Magnetospheric Response to the IMF: Substorms

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We review the evidence for the control of magnetospheric substorms by the interplanetary magnetic field (IMF). Early statistical results, as well as recent correlation studies, are cited to show the strong degree of control exerted by the IMF over substorms as measured by auroral electrojet (AE , AL) parameters. Recent case studies and linear prediction filtering methods reveal quite clearly that substorms have both a “driven” and an “unloading” aspect. The driven component has a response time of 10–20 min, while the unloading time scale is ~ 1 hr. ISEE-3 deep-magnetotail results and recent Dynamics Explorer polar imaging data are related in this paper to these two separate facets of the substorm sequence. Dimensional analysis studies have delineated which solar wind-magnetosphere coupling formalisms are physically tenable and which give the best representation of the empirical data. The review concludes with a discussion of the total magnetospheric energy output parameter, U_T , and some of the problems inherent in its calculation. It is shown that as presently formulated, U_T cannot be meaningfully compared to solar wind input parameters by the usual correlation methods.

1. Introduction

Magnetospheric substorms are the embodiment of many physical processes that occur as the earth’s magnetosphere extracts and dissipates energy from the solar wind. The magnetic field that is embedded within the continuously flowing solar wind plays a crucial role in the magnetospheric interaction since it effectively acts as a “gating” mechanism and thereby controls the amount of energy (and mass) that is extracted from the solar wind flow. In this sense, the magnetospheric substorm may be viewed as the response of the magnetospheric system to the interplanetary magnetic field (IMF).

The status of substorm research (as of 1983) was reviewed in a summary report prepared for NASA and the National Science Foundation (BAKER *et al.*, 1984a). A theme developed in that report was that substorms have components which are “directly driven” by the solar wind, but also have components which are due to energy “loading” and “unloading.” In fact, much of the controversy and debate associated with substorm research in the past several years has revolved around the relative roles of these two aspects of the magnetospheric response.

Figure 1 shows a flow diagram which illustrates the solar wind-magnetosphere-ionosphere interaction sequence during substorms. The figure attempts to summarize how the driven and the unloading facets of the magnetospheric response are combined into an overall substorm sequence. Thus, the diagram represents a synthesis of the two disparate substorm schools of thought.

Fig. 1. A summary of the substorm sequence showing the roles of the magnetotail and the ionosphere and also showing the aspects of substorms which are regarded as driven and unloading processes (adapted from BAKER *et al.*, 1984a).

As shown by Fig. 1, there is universal agreement that the energy to drive substorms comes ultimately from the solar wind. (Note that the mass, i.e., the low-energy seed plasma involved in substorm processes, may come either from the solar wind or the terrestrial ionosphere). As solar wind energy is added to the magnetosphere (normally during an episode of southward IMF) there are two responses. One response is the direct ohmic or convective dissipation of some of the added energy in the ionosphere; the other response is storage of some of the added energy in the earth's magnetotail as excess magnetic energy. To qualify as a substorm, BAKER *et al.* (1984a) concluded that a period of geomagnetic activity must have one or more episodes of sudden onsets of energy dissipation. These are the expansive phase onsets normally identified with auroral intensifications, plasma jetting in the magnetotail, plasma injections at geostationary orbit, etc. This quality of suddenness in substorms is due to the rapid unloading of the magnetotail energy previously loaded from the solar wind. The period of unloading is often a time of very intense, but localized, energy dissipation in the nighttime sector. During the unloading process, much of the added energy appears to leave the magnetotail as plasmoids, and, thus, this is termed "return to solar wind" in Fig. 1.

The synthetical concepts of Fig. 1 have their basis in many relatively old observational results and are supported also by very new observations. As is evident, both the driven and unloading mechanisms are seen to play an important role. This duality is one that should be well-appreciated by the magnetospheric community, and

neither extreme of a completely driven nor a completely internally-unstable system should be adhered to any longer. It is this unifying theme that we would like to pursue in this review. In particular we will try to recount evidence concerning the time scales of the response of the magnetosphere to IMF variations and we will discuss issues surrounding the “best” measures of solar wind energy input and magnetospheric energy output.

2. Empirical Coupling Studies

Most of our understanding of the magnetosphere’s response to solar wind variations has come about from empirical observational studies. Here we review several types of analyses that have been performed.

2.1 *Early statistical studies*

Some of the most important early work on solar wind-magnetosphere coupling resulted from linear cross correlation analyses using hourly-averaged quantities (e.g., review by BAKER, 1986). An example of such a correlation study was the significant study by ARNOLDY (1971). Several solar wind parameters studied by Arnoldy such as plasma number density, velocity, and total IMF strength showed unimpressive cross-correlation strengths when compared with the hourly-averaged *AE* index. On the other hand, the sum of the negative (southward) component of the IMF for the 1-hour interval preceding the *AE* averaging period ($\Sigma B_s \tau$) gave a large value of correlation coefficient ($r \sim 0.8$) with *AE*. This result, which has been confirmed by many subsequent studies, was taken as evidence that substorm activity was causally related to the amount of southward IMF in the impinging solar wind for the hour preceding a substorm expansive phase.

Many solar wind parameters, and many magnetospheric processes, have relatively high-frequency components (compared to an hour time scale). Hourly time averaging of subsequently correlated data is tantamount to a low-pass filtering operation (BAKER, 1986). Thus one-hour averaging may eliminate real, high-frequency features of solar wind-magnetosphere coupling. It is concluded that broad averaging may artificially increase apparent correlations, as well as possibly masking true magnetospheric response time scales. If one is studying such high frequency aspects as IMF control of substorm onset times, one must of course use appropriately time-resolved data set. On the other hand, solar wind components (such as bulk flow speed) which control longer-term magnetospheric variation and which change more slowly can be studied without necessary reliance on very high resolution data.

Figure 2 shows a quasilogarithmic time line marking some of the commonly used averaging intervals for solar wind and magnetospheric data sets. As implied by the diagram, data averages of an hour or more in length make statements primarily about the gross coupling relationships between the IMF and the magnetosphere. During a period of one to several hours, solar wind flow typically carries a parcel of plasma (and embedded magnetic field) over a scale length comparable to, or longer than, the known length of the magnetotail. Further, as pointed out above, such averaging times may mask true magnetospheric response signatures and so one is exploring the broader interactions in using hourly (or greater) averages. On the other hand, for data averages < 1 min, information propagation time scales (for example, Alfvén transit

CORRELATIVE ANALYSIS TIME SCALES

Fig. 2. A quasilogarithmic time scale illustrating commonly used data averaging intervals in solar wind magnetosphere coupling studies (from BAKER, 1986).

times from the magnetosphere to the ionosphere) make it meaningless to correlate magnetospheric parameters with solar wind parameters. BAKER (1986) concluded that since substorm variation time scales are typically in the several minute range, data averages in the 1–10 minute range should be used for substorm studies.

In recognition of the need to correlate solar wind parameters with magnetospheric parameters on relatively short averaging scales, several early researchers almost immediately focused attention on Arnol'dy-type studies with improved data sets. Early studies of this sort, however, tended to preselect analysis intervals based upon the type of geomagnetic activity (i.e. very isolated substorm activity) which was present (e.g., MENG *et al.*, 1973). Figure 3 illustrates the main result from a paper by ROSTOKER *et al.* (1972) which used 5.46-min averages of the solar wind parameter ($E_\phi = -VB_z$), the azimuthal interplanetary electric field component) and the *AE* index. For this limited period of data, the correlation analysis showed a peak correlation coefficient of nearly 0.7 at a lag time of ~ 40 min.

Over the last decade, or so, a great deal of discussion has gone on concerning the “best” interplanetary energy input parameter or function. As noted above, ARNOLDY (1971) emphasized the southward IMF component (B_s) and/or its product with solar wind speed (VB_s). This product has units of electric field and suggests an electrostatic solar wind coupling with the magnetosphere. ROSTOKER *et al.* (1972), as shown in Fig. 3, used the closely related parameter $-VB_z$. This type of physical coupling parameter was quantified by BURTON *et al.* (1975) and termed the half-wave rectifier model: they advocated VB_s as the best solar wind parameter for coupling studies. A different formulation by PERREAULT and AKASOFU (1978) suggested that

Fig. 3. Correlation coefficient of the azimuthal component of the interplanetary electric field with AE for lag intervals of 5.46 min. (from ROSTOKER *et al.*, 1972).

$$\varepsilon = VB^2 \sin^4(\theta/2) l_0^2$$

was the best coupling parameter, where $\theta = \tan^{-1}(B_y/B_z)$ or this angle's supplement for $B_z < 0$, and $l_0 = 7 R_E$. A third point of view (e.g., MURAYAMA *et al.*, 1980) is that $V^2 B_s$ is the best parameter to use.

In relatively recent high-resolution correlation studies, BAKER *et al.* (1981a, 1983) have emphasized evaluations of the VB_s , $V^2 B_s$, and ε parameters. BAKER *et al.* (1981a) found that VB_s and $V^2 B_s$ were virtually identical in their correlative behavior with AE . Furthermore, in this study using 2.5-min time resolution data without event selection, they found VB_s to have features which appeared both qualitatively and quantitatively superior to ε in several respects in the prediction of substorms (as measured by AE). This result is shown in Fig. 4.

This type of work was extended by BAKER *et al.* (1983) to include continuous solar wind measurements by ISEE-3 at 1-min time resolution. In this study the data were separated according to general levels of geomagnetic activity. The overall result found by BAKER *et al.* (1983) was that VB_s , $V^2 B_s$, and ε had virtually identical correlation properties with AE during quiet intervals, whereas ε was less well correlated with AE than VB_s during disturbed intervals. Generally speaking, all correlation levels were lowered during disturbed conditions presumably due to higher frequency, uncorrelated components present in both in the solar wind and magnetospheric data.

Fig. 4. High time resolution, lagged cross-correlation analysis results comparing the efficacy of ϵ and $V B_z$ as predictors of the AE index using IMP-8 data (from BAKER *et al.*, 1981a).

Nearly all workers using high resolution data for cross-correlation analyses have interpreted the lag times between solar wind and magnetospheric parameters in terms of a “response” time of the magnetosphere. This interpretation is probably justified to a significant extent, but due caution should be applied since alternative causes of time lag are possible (BAKER, 1986). To pin down magnetospheric response times, several other methods have proven useful.

2.2 Recent case studies

In magnetospheric coupling studies we need not be content with only remote (i.e., auroral zone) estimates of energy loading and unloading processes—often we can observe magnetotail storage and dissipation directly. A well-documented example taken from in situ spacecraft observations is shown in Fig. 5 (BAKER *et al.*, 1981b). The figure combines particle measurements at geostationary orbit ($6.6 R_E$) with magnetic field data from IMP-8 positioned in the middle of the magnetotail lobe at $\sim 35 R_E$ geocentric distance. The small inset in the middle panel shows the spacecraft positions projected onto the equatorial plane.

Between 2300 and 0100 UT of 28–29 December 1976 the measured IMP-8 tail field strength increased (25→40 nT). It was shown that the tail diameter was approximately constant and, therefore, the magnetic energy density in the tail increased by

$$\delta(B^2/8\pi) = 2B\delta B/8\pi.$$

Using an average $B \sim 32$ nT and $\delta B \sim 15$ nT gave

Fig. 5. The upper panel shows the total magnetic field strength measured by IMP-8 in the Earth's magnetotail lobe at $\sim 35 R_E$ geocentric distance for a portion of 28 and 29 December 1976. The lower four panels show data from geostationary spacecraft 1976-059 at $6.6 R_E$ radial distance. As described in the text, the data provide strong evidence for storage of energy in the tail between 2300 UT and 0100 UT and for rapid dissipation of this energy after the 0100 UT substorm onset (adapted from BAKER *et al.*, 1981b).

$$\delta(B^2/8\pi) \simeq 4 \times 10^{-9} \text{ ergs/cm}^3.$$

Assuming that this energy density was characteristic of the whole lobe region allowed an estimate of the amount of energy stored in the tail for this event. For an effective tail length of $\sim 100 R_E$ and a constant (and conservative) $15 R_E$ tail radius the volume of the tail is

$$V \sim 2 \times 10^{31} \text{ cm}^3.$$

Thus the excess free energy in the tail was estimated to be

$$\delta W = V \cdot \delta(B^2/8\pi) \sim 8 \times 10^{22} \text{ ergs}.$$

Further, by taking a characteristic time δt for the substorm energy dissipation time (see Fig. 5) as ~ 40 min (i.e., ~ 0100 to ~ 0140 UT), then

$$\delta W / \delta t \simeq 8 \times 10^{22} / 2400 \text{ s} \sim 3 \times 10^{19} \text{ ergs/s}.$$

Such results provide direct in situ evidence that large amounts of energy are accumulated in the magnetosphere for an hour or more before substorms and this energy is rapidly converted to other forms (e.g., energetic plasma) during the substorm itself. It was estimated that the total energy contained in the energetic electron component in the outer magnetosphere (cf. Fig. 5) in this case was

$$W_e \sim 6 \times 10^{20} \text{ ergs}.$$

Similar, or larger, estimates were expected to apply to the total substorm-generated energetic proton component. Thus, of order 10^{21} ergs, or greater, appeared in the energetic particle population during this substorm, and this could be readily accounted for by the $\sim 8 \times 10^{22}$ ergs of dissipated energy suggested by IMP 8 observations.

Several recently assembled data sets have provided excellent information with which to examine the details of solar wind-magnetosphere coupling. Among such data sets is the information put together for the CDAW-6 interval (MCPHERRON and MANKA, 1985) and illustrated in part in Fig. 6.

The dotted line in Fig. 6 shows a measure of solar wind energy input to the magnetosphere for a portion of 22 March 1979, namely $-VB_z$. In the half-wave rectifier picture of magnetospheric response to the solar wind, the energy input rate would have greatly increased (due to dayside reconnection) at ~ 1010 UT, i.e., when $-VB_z$ went to positive values (NISHIDA, 1983). This is well supported by the data, since $AE(12)$ began to increase greatly (as did $AE(57)$, available for CDAW-6) at a time ~ 10 min following the "turn-on" of the rectified solar wind energy input. Figure 6 compares the IMP-8 solar wind data explicitly with the total Joule heat production rate (solid line) for the period 0900–1300 UT on March 22; see KAMIDE *et al.* (1983) for a description of the Joule heat derivation.

A relatively modest increase in the total Joule heat production rate was seen from ~ 1020 UT to ~ 1105 UT, and a similar level was again seen after ~ 1240 UT. In

Fig. 6. A comparison of solar wind energy input to the magnetosphere (dashed line) compared to a measure of magnetospheric substorm energy output (Joule heat rate; solid line) for a particular event observed on 22 March 1979. The parameter $-VB_z$ is the dawn-to-dusk component of the solar wind electric field and is a measure of solar wind-magnetosphere coupling. W_{in} is positive for $-VB_z > 0$ and this energy input is estimated by the scale at the far right. W_{out} has several components (see text) but a major one is the Joule heating rate scaled to the far left. These actual results are very similar to the idealization shown in Fig. 7 (adapted from BAKER *et al.*, 1985).

contrast, a large increase in the Joule heat rate was seen between 1105 and ~ 1230 UT. CLAUSER and KAMIDE (1985) and KROEHL and KAMIDE (1985) have shown that the period prior to ~ 1055 UT on March 22 was characterized by the DP 2-type current system, i.e., a twin-cell polar cap convection pattern. After ~ 1055 UT an intense DP 1 current system, centered at approximately the 0200 LT meridian, dominated the ionospheric current and the Joule heat production pattern. Thus the conclusion in this case is rather clear: energy was added to the magnetosphere during the interval ~ 1015 – 1055 UT via coupling to the solar wind. The enhanced DP 2 polar cap current system was the manifestation of this coupling. Relatively small (in absolute magnitude), but global in spatial extent, dissipation was associated with this period preceding the major expansion of the substorm. Then, following 1100 UT, very large, intense dissipation of energy took place, and this dissipation was quite localized in the postmidnight sector of the magnetosphere-ionosphere system.

Figure 6 presents a clear demonstration of the relative roles of “directly driven” and “unloading” processes. As noted above, the dotted curve in the figure is a good solar wind coupling function ($-VB_z$, VB_s , ε , etc., all look very similar in this case), while the solid curve (Joule heat rate) can be regarded as a measure of the

magnetospheric energy output rate. Figure 6 shows a nearly square wave energy input pulse from ~ 1010 UT to ~ 1110 UT after which energy input was turned off. With little delay (~ 10 min after input began) the weak dissipation associated with loading the magnetospheric system was seen in the Joule heat curve. After the energy input was completely turned off, by far the largest Joule heat production rate was recorded (~ 1110 – 1230 UT). Based on these data, it is clear that the energy for this intense phase of dissipation came from the magnetotail, not directly from the solar wind, and was of the classic DP 1 pattern usually associated with a localized nightside substorm “current wedge.”

BAKER *et al.* (1985) concluded that quite often during the energy loading phase of substorms there is a relatively long interval (≥ 1 hr) of fairly low level energy dissipation. This most nearly resembles the directly-driven phase for isolated substorms. This period corresponds to the global polar cap convection interval in which energy is loaded into the magnetotail lobes. At the time of the substorm expansive phase onset, there frequently is a strong intensification of the ionospheric energy dissipation rate which corresponds to the unloading of energy from the tail. Figure 7 summarizes this idealized representation of the isolated substorm sequence and points out quite explicitly the sense in which both driven and unloading aspects of substorms are present. Of course, as geomagnetic activity intensifies it is often true that energy input and energy output become much more commingled than the idealization of Fig. 7 would suggest.

Fig. 7. An idealized illustration of the relationship between magnetospheric energy input (W_{in}) and energy output (W_{out}) during substorms. Energy is typically stored for ~ 1 hr (with concomitant weak dissipation) after which the stored energy is strongly and rapidly dissipated (adapted from BAKER *et al.*, 1985).

A point to note in Figs. 6 and 7 is that case studies show that the directly driven (loading) dissipation sequence for substorms begins quite quickly (10–20 min) after energy input begins. In contrast, the unloading of stored tail energy occurs after a substantially longer delay (~ 1 hr). Hence, it is probably this latter time delay which is largely reflected in the cross-correlation studies described in the previous section. Furthermore, the broadness of cross-correlation peaks probably implies substantial contributions from auto-correlation within the data sets as well as intrinsic “noise” in the measurements.

2.3 Linear prediction filtering

It has proven highly desirable to utilize more powerful statistical methods to assess further the most general response of the magnetosphere to solar wind variations. The method of linear prediction filtering (IYEMORI *et al.*, 1979; CLAUER *et al.*, 1981) has been used quite successfully for such assessments. Such analysis assumes that the magnetosphere can be represented as a linear, time-stationary system. An input time series ($I(t)$, representing a solar wind input parameter) is then compared to an output time series ($O(t)$, representing the magnetospheric response). It is assumed that $O(t)$ can be related to $I(t)$ by specification of an impulse response function, $g(t)$. In practice $g(t)$ can be obtained by deconvolution and transform methods in the frequency domain (see CLAUER, 1986 for details). The values of $g(t)$ are the filter elements and, in principle, specify completely the relationship between the solar wind and the magnetosphere, insofar as these two regimes are, in fact, linearly related.

Linear prediction filtering provides a means of comparing the directly driven and unloading models of magnetospheric response. Since it uses a filter of time lagged response coefficients to quantify the relationship between the input and output of a linear, time-invariant system, the linear prediction filtering method has a major advantage over conventional cross-correlation methods. Once a filter is obtained, it can be convolved with the input time series to predict the output time series of the system. A comparison of the predicted and observed time series reveals which input components are transferred through the system to the output time series.

BARGATZE *et al.* (1985) used linear prediction filtering to study IMP-8 solar wind plasma data, IMP-8 IMF measurements, and the auroral electrojet AL index from the time interval November 1973 to December 1974. All of the data were at 2.5-minute time resolution and were a subset of the data used by BAKER *et al.* (1981a) to study the correlation between the AE index and interplanetary parameters.

An innovative method of ranking geomagnetic activity was used by Bargatze *et al.* in which the integral occurrence percentages of the AL index for each data period were calculated to find the median value of the index in each interval. The median AL index values were then used to order the data intervals from weakest levels of geomagnetic activity (small absolute AL index medians) to strongest levels of geomagnetic activity (large absolute AL index medians). In all, thirty filters were calculated using the 34 intervals in the analysis data set. These filters were numbered from 1 to 30 with #1 and #30 representing the impulse response of the magnetosphere during weakest and strongest levels of geomagnetic activity, respectively.

In Fig. 8, filters #10 and #27 of the BARGATZE *et al.* (1985) analysis are displayed. Both of these filters have a response pulse which rises quickly from near zero response at zero time lag, which reaches a peak value near 20-minutes time lag, and which

Fig. 8. A plot of filters #10 and #27 in the analysis of BARGATZE *et al.* (1985). These filters correspond to moderately and strongly active data intervals respectively. The vertical axis is plotted using the units of the AL index (nT) divided by units of the solar wind electric field (mV/m) and normalized by the data sampling period (150 seconds).

decays thereafter. In addition, filter #10 possesses a second response pulse which reaches a peak value at a time lag of about 60-minutes. Both filters decay back to zero response at a time lag of about 2.5-hours.

The Bargatze *et al.* interpretation of these results is that the 20-minute and 60-minute pulses each correspond to a separate response mode of the magnetosphere. It is concluded that the 20-minute pulse corresponds to the enhancement of current flow in the ionosphere in response to magnetospheric convection driven directly by solar wind interaction. Similarly, it is concluded that the 60-minute pulse corresponds to the enhancement of current flow in the ionosphere in response to the release of stored electromagnetic energy from the magnetotail. Hence, the linear filtering results suggest that both the directly driven and unloading models of magnetospheric response are important in describing the complete response of the magnetosphere to solar wind variations—very much in keeping with the case study results presented above.

2.4 Polar cap and distant tail results

Most of the unloading aspects of substorms have been inferred using instrumentation on spacecraft at geocentric distances $\leq 40 R_E$. The model has been quite successful in ordering many of the observations in the near-earth plasma sheet (see, for example, the review by HONES (1979)), but definitive further tests of the model can be envisioned wherein observations in the more distant magnetotail ($r > 40 R_E$) are invoked. In particular, the usual unloading model of substorms argues that substorm neutral lines form within the near-earth plasma sheet ($r = 10\text{--}20 R_E$) and thus it is in

this region that major substorm energy dissipation initially occurs.

The redeployment of ISEE 3 from its continuous monitoring of the solar wind in a large orbit about the upstream Lagrangian point to an extended magnetotail orbit afforded an opportunity for deep-tail correlative studies. Through the use of lunar gravitation-assisted orbital maneuvers, ISEE 3 was kept for extended periods (~ 3 months) during 1983 in the deep-tail region. Initial findings concerning plasmas at $\sim 220 R_E$ on the first deep-tail pass have been reported by BAME *et al.* (1983) and HONES *et al.* (1984). BAKER *et al.* (1984b) described results obtained in the geocentric radial range of 60–90 R_E during the first tail passage of October 1982 and in the radial range 200–220 R_E during the near-apogee part of the second tail passage in January–February 1983.

Much observational work has shown that the occurrence of taillike field (and concomitant cigarlike pitch angle distributions of low-energy electrons) at 6.6 R_E is a repeatable substorm storage phase feature. Such phenomena, therefore, have been interpreted in terms of an increase of stored magnetic energy in the magnetotail (e.g., BAKER *et al.*, 1981b) which is available free energy for the unloading process of substorm expansion phase onset. Both on observational grounds (FAIRFIELD and NESS, 1970; MCPHERRON *et al.*, 1973) and on theoretical grounds (CORONITI and KENNEL, 1972; BIRN and SCHINDLER, 1983) it is expected that during the storage phase there should be an increased flaring of the magnetotail and thus the cross-sectional dimension of the distant tail would increase. Similarly, as energy is released (dissipated) from the tail, the diameter of the tail should decrease. Strong corroboration of this idea, in fact, was obtained from observations in the cislunar region by MAEZAWA (1975) and CROOKER and SISCOE (1979). The ISEE 3 data along the deep magnetotail flank provided an additional test of this feature.

The ISEE-3 distant tail data (BAKER *et al.*, 1984b) were most simply interpreted as indicating that during the growth phase of a substorm in the near-earth region, the distant tail increases in diameter (flaring tail model). Conversely, when a substorm expansion phase onset occurs and magnetotail energy is rapidly converted to other forms (hot plasmas, etc.), in the near-earth region, the tail apparently collapses substantially in radius.

The ISEE-3 results have led us to picture (Fig. 9) the storage phase as follows. A southward turning of the interplanetary field lines enhances the rate at which magnetic reconnection occurs on the dayside of the magnetosphere. As these newly connected lines are dragged into the tail, magnetic and plasma energy is added at an enhanced rate, and the tail grows in diameter. During such observations, ISEE-3 was often positioned in an almost stationary fashion outside the distant magnetotail surface so that growth of the tail would eventually cause it to envelop the spacecraft. Models (see below) show that during a substorm growth phase we should expect the magnetotail to increase in diameter by several earth radii. The observations with ISEE-3 are a strong confirmation of this idea (BAKER *et al.*, 1984b).

CORONITI and KENNEL (1972) estimated the tailward distance at which tail flaring would cease to be important. This distance, X , is given by

$$X_f = X_0 + MR_f \left[0.6 - \frac{1}{3} (R_0/R_f)^3 \right]$$

where X_0 is the initial downstream position of a taillike field, M is the upstream sonic

DE AURORAL IMAGES:

TAIL ENERGY STORAGE (GROWTH) PHASE

EXPANSIVE PHASE

Fig. 9.

Mach number, R_0 is the tail radius at X_0 , and R_f is the asymptotic radius of the tail at the end of the flaring region. Using values of $X_0 \sim 10 R_E$, $M \sim 7$, $R_0 \sim 20 R_E$, and $R_f \sim 30 R_E$, SLAVIN *et al.* (1983) estimated $X_f \sim 115 R_E$. This point for flaring to cease was found by SLAVIN *et al.* (1983) to be in good agreement with direct ISEE 3 field measurements along the length of the distant tail.

Beyond the flaring region, magnetic pressure ($B^2/8\pi$) should not increase as flux is added to the magnetotail during substorm storage phases. Thus roughly beyond $\sim 100 R_E$ geocentric distance in the tail one would simply expect the tail to grow in cross-sectional area A as magnetic flux is added. The added flux is related to the area A and the field magnitude $|B|$ by

$$\phi = \int |B| dA$$

and therefore for an approximately constant tail lobe field strength (SLAVIN *et al.*, 1983) and assumed circular tail cross section we have

$$R^2 = \phi / \pi B_0, \quad \Delta R = \frac{\Delta \phi}{2\pi R B_0}.$$

Assuming a change of flux of 10–20% in each tail lobe during a typical growth phase, the above formula shows that radial expansions of the distant tail radius by 2–4 R_E are readily obtainable.

Inside a geocentric distance of $\sim 100 R_E$, the flaring tail model would predict increasing tail radius *and* increasing magnetic energy densities in the tail lobe during energy storage phases. Such predictions have been well substantiated both by the recent ISEE 3 observations (BAKER *et al.*, 1984b) and by many previous studies (e.g., MAEZAWA, 1975; FAIRFIELD *et al.*, 1981; BAKER *et al.*, 1981b). Thus there is little doubt concerning the loading of energy into the magnetotail lobes during substorm storage phase episodes, with the subsequent unloading of this energy by near-earth dissipative processes.

Such results in the distant tail fit very well with recent auroral imaging results obtained from the Dynamics Explorer (DE) spacecraft (FRANK, 1986). As shown at the top of Fig. 9, in a general sense, the polar cap is seen to increase in area during the substorm storage phase (i.g. for periods of 40–60 min before the substorm expansion phase onset). Since the polar cap maps into the distant tail lobes, an increased polar

Fig. 9. (Upper portion) Storage-phase model. Before the storage phase of a substorm begins, the magnetotail is relatively small in cross section, and, quite often, ISEE-3 resides outside the distant ($\sim 200 R_E$) tail. As plasma and energy are added to the tail, the cross section apparently grows until ISEE-3 is enveloped. The data show this as an inward transition from outside the magnetosphere to one of the tail lobes. such lateral growth of the tail is seen all the way from geosynchronous orbit (6.6 earth radii) to more than 200 earth radii down the tail. It is also manifested in auroral and polar cap images taken at low-altitudes by the DE-1 spacecraft, illustrated at the very top. (Lower portion) After plasma and energy have built up in the magnetotail during the storage phase, a portion of the plasma sheet is severed by reconnection close to Earth, causing substorm onset. The plasmoid thus formed hurtles down the tail, eventually enveloping ISEE-3 about thirty minutes later at its vantage point nearly 1,400,000 kilometers from Earth. The envelopment is seen by instruments in the spacecraft as a transition into the plasma sheet. White arrows indicate plasma flow; black arrows indicate the direction of the magnetic field (adapted from HONES *et al.*, 1984).

cap area translates into an increased magnetic flux in the lobes. Frank and coworkers have performed flux computation analogous to those above (within the Kennel-Coroniti framework) and find good agreement with the polar cap areal changes recorded by *DE* images. Hence the storage (growth) phase is a global, self-consistent phenomenon.

An additional, exciting aspect of the ISEE-3 data in the distant tail was the confirmation of the release of plasmoids at substorm expansive phase onset. This feature is illustrated in the lower part of Fig. 9. In the neutral line model of substorm energy unloading (e.g., HONES, 1979), the plasma sheet is severed close to earth, flows tailward as a plasmoid, and reaches ISEE-3 about twenty or thirty minutes later. The delay in arrival is consistent with the bulk flow speeds measured for the plasma of about 500 to 1000 kilometers per second. The plasmoid's dimensions increase substantially as it departs because it is moving through regions of decreasing magnetic pressure. The large size of the plasmoid results in a bulge in the magnetopause that travels along with it (HONES *et al.*, 1984).

Thus, the ISEE-3 results in the distant tail indicate several things:

1. The growth phase is a global feature which involves the storage of energy throughout the entire length of the tail from 6 R_E to at least 200 R_E .
2. Substorm disturbances are clearly initiated in the near-tail region and propagate at large velocities into the distant tail.
3. The tail regularly grows in diameter by several earth radii during the growth phase of substorms and may expand locally by an even larger factor as plasmoid structures move tailward past a given location.
4. Large tailward bulk plasma motions at $\sim 200 R_E$ are usually related to substorm dynamical processes that produce particle injection events at 6.6 R_E and intense auroral dissipation events.

3. Recent Dimensional Analysis Results

Empirical studies of coupling parameters in the solar wind which appear to control geomagnetic activity have taken a variety of forms as discussed above. In fact, however, there are physical constraints placed upon the form of coupling parameters. Such constraints emerge from a proper dimensional analysis of the coupling problem (VASYLIUNAS *et al.*, 1982).

BARGATZE *et al.* (1986) used the theoretical constraints imposed by dimensional analysis as a guide to develop a general formula for P_i , the rate of solar wind-magnetosphere energy transfer. This general equation is:

$$P_i = \rho V^3 l_{CF}^2 F(M_A, \theta) \quad (1)$$

where, ρ is the solar wind plasma density, l_{CF} is the Chapman-Ferraro scale length ($l_{CF} = (M_E^2 / \mu_0 \rho V^2 P)^{1/6}$), M_A is the Alfvén Mach number ($M_A^2 = (\mu_0 \rho V^2 / B_T^2)^{1/2}$), θ is the IMF clock angle, and F is a function whose form is to be specified by the analysis. Other quantities include M_E , the earth's magnetic dipole moment, μ_0 , the permeability of free space, B_T , the magnitude of the vector sum of the IMF B_Y and B_Z components measured using geocentric solar magnetospheric (GSM) coordinates, and θ , the angle equal to the arc subtended by the GSM Z -axis and $\vec{B}_T$.

Equation (1) above explicitly assumes that the amount of energy which is transferred from the solar wind to the magnetosphere is proportional to the amount of solar wind kinetic energy that is intercepted by an energy "collection" region on the magnetopause. It includes the function F in order to model the magnetohydrodynamic interactions which are responsible for the energy transfer. BARGATZE *et al.* assumed along with VASYLIUNAS *et al.* (1982) that $F = M_A^{-2\alpha} G(\theta)$, where α is the MHD coupling exponent, and $G(\theta)$ is a function which modulates the rate of energy input depending upon the orientation of the IMF.

In Eq. (1), if one assumes $P_i \propto AL$ and if one has an upstream solar wind monitor, only the quantities α and $G(\theta)$ remain undetermined. BARGATZE *et al.* (1986) then performed several different analyses to specify the best forms of the α - and $G(\theta)$ -dependences through statistