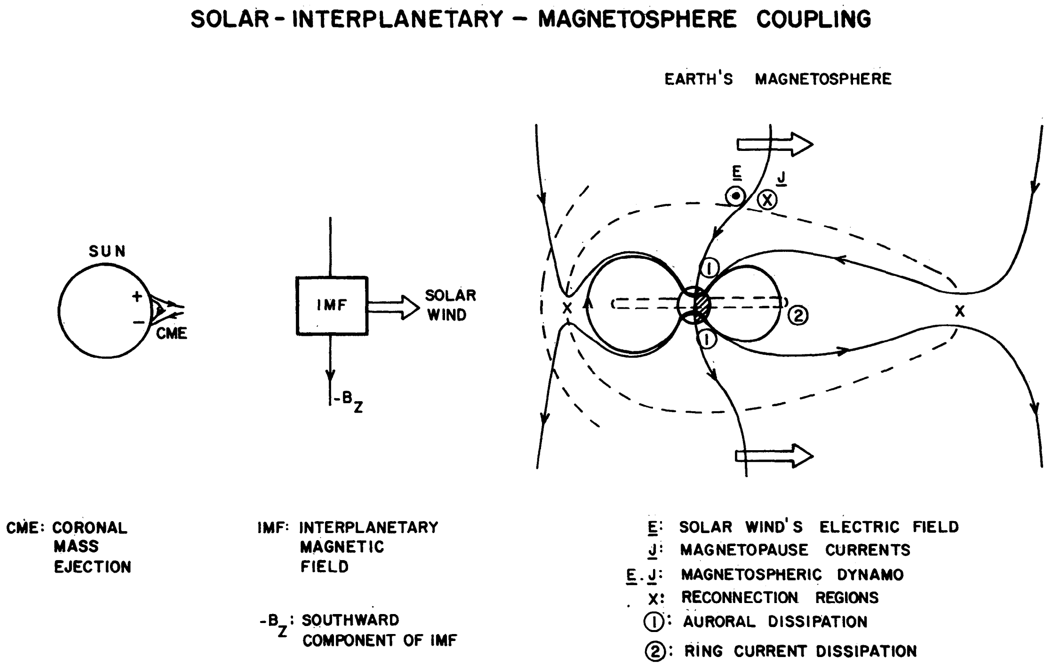

Figure 4. Schematic of the solar-interplanetary-magnetosphere coupling during solar maximum years, during which a coronal mass ejection is the most important solar source for interplanetary and magnetospheric disturbances.

Gonzalez et al., 1989; *Prigancova and Feldstein,* 1992], thus requiring energy input rates higher than those associated with substorms.

Since early studies, magnetic field reconnection between the southwardly directed IMF and the geomagnetic field is the most widely accepted mechanism for magnetospheric energization and therefore for magnetic storms [e.g., *Dungey,* 1961; *Petschek,* 1964; *Rostoker and Fälthammar,* 1967; *Arnoldy,* 1971; *Tsurutani and Meng,* 1972; *Akasofu,* 1981a; *Gonzalez et al.,* 1989]. Quantitative studies of large-scale magnetopause reconnection [e.g., *Gonzalez and Mozer,* 1974; *Vasyliunas,* 1975; *Sonnerup,* 1984; *Cowley,* 1984] have provided sufficient understanding about the rate of energy transfer from the solar wind to the magnetosphere during magnetic storms. *Gonzalez* [1990] showed that most of the widely used coupling functions that correlate well between solar wind parameters and magnetospheric dissipation parameters can be derived as particular cases of general expressions for the momentum and energy transfer at the magnetopause due to large-scale reconnection.

Table 2 is a summary of the most commonly used coupling functions. In this table V and ρ are the solar wind speed and density, respectively; B_T is the transverse (to the Sun-Earth line) component of the IMF vector, $B_T = (B_z^2 + B_y^2)^{1/2}$ in solar magnetospheric coordinates; B is the IMF magnitude and θ is the clock angle between $\mathbf{B}_T$ and the geomagnetic field vector projected at the magnetopause; L_o is a constant scale-length factor (equal to 7 R_E). As mentioned above, it has been shown extensively that among the parameters involved in these coupling functions the dominant ones are B_S and V (e.g., see *Baker et al.,* [1983] for a review).

Since the initial work by *Russell and Elphic* [1979] and by *Haerendel et al.* [1978], the so-called flux transfer events (FTEs) or flux erosion events have been argued to represent the small-scale structure of magnetopause reconnection. There is some controversy in the literature about the coexistence of FTEs with large-scale reconnection, as recently reviewed by *Gonzalez* [1991] with suggestions toward a reconciliatory model of magnetopause reconnection. Although the coupling functions of Table 2 were derived from large-scale reconnection models, one could argue that they also represent the integrated contribution of the smaller-scale FTE processes.

Using most of the coupling functions listed in Table 2 as the energy input function for equation (3), *Gonzalez et al.* [1989] and *Mendes et al.* [1994] have followed the time evolution of Dst^* during the main phase of intense (peak $Dst < -100$ nT) and moderate (-100 nT $\leq$ peak $Dst < -50$ nT) storms. It was shown that several of these coupling functions, especially ϵ and VB_S, represent the energy input fairly well, although functions such as $p^{1/2}VB_S$ seem to become more important during intervals of time with large solar wind pressure variations. Figure 5 [*Mendes et al.,* 1994] gives an example of a moderate storm's Dst^*, together with the function Q of equation (3) and the best representative coupling functions (ϵ, $E_y = VB_z$ and $F_4 = p^{-1/3}VB^2 \sin^4(\theta/2)$). A more detailed comparison between the behavior of Q and ϵ is also shown.

Using some of the most commonly known coupling functions, such as VB_z and ϵ, linear filters were constructed for substorm prediction [*Iyemori et al.,* 1979; *Bargatze et al.,* 1985; *Clauer,* 1986]. From the studied response times it was suggested that substorms have

Table 2. Most Commonly Used Coupling Functions for the Solar Wind-Magnetosphere Interaction

Electric Field Related	References	Power Related	References	Simple Expressions	References
vB_z	*Rostoker et al.* [1972] *Burton et al.* [1975]	$\epsilon = vL_o^2B^2sin^4(\theta/2)$	*Perreault and Akasofu* [1978]	B_z	*Arnoldy* [1971] *Tsurutani and Meng* [1972]
vB_T	*Doyle and Burke* [1983]	$(\rho v^2)^{1/2}vB_z$	*Murayama* [1986] *Gonzalez et al.* [1989]	B_zv^2, Bv^2	*Murayama and Hakamada* [1975] *Baker et al.* [1981] *Holzer and Slavin* [1982]
$vB_Tsin(\theta/2)$	*Gonzalez and Mozer* [1974] *Doyle and Burke* [1983]	$(\rho v^2)^{-1/3}vB_T^2sin^4(\theta/2)$	*Vasyliunas et al.* [1982] *Gonzalez et al.* [1989]	B_z^2v, B^2v	*Holzer and Slavin* [1982] *Baker et al.* [1981]
$vB_Tsin^2(\theta/2)$	*Kan and Lee* [1979] *Gonzalez and Gonzalez* [1981] *Reiff et al.* [1981] *Wygant et al.* [1983] *Doyle and Burke* [1983]	$(\rho v^2)^{1/6}vB_Tsin^4(\theta/2)$	*Vasyliunas et al.* [1982] *Bargatze et al.* [1986] *Gonzalez et al.* [1989]		
$vB_Tsin^4(\theta/2)$	*Wygant et al.* [1983] *Doyle and Burke* [1983]				

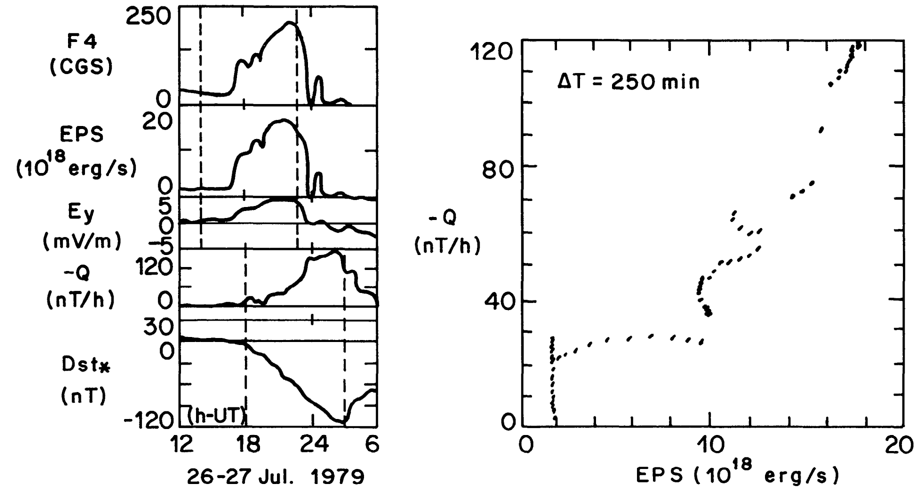

Figure 5. Example of coupling functions (ϵ, E_y, and F_4), energy input function Q, and Dst^* curve for the storm of July 26 and 27, 1979. The associated Q/ϵ variability is also shown. See text for details. [After *Mendes et al.,* 1994].

two energy input components, one "directly driven" by the solar wind and the other indirectly, namely "unloaded" from the tail reservoir. For a comprehensive discussion on the relative roles of directly "driven" and "unloaded" components of substorm energy input, the reader is referred to the review paper by *Rostoker et al.,* [1987]. The linear prediction filter technique has not as yet been applied to the study of storms with enough detail to see if storms also have driven and unloading components and in which proportion as a function of the level of storm intensity. Some limited results of linear filters for storm predictability, as governed by equation (3), have been presented by *Fay et al.* [1986].

On the other hand, observationally, it was shown [*Gonzalez et al.,* 1989] that most of the intense storms seem to be directly driven, whereas the lesser the intensity of storms the smaller the correlation coefficients were found to be between the directly driven-coupling functions and the response of the ring current, as obtained from equation (3). Therefore it was suggested [*Gonzalez et al.,* 1989; *Mendes et al.,* 1994] that unloading components seem to become more important for moderate (and weaker) storms.

Recently, there has been a considerable effort to find mechanisms in the magnetosphere that could model the driven and unloading components [e.g., *Baker et al.,* 1991; *Klimas et al.,* 1992; *Goertz et al.,* 1993] in the interest of finding linear and nonlinear filters to use in substorm prediction [e.g., *Vassiliadis et al.,* 1993]. Eventually, it would be of great interest to extend such efforts to the study of storms.

3.3. Seasonal and Solar-Cycle Distribution of Storms

It is known that geomagnetic activity as a whole has a seasonal variability with maxima at the equinoxes [e.g., *Russell and McPherron,* 1973]. Figure 6 shows a seasonal distribution for intense storms with peak $Dst \leq -100$ nT, during the 1975–1986 interval (taken from *Gonzalez and Tsurutani* [1992]. Note that this distribution shows a very large seasonal modulation as compared to the less marked modulations usually found for less intense storms [e.g., *Clúa de Gonzalez et al.*, 1993]. There is no consensus as yet about the origin of the seasonal distribution of storms, especially with respect to the distribution of intense storms.

Recently, *Crooker et al.* [1992] argued that the strong B_S fields that are responsible for the seasonal distribu-

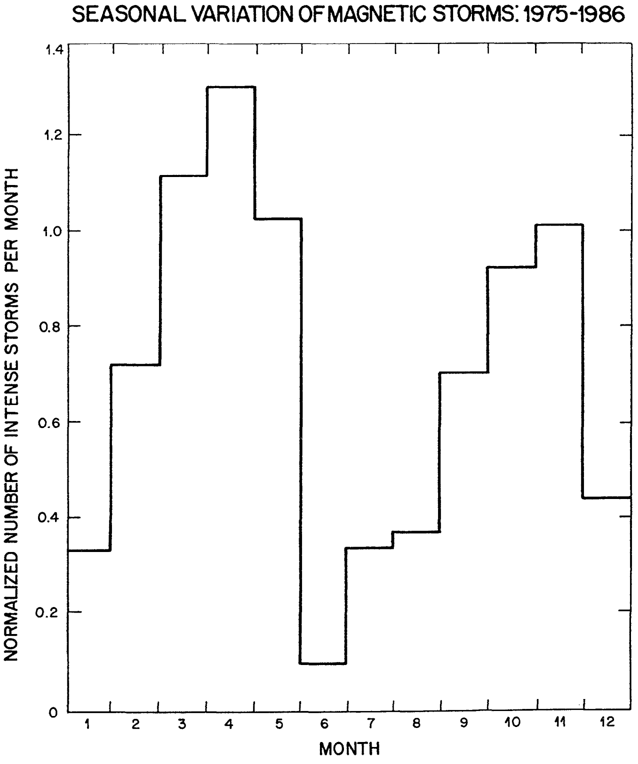

Figure 6. Seasonal distribution of intense storms (peak $Dst < -100$ nT) for the interval 1975–1986. The normalized number of these storms per month is given.

tion of intense storms can originate in the postshock flow from a major increase in the Russell-McPherron polarity effect through a systematic pattern of compression and draping within the ecliptic plane. However, this effect does not seem to substantially alter the B_S fields which are already large in solar ecliptic coordinates and which even seem to have a type of "axial."[*Cortie,* 1915] seasonal distribution already incorporated into them [*Gonzalez et al.,* 1993].

It is well known that geomagnetic activity as a whole tends to become enhanced during the descending phase of the solar cycle, near solar minimum [e.g., *Sugiura,* 1980; *Legrand and Simon,* 1991]. However, *Gonzalez et al.* [1990] showed that intense storms (peak $Dst \leq -100$ nT) tend to show two peaks within the solar cycle, one somewhat ahead or at solar maximum and the other 2 to 3 years after solar maximum. Figure 7a is an example of a dual peak distribution for intense storms (peak $Dst < -100$ nT) for solar cycle 21. It was also found [*Gonzalez et al.,* 1990] that the solar cycle distribution of B_z fields with intensities < -10 nT and duration > 3 hours have a similar dual-peak distribution during cycle 21 as shown in Figure 7b. This association of intense storms to such a class of B_S fields was initially suggested by *Gonzalez and Tsurutani* [1987] from a study of intense storms for the August 1978 to December 1979 ISEE 3 interval.

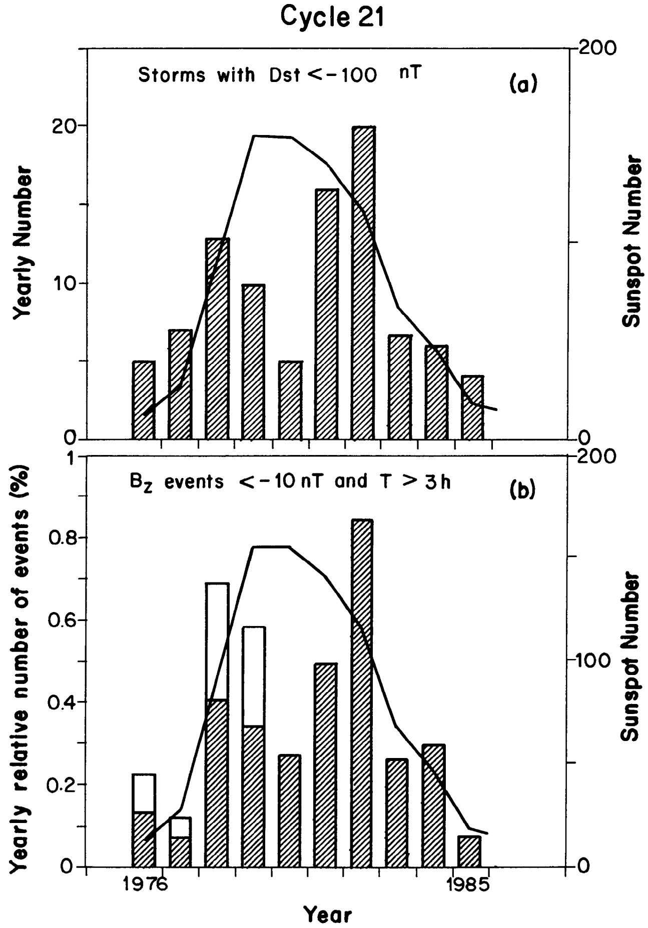

Figure 7. (a) Dual-peak distribution of intense storms (peak $Dst < -100$ nT) for solar cycle 21. (b) Corresponding dual-peak distribution of B_z fields with amplitudes < -10 nT and duration $T > 3h$. (The yearly relative number of events is given.) The unhatched bars are the corrected values after those intervals were normalized to the available satellite data coverage. Updated from *Gonzalez et al.* [1990].

4. Relationships of Storms and Substorms

4.1. A Question of Definition

Intense substorms are observed to occur during the main phase of magnetic storms. Many researchers believe, or tacitly assume, that magnetic storms develop as a result of the frequent occurrence of substorms. In fact, in an early paper dealing with this question *Chapman* [1962, p. 9] stated that:

> A magnetic storm consists of sporadic and intermittent polar disturbances, the lifetimes being usually one or more hours. These I call polar substorms. Although polar substorms occur most often during magnetic storms, they also appear during rather quiet periods when no significant storm is in progress.

In a retrospective view of his work with S. Chapman, Akasofu (private communication, 1991) commented:

> One of the first findings from studying intense storms during the International Geophysical Year was that the aurora underwent a systematic change several times during the storm from a quiet condition to a very disturbed one and back to a quiet condition. It was a great surprise to us that the aurora could be very quiet even during the maximum epoch of the main phase.

Thus, in principle, a magnetospheric substorm [*Akasofu,* 1968] can occur independently of a magnetic storm. A modern definition of a substorm [*Rostoker et al.,* 1980, p. 1663] is

> A magnetospheric substorm is a transient process initiated on the night side of the Earth in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and magnetosphere.

There are certainly good physical reasons to believe that a magnetic storm consists of intense substorms. During episodes of substorm activity, energy can be deposited into the inner magnetosphere, leading to the formation of the so-called partial ring current (which is connected to the auroral electrojets through field-aligned currents). The nightside portion of the partial ring current is probably contiguous with the cross-tail current in the magnetotail [*Sugiura,* 1972]. Since the characteristic response time of this partial ring current is approximately 2–3 hours [*Clauer et al.,* 1983], if intense substorms occur successively when the effects of previous substorms still remain in terms of the partial ring current, the local time extent of that partial ring current could become larger and evolve into a storm time symmetric ring current. In other words, an individual substorm may cause an azimuthally localized "mini" ring current. If substorms occur frequently enough, the injected ring current particles may accumulate in the trapping region, forming the symmetric ring current associated with the main phase of a geomagnetic storm. It is also quite conceivable that plasma injection associated with intense substorms occurring during the main phase of a magnetic storm takes place over a wide longitude range, so that it does not take long for the successive injections to form a symmetric ring current. While this is a plausible scenario, one must ask if it really is the case that the observed *Dst* variations can be reproduced quantitatively purely from a knowledge of the substorm activity.

To address this matter, there is a series of questions we must consider. Is the successive occurrence of many intense substorms a necessary condition for a magnetic storm? If so, how many is many? How intense is intense? How successive is successive? If the answer of the first of these questions is no, why are substorms therefore incidental, and what is their role in the solar-terrestrial interaction?

4.2. Storm Conditions

The ring current evolution is governed by equation (3). To test whether *Dst* can be reproduced through knowledge of ongoing substorm activity (or, more practically, by a knowledge of the *AE* indices), we assume that Q is simply proportional to substorm activity. In other words, we simply assume that the storm main phase is described simply by a linear superposition of substorm disturbances. The logic (or physics) behind this assumption does not demand that the auroral electrojets in the ionosphere directly generate the magnetospheric ring current. Rather, it suggests there is an energy reservoir in the solar wind/magnetosphere/magnetotail which concurrently delivers energy to the ring current and the polar ionosphere (the latter being responsible for substorm signatures). When there is no energy input to the ring current, the ring current intensity decays according to equation (4). This seems to be consistent with observations [e.g., *Davis and Parthasarthy,* 1967; *Feldstein et al.,* 1984]. However, many researchers have noticed that this simple assumption does not work very well on many occasions [cf. *Davis,* 1969; *Kamide and Fukushima,* 1971]. For the auroral electrojets having the same strength (as quantified by *AE*), the ring current grows more efficiently during the main phase of storms than during nonmain phase periods, indicating that the energy injection rate into the ring current is not simply proportional to the level of substorm activity. It may, however, be possible to write the storm-substorm relationship as

$$\text{storm} = \sum \alpha_i (\text{substorm})_i,$$

where α_i is the efficiency of the ith event, which is largest during the early main phase of a magnetic storm. That is

$$Q(t) = \alpha(t)\, AL(t),$$

where the parameter $\alpha\,(0 < \alpha < 1)$ expresses the efficiency of the ring current growth relative to the corresponding substorm intensity.

The result is shown in Figure 8 [cf. *Kamide and Fukushima,* 1971], in which the efficiency is assumed to be an exponential function of time. For both weak and great storms, the observed *Dst* variations are quite nicely reproduced by a superposition of *AL* times the efficiency. This indicates that, although the development of the ring current and that of the auroral electrojet are closely related, the partition of energy injected into the ring current and into the polar ionosphere is not always in constant proportion. One might reasonably ask what determines this partition rate which changes with time. In the mathematical treatment, α is the efficiency of energy input into the ring current. Thus we have the fundamental question: what is the physics of the processes controlling this efficiency?

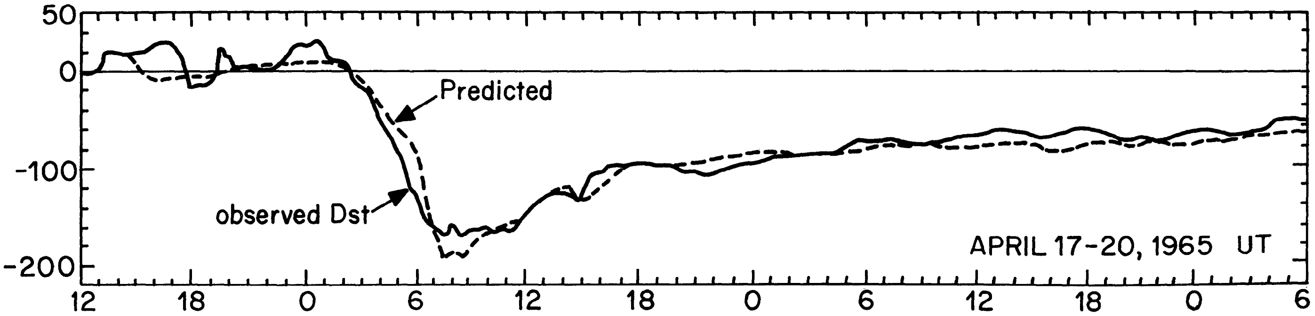

Figure 8. Comparison of the *Dst* index and the energy of the ring current computed on the basis of the assumption that the injection rate into the ring current is related to *AE* so that it is maximum at the beginning of the main phase and decays exponentially thereafter. [After *Kamide and Fukushima,* 1971].

As reviewed in section 3, it is now well recognized that the solar wind parameters, and, in particular, the magnitude and direction of the interplanetary magnetic field (IMF), control the level of the solar-terrestrial interaction, since the initial work by *Rostoker and Fälthammar* [1967] and by *Kokubun* [1972]. As summarized in Table 1, the IMF B_S field has to exceed a threshold level both in amplitude and in duration in order for a storm main phase of a given intensity to develop.

From the discussion in section 3, it seems reasonable to suggest that the efficiency $\alpha(t)$ is a function of the southward component of the IMF or dawn-to-dusk component of the electric field in the interplanetary medium. This manifests itself in the regulation of the rate of injection of ring current particles into the inner magnetosphere by the IMF.

For the formulation of any storm/substorm relationship model, the following three points must be taken into account:

1. There is no apparent difference between storm time substorms and substorms occurring at times of no significant *Dst* enhancement, except that the most intense substorms are usually found within the main phase of storms.
2. No magnetic storms have been observed in the absence of substorms.
3. When geomagnetic activity is exceptionally high (i.e., $Kp = 9$), it is always during a magnetic storm.

Another complication in understanding magnetic storm/substorm processes in the magnetosphere lies in the existence of quasi-steady magnetospheric conditions. Evidence for such behavior is found in the existence of convection bays [*Pytte et al.,* 1978] and steady magnetospheric convection episodes [*Sergeev and Lennartson,* 1988]. Such behavior of the magnetosphere has been shown to be in evidence during long intervals of relatively constant large southward IMF. In addition, the HILDCAA events studied by *Tsurutani and Gonzalez* [1987] suggests a certain unique response of the magnetosphere to quasi-periodic disturbances in the IMF.

The presence of substorms is certainly not a sufficient condition for the development of a magnetic storm. Sometimes, there may even appear to be an anticorrelation between substorm intensity during the storm and the intensity of the storm itself as quantified by *Dst* [*Akasofu,* 1981b]. Nonetheless, it is probably true that the IMF condition for substorms is included in the IMF condition for storms. According to *Kamide et al.* [1977], substorms occur with 100% probability whenever the 1-hour-averaged IMF B_z has a value < -3 nT, as also indicated in Table 1. According to this table, a necessary condition for intense (peak $Dst < -100$ nT) magnetic storms is that the southward IMF must be large (< -10 nT and sustained (> 3 hrs). The main phase of a magnetic storm starts when solar wind parcel carrying a large southward IMF impacts the magnetopause. At least, in a working model, it is convenient to assume that substorms occur as a by-product of enhanced magnetospheric convection which results from the imposition of the enhanced solar wind dawn-to-dusk electric field across the magnetosphere. This view is consistent with the predictions of the ring current coupling model of *Siscoe* [1982] which suggests that *Dst* is directly derived from the solar wind parameters, whereas *AE* is not.

Therefore we should refocus on the question of why some large substorms are associated with significant increases in *Dst*, while other equally large substorms seem to have little effect on it. Part of the answer may lie in the fact that the ring current strength may reflect the cumulative effect of a lengthy period of exceptionally enhanced energy input from the solar wind into the magnetosphere, as suggested initially by *Rostoker and Fälthammar* [1967]. That is, if the combined effect of the strength of the interplanetary electric field and the length of time that strength is maintained is inadequate, one might observe significant expansive phase activity yet little ring current enhancement. Alternatively, one might argue that the level of substorm activity (as quantified by the *AL* or *AE* indices) may bear no relationship to the enhancement of *Dst*, since substorm expansive phase activity reflects dispensation of energy in a way that makes it unavailable for storage in the ring current. Yet a third explanation may center on the manner in which *AE* and *AL* are measured (namely, the way in which the level of substorm activity is quantified). The stations, whose measurements are used to evaluate *AE* and *AL*, are positioned close to the average auroral oval location. For great storms, the auroral oval is displaced far equatorward of its normal position, in which case the *AE* observatories do not sample the electrojet perturbations at their peak in latitude [*Feldstein,* 1992]. Thus the strength of substorm activity might be seriously underestimated for times when the particle injections [cf. *McIlwain,* 1974] occur relatively close to the Earth. It is very likely that significant ring current enhancements occur when the particle injections occur unusually close to the Earth, as we shall discuss in the next section.

4.3. Origin of *Dst* Through Injection of Energetic Particles

It is fairly clear that the ring current enhancement is at least partly associated with the injection of energetic particles associated with substorm expansive phase activity. Therefore we return to the question of why it is that certain expansive phase events are associated with significant ring current injection, while others seem to have little effect and try to establish a physical reason for this apparent fact. One way of approaching the question is to note that a symmetric ring current will develop only if the injected energetic particles can make complete drift paths around the Earth. Two possibilities prevent this happening. On one hand, if the injection takes place too far behind the Earth (large L), the drift paths will intersect the magnetopause along the magnetotail flank space and the injected particles will be unable to contribute to a symmetric ring current. On the other hand, if the injection reaches close to the

Earth (low L), it is likely that the convection electric field will be very high in order to set up such a situation and under those circumstances, at least for a long time the injected particles may convect to the dayside magnetopause and will again be lost before they are able to make a complete circuit of the Earth. Thus it seems likely that a symmetric ring current will be set up when the injection is close enough to the Earth and the convection electric field terminates in a way that the majority of particles remain trapped in the magnetosphere and the injected particles will make complete circuits of the Earth's magnetosphere. This, in turn, can occur when there is a marked reduction in the convection electric field at the time of onset of the substorm expansive phase activity responsible for the injection. The condition necessary for this combination of circumstances to prevail is a reduction of energy flow into the magnetosphere at the time of substorm expansive phase onset, and the most probable way in which this can be achieved is by a change in the IMF B_S component to make it northward or, at least, less southward. It would be worthwhile to carry out a study of the change in the interplanetary conditions at the time of significant enhancements in *Dst* to see if the suggestion regarding the reason for the lack of a simple correlation between *Dst* and *AE*/*AL* is borne out.

In a recent simulation study, *Takahashi et al.*, [1990] have tested the formation of a closed ring current from a partial ring current using a monochromatic particle trajectory tracing method and a time-varying convection electric field. It was also shown [*Takahashi et al.*, 1991] that the asymmetric component of the ring current can dominate the symmetric one during the main phase with strong ionospheric and field-aligned current components.

It is worth noting that the last five years have seen important advances in our knowledge of the changes at geostationary orbit during substorm activity. In particular, *Kauffman* [1987] has been able to show that the intensity of the cross-tail current near geostationary orbit has to be at least an order of magnitude larger than what had been previously imagined in order to account for the ability of the magnetic field in that region of space to become very taillike. It is then quite apparent that the dipolarization of the field lines near geostationary orbit at the time of some substorm expansive phases must involve very large inductive electric fields (namely a large rate of change of field associated with the sudden reduction of the cross-tail current near geostationary orbit). *Mauk and Meng* [1987] have accounted for the "injection" of energetic particles by calling on an inductive electric field associated with the sudden changes in the cross-tail current, and studies by *Wang et al.* [1990] and by *Lui et al.* [1991a] have suggested physical mechanisms which account for the sudden reduction of the cross-tail current. Therefore there is every reason to believe that the dipolarization of the magnetic field in the near-Earth magnetotail at the time of substorm expansive phase onset is an important cause for the energization of particles which would become part of the asymmetric ring current. Whether or not those particles contribute to the symmetric ring current depends on the considerations discussed above.

5. Discussion

5.1. Origin of *Dst* Through Additional Mechanisms

It was shown by *Lyons and Williams* [1980] that flux increases of trapped ions and electrons observed at L values ≤ 4 during intense geomagnetic storms can be quantitatively explained by a 1 to 3 R_E inward radial displacement of the preexisting trapped particle distributions. This proposed source for the storm time ring current at $L \leq 4$ requires only the acceleration of the previously existing trapped particle population via inward displacement under conservation of the first two adiabatic invariants. It was not possible to test whether such an inward radial displacement can account for storm time flux increases at any radial distance beyond $L = 4$. However, the existence of particle losses implies that new particles are injected into the trapped region beyond $L = 4$. It was also suggested by Lyons and Williams that a significant difference between intense geomagnetic storms and typical substorm activity may be inward convection occurring over a much larger longitudinal range during storms than during typical substorms. Similarly, the convection electric fields involved in the radial displacements during intense storms would be at least 2 to 3 times greater than those typically observed during substorms.

Because the above mechanism applies mostly to trapped particles in the energy range ≤ 40 keV, since at higher energies the ring current particles have drift periods that are typically shorter than the time of the main phase development, *Lyons and Schulz* [1989] have suggested that at those higher energies, the radial transport is performed instead by stochastic electric fields. For such a diffusive radial transport, *Chen et al.* [1992] have performed a guiding-center simulation using a quasi-linear theory of radial diffusion initially proposed by *Fälthammar* [1965].

Figure 9 is a summary of the above reviewed mechanisms (subsections 4.3 and 5.1) for the storm time ring current formation. Note in this figure that (1) and (2) need not necessarily involve the occurrence of substorms.

5.2. Ring Current Loss Processes

Since early works [e.g., *Akasofu and Chapman,* 1972] it was suggested that the ring current consists at least of two distinct belts: one developing into a large component (but decaying quickly) and the other having a weaker nature (decaying slowly). A modern interpretation implies the existence of oxygen ions at close distances (2–4 R_E) for the former type, while the latter is usually identified with a belt consisting mostly of protons at a greater distance [e.g., *Williams,* 1985; *Lui et al.,* 1987; *Hamilton et al.,* 1988].

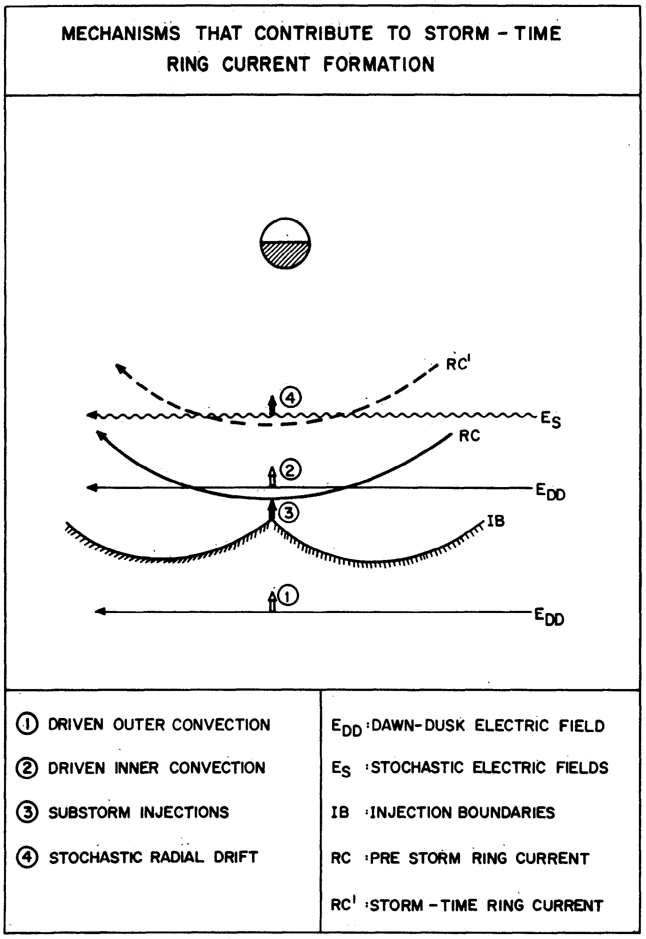

Figure 9. The various mechanisms that contribute to the storm-time ring current formation.

Thus the ion composition and location of the ring current belts must be known in order to have a better quantitative understanding of the loss processes and therefore of the τ parameter in equation (3). Some simulation efforts have been already undertaken [*Wodnicka,* 1991] in order to follow the storm development as a function of injection energy, initial pitch angle distribution, site of ion injection and ion species. As discussed in section 2, τ is a complex function of the several loss processes. To calculate an overall value of τ, all of the particles composing the ring current for all loss processes should be considered.

There are three basic processes that contribute to the removal of geomagnetically trapped ions within the Earth's radiation belts, namely charge exchange, Coulomb scattering, and resonant interactions with plasma waves. Each process depends sensitively on the ion energy, composition, pitch angle distribution and general location in the radiation belts. Because of this sensitivity, one must be able to determine both the absolute value and relative importance of each process during all phases of the storm.

These loss processes are not totally independent of one another. As one example, the pitch angle anisotropy produced by charge exchange results in a particle distribution which is unstable to the excitation of electromagnetic ion cyclotron waves [*Cornwall,* 1977; *Solomon and Picon,* 1981]. We thus anticipate that the accompanying wave excitation could become important during the storm main phase, when the ring current is closest to the Earth. In addition, the betatron acceleration of ions during the storm main phase will also preferentially heat ions in the direction perpendicular to B_o. This process will further contribute to producing a distribution which is unstable to wave excitation.

One should therefore attempt to make a quantitative assessment of the excitation of electromagnetic ion-cyclotron and other plasma waves during the main phase of the storm. The lifetime for ion losses due to resonant interactions with such waves [e.g., *Cornwall et al.,* 1970] can be substantially shorter than the lifetime due to charge exchange or Coulomb scattering. Thus this mechanism may account for the exceptionally short lifetimes that have been obtained during the main phase by previous empirical studies [e.g., *Akasofu,* 1981a; *Gonzalez,* 1989].

During the storm recovery, the convection electric field subsides, and the plasmapause (which is the outer boundary of plasma of ionospheric origin) will consequently begin to move outward away from the Earth [*Chappell,* 1972], refilling the plasmasphere. Coulomb scattering of ring current ions can become an important loss process for ions located inside the high-density plasmasphere ($Ne \geq 10^3$) during this phase of the storm [*Fok et al.,* 1991]. Coulomb scattering by thermal electrons could cause a gradual energy degradation of the trapped ions along the inner edge of the ring current. It may also tend to reduce the anisotropy in the ion pitch angle distribution and thus terminate or decrease wave growth. In the region outside of the expanding plasmapause, charge exchange will remain an important, if not dominant [*Smith l et al.,* 1976], loss process. The strong dependence of the charge exchange lifetimes on ion energy and composition [*Tinsley,* 1976; *Lyons and Evans,* 1976; *Spjeldvik,* 1981; *Fok et al.,* 1991] should determine the energy spectrum, pitch angle distribution and composition of ions in the outer ring current during the storm recovery. Whether wave excitation and associated loss is possible under these conditions remains to be established.

From the rough empirical modeling done for the storm main phase, it has been found that τ tends to decrease with increasing injection rate. *Prigancova and Feldstein* [1992] have suggested that, for intense injections, the value of τ may decrease to $\sim$ 1 hour. *Gonzalez et al.* [1989] have empirically determined even lower values of τ at the peak of the main phase of very intense storms. Currently, no physical model has been proposed that accounts for decay times of $\sim$ 1 hour or less [e.g., *Fok et al.,* 1991].

5.3. Relationship of *Dst* to Other Geomagnetic Indices

There have been only few attempts to relate statistically the *Dst* index to other geomagnetic indices [*Campbell,* 1979; *Saba et al.,* 1994]. Through these studies, useful information has emerged for a better understanding of the storm/substorm relationship. In addition, through relations determined between *Dst* and *ap* (or *Kp*), one could extrapolate values for *Dst* during intervals of time when they were not still available (before 1957). Examples of these relationships have been presented by *Saba et al.* [1994] from pair correlation studies between *Dst*, *ap*, and *AE*, separately for intervals of time around solar maximum as well as around solar minimum. These authors have also used a multicorrelation approach for the correlation study of *ap* as a function of *Dst* and *AE* and found larger correlation values than those obtained for the simple pair correlations *Dst* versus *AE* and *Dst* versus *ap*. This follows from the idea that middle latitude magnetometer records have contributions both from substorms currents and the ring current. The relative proportion of such contributions as a function of storm phase and level of storm amplitude is presently under investigation.

Among the very few studies published on the storm/substorm relationship, the early work by *Davis and Parthasarathy* [1967] and that by *Akasofu* [1981b] deserve special attention. It was shown by Davis and Parthasarathy that peak *Dst* values tend to be correlated with the sum of hourly values of *AE* during the 10 hours preceding the time of peak *Dst*. The analysis was done for a set of moderate and intense storms of 1958 and for other integration intervals, from a few to about 15 hours, obtaining a better correlation coefficient for 10 hours.

Recently, *Saba et al.* [1994] have performed a similar analysis for a set of 22 intense storms of 1974, 1978, and 1979 and found the same result obtained by Davis and Parthasarathy, namely that the peak *Dst* values correlate the best (correlation coefficient of 0.87) with the time integral of *AE* during the preceding 10 hours from peak *Dst*. The *AE* time integration was also performed for the main phase duration interval of each storm, but the correlation coefficient was considerably lower (0.65).

The explanation behind the 10-hour integral of *AE* when compared with the peak $-Dst$ value of the storm is not clear. Some preliminary suggestions involve (1) the existence of about 10-hour "packages" of *AE* during intense storms, which are formed by three to four consecutive intense substorms; (2) the typical duration of a B_S field within interplanetary structures of the magnetic cloud type; and (3) critical time scales for the combined storm/substorm dissipation mechanisms.

On the other hand, *Akasofu* [1981b] studied the *Dst*-*AE* relationship during a few intense storms in order to test the linearity of the growth of *AE* during the storm main phase. He suggested that at the moderate storm level, *AE* and $|Dst|$ grow together in a practically linear manner. However, for more intense storms he found that *AE* tends to saturate at a level of about 1000 nT, suggesting a sort of storm/substorm decoupling.

Saba et al. [1994] have also updated this study using 15 intense (-250 nT $\leq$ peak $Dst < -100$ nT) and very intense (peak $Dst < -250$ nT) storms. Figure 10 illustrates the results obtained for several levels of storm intensity. A linear behavior for moderate storms (storm of October 13, 1974) and a saturation for *AE* values at about 1000 nT (decoupling) for intense storms (storm of April 4, 1974), as suggested by Akasofu, can be seen

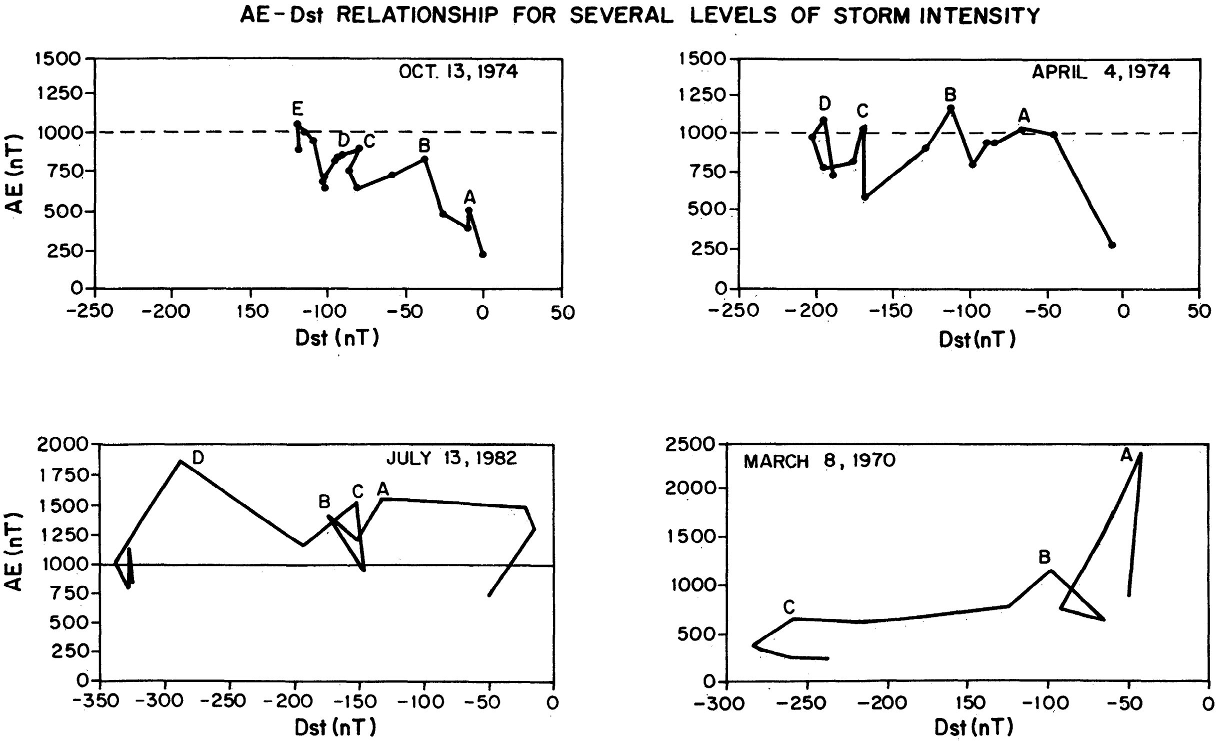

Figure 10. *AE*–*Dst* relationship for several levels of storm intensity. Updated from *Saba et al.* [1993].

in this figure. However, at higher storm intensities, such a behavior seems to change considerably, showing in some cases saturation at higher AE values (storm of July 13, 1982) or even a rapid decrease in AE (storm of March 8, 1970).

Feldstein [1992] has suggested that the apparent saturation or even decrease in AE for intense storms can be due to the fact that during such cases the auroral oval becomes considerably lower in latitude and the AE stations do not correctly monitor the substorm evolution. However, the intense storm of March 23 and 24, 1969, studied by Feldstein, using (latitudinal) corrected AE values, still shows a clear saturation during the final hours of the storm's main phase.

6. Summary Concepts

In reviewing the concept of a geomagnetic storm, we find that the term storm is based on a phenomenology of middle- and low-latitude-geomagnetic variations, identified by the intensification of the ring current as the source of the low-frequency component of storm magnetic variation and quantified by the Dst index.

Both the storm and substorm phenomena owe their origin to physical processes in which energy from the solar wind is redistributed in the magnetosphere-ionosphere system. The properties of the substorms are in some way related to the properties of the ring current development as pointed out in sections 4.2 and 5.1 and illustrated in Figure 9 of this paper, but the physics of this relationship is not at this time fully understood. Clearly, substorm expansive phase effects can lead to changes in the magnetospheric electric field that have profound effects on the ring current formation which appear to be nonlinear in nature. A possible feedback mechanism of ring current intensification in modulating substorm dynamics should also be explored.

Present assignment of a lower threshold for Dst, below which the term storm is not applicable has no physical basis. However, assigning a lower threshold serves an operational need in terms of identifying a data set taken during intervals of strong penetration of solar wind energy into the magnetosphere-ionosphere systems, which are vulnerable to effects produced by the solar-terrestrial interaction. Thus a storm can then be understood to be a special case of such interaction in which the ring current grows until some key threshold of the quantifying index Dst is exceeded.

Why some intervals of enhanced solar-terrestrial interaction feature ring current growth leading to a Dst exceeding the specified threshold (in the case of this paper, the threshold being -30 nT) seems to depend on the behavior of the convection electric field in the magnetosphere. Fairly intense substorm injections are known to occur at modest levels of the convection electric field. However, to bring the ring current closer to Earth, convection electric fields of larger intensity (and duration) are necessary. Therefore one can say that an intense storm is accompanied by intense and frequent substorms but that intense substorms can also occur in the absence of an intense storm. In this way both concepts, initially suggested by *Chapman* [1962] and by *Akasofu* [1968] become incorporated in a more general concept. This is also confirmed by the class of HILDCAA substorms, which has a frequent and intense character but does not involve an intense storm due to the lack of a sufficiently large and sustained convection electric field.

Since the amplitude and duration of the convection electric field depend on the amplitude and duration of the IMF B_z component, the above concepts can be better understood with the help of Figure 11. Here we illustrate the B_z conditions for substorms, HILDCAAs, and intense storms. A modest B_z value of, say, -3 nT (see Table 1) with duration of ~ 1 hour is known to be sufficient to lead to a substorm. Because the associated convection electric field is relatively small, a ring current intensification can occur, in principle, but with a small contribution to Dst due to the expected small injection and distant location of the ring current. This situation occurs repeatedly during HILDCAA events since the B_z field, which belongs to a train of interplanetary Alfvén waves [*Tsurutani and Gonzalez,* 1987], also has a modest B_z amplitude, typically > -5 nT. On the other hand, during intense storms the B_z field has a large amplitude and a sustained duration (as those indicated in Table 1), which are most commonly observed during intense CME events.

In summary, we can define a storm as an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere

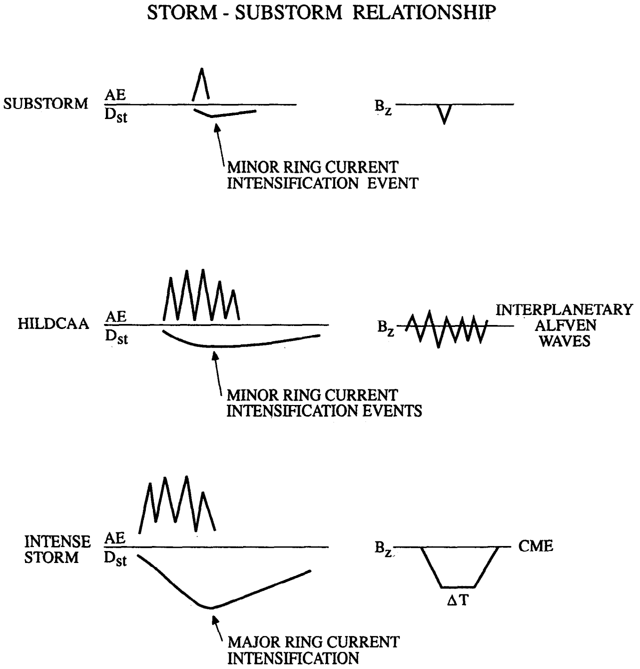

Figure 11. Schematic of the storm/substorm relationship in terms of the Dst and AE indices for the three basic classes of activity known as substorm, HILDCAA, and storm. The associated B_z field behavior and origin are also shown.

system, to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time *Dst* index.

Because such an interplanetary electric field condition is also expected to lead to the frequent occurrence of intense substorms, the fact that the main phase of storms has been observed to be always accompanied by substorms is consequently explained. However, to what extent such occurrence of frequent substorms is necessary for ring current intensification is still an open question.

When we refer to an intensification of the "ring current," we still do not know, physically, which currents are being monitored by the *Dst* index. Do the tail currents and the field-aligned currents have an appreciable effect? We also do not know the relative contribution of symmetric and asymmetric currents to the total ring current being monitored by the *Dst* index.

Finally, in situ monitoring of particle and energy composition of the ring current has reached a mature stage [e.g., *Roelof and Williams,* 1988], but the crucial question concerning the origin of this composition is not yet settled. With reference to Figure 9, for instance, it would be interesting to know how such diverse mechanisms affect different particle species and energies in ring current formation. This knowledge would certainly help us to understand more about the storm/substorm relationship problem, since some of these mechanisms seem to be more directly governed by the enhanced magnetospheric convection, whereas others appear to be associated more with the substorm dynamics itself. Considering the studies presented by *Lyons and Williams* [1980], *Lyons and Schulz* [1989], and *Chen et al.* [1992], mentioned in section 5.1 of this paper, one could expect that the direct role of the magnetospheric convection (dc) electric field in energizing the ring current would be more efficient at the lower-energy domain (around 40 keV) of the ring current particles, whereas substorm-associated (ac) electric fields would play a major role at higher energies. However, the knowledge of this relative role should be incorporated with that involving other important factors, such as those discussed in section 4 of this paper, in efforts to understand the total role of substorm dynamics in the storm time-ring current development.

7. Recommendations

7.1. Recommended Improvements in Existing Indices to Facilitate the Study of Magnetic Storms

In trying to establish the characteristic development and decay of magnetic storms, many researchers try to quantify the level of geomagnetic activity using indices derived from ground-based magnetograms. However, those indices suffer from several deficiencies which reduce their effectiveness in establishing the strength and temporal development of magnetospheric activity.

First and foremost amongst these indices, for the purpose of studying magnetic storms, is *Dst*. As reviewed in section 2.1, this index was introduced [cf. *Sugiura,* 1964] to provide a measure of the strength of the symmetric ring current and has remained the most commonly used measure of the strength to this day. The index is derived using the N–S component of the perturbation magnetic field at four widely distributed low-latitude stations. The measured magnetic field perturbations are corrected for the effects of *Sq* and for differences in latitude between the stations, and the four final values of the magnetic perturbation are averaged to produce the value *Dst*. *Dst* is generally available as a table of hourly values.

There are two severe problems associated with the present evaluation of *Dst* index (see also the related discussion by *Baumjohann* [1986]). The first of these relates to the fact that only four stations are used to compute values. Because the low-latitude perturbation magnetic field is also influenced by contributions from substorm-related current systems (namely, the asymmetric ring current described by *Kamide and Fukushima* [1972] and by *Clauer and McPherron* [1978], involving field-aligned currents, the ionospheric currents [cf. *Takahashi et al.,* 1991], and by the occasional collapse of the cross-tail current near the inner edge of the plasma sheet [cf. *Lui et al.,* 1991b]), it is very difficult to extract the effect of the asymmetric component of the disturbance field from the symmetric component which is supposed to be represented by *Dst*. It would be very valuable to increase the station coverage for the *Dst* network so as to minimize this source of error. This network should be located below the *Sq* focus to minimize the effects due to changes in the position of the focus and above the equatorial electrojet (about 5° to 20°N and S). A second major problem relates to the fact that the measured magnetic field perturbations are not corrected for Earth induction effects. This, in itself, might not be a severe problem if the conductivity under all the stations was relatively uniform. Unfortunately, this is not the case, particularly for stations that are located on coastlines or on islands. For example, the station of Honolulu is located on a volcanically active island chain, and preliminary study of the *Sq* variation of the data from that station suggests it to be severely anomalous. It is recommended that all *Dst* stations have their subsurface conductivity structure investigated for the purpose of developing correction terms for any conductivity anomalies that might be present.

If one is to try to establish a relationship between storm and substorm activity, it is advantageous to try to improve the auroral electrojet indices (*AL*, *AU*, and *AE*) so as to provide the most accurate estimates of the eastward and westward current flowing in the auroral ionosphere. These indices are derived from the N–S components of the perturbation magnetic field at 12 stations distributed around the world. They actually represent the envelope of the ensemble of time series of values from the contributing stations, and, as such, may not resemble the actual variation of the perturbation magnetic field at any particular station. Probably the most important source of error in establishing the strength of the auroral electrojet lies in the fixed locale of the contributing stations. The stations are relatively well distributed in longitude and are located near the average position of the auroral oval near magnetic midnight. During periods of relative quiet, the average position of the auroral oval is poleward of the AE stations and thus, while there may be current flowing in the electrojets, the AE stations are unable to monitor that current since the N–S component of the perturbation magnetic field drops off rapidly from the edges of the electrojet(s). Furthermore, when it is very active, the auroral electrojets are driven to latitudes significantly equatorward of the average locale of the AE stations. In this case, as well, the actual level of ionospheric current strength can be severely underestimated. This particular problem could be minimized by the following suggestions.

1. Improve the coverage of stations contributing to AE by including the contributions from stations slightly to the north and south of existing AE stations. The use of data from four stations, a couple of degrees poleward and equatorward of two of the AE observatories, which are approximately 180° separated in longitude, would significantly improve the index.
2. Use a forward model of the electrojets to compute H/Z ratios at different distances from the center of the model electrojets, and use those ratios to compare with observed H/Z ratios at the AE observatories. This would allow one to predict the maximum value of the N–S magnetic perturbation field at any station (which would occur directly under the center of the auroral electrojet). While implementing this procedure is more complex in the region of the Harang discontinuity (where a westward jet may flow at the polar edge of the eastward electrojet during substorm expansive phase activity) it is still better than allowing a situation to develop in which the observation site is at the interface between the eastward and westward electrojets. For such a circumstance, the N–S component of the perturbation will be zero, and the strength of the electrojets in that local time sector will be grossly underestimated.

Finally, we note that in evaluating the level of magnetospheric activity, one ought to consider the amount of magnetic flux stored in the magnetotail as this may be an indicator of how large the storm time ring current may ultimately become. It is well known that the size of the polar cap is a measure of the amount of magnetic flux threading the tail lobes and hence a measure of the colatitude of the equatorward edge of the open field line region. This would be a useful indicator of the amount of stored energy which might be available for deposition in the ring current. One possible measure of this position may be the evaluation of the position of the poleward edge of the eastward (westward) electrojet in the evening (morning) sector. These positions are marked by the extreme value of the Z components in the poleward portion of the electrojets [*Kisabeth,* 1972]. Such a measure would be quite desirable; however, it is likely to be achievable only when the polar cap has expanded considerably. This is because closed field lines may often extend poleward of the region of auroral luminosity normally identified with the auroral oval. Thus the electrojet border, particularly during quiet times, may lie significantly equatorward of the boundary between open and closed field lines. Despite this qualification, for events which develop into major geomagnetic storms, the poleward edge of the electrojet is likely to be rather close to the boundary between open and closed field lines shortly before the events which lead to significant ring current enhancement.

Accordingly, we recommend that the area of the polar cap be monitored by upgraded meridian lines approximately 180° apart at high latitudes, with the colatitude of the polar cap boundary being evaluated by the position of the Z component extremum in the poleward portion of the auroral electrojets.

7.2. Solar Wind Monitoring

Since the ISEE 3 spacecraft monitored the solar wind continuously (for a few years around 1980) at a vantage position such as the L_1 inner Lagrangian point of the Earth-Sun system, no other spacecraft has been dedicated to such type of observations. As a consequence, the study of the solar wind-magnetosphere interaction during the last decade was reduced to monitoring discontinuous events only when geocentered satellites, such as IMP 8, happened to be sporadically in the solar wind. Therefore very important magnetic storm events such as that of March 1989 (Dst around -600 nT!) passed without a record of the associated solar wind parameters.

Continuously monitoring the solar wind at L_1 also provides the needed information to compute the solar-wind pressure corrected Dst^* index. Consequently there have been recent efforts to propose projects, especially within the International Solar Terrestrial Program, in order to have solar wind monitors at L_1 in the near future. For instance the text of IAGA Resolution 13 (p. 36), passed at the Vienna Assembly, August 1991, reads as follows:

> IAGA, noting that advanced technological systems (especially electric power distribution and radio communications) are increasingly sensitive to natural variations in the Earth's magnetic field, magnetosphere and ionosphere, and noting that considerable progress has been made in quantitative understanding of the physical relations between solar wind parameters and the responses in geophysical parameters, recommends that the solar wind plasma and interplanetary magnetic field parameters be monitored upstream of the Earth in near real-time, and that the data be distributed internationally to anticipate possible terrestrial responses to severe solar wind fluctuations.

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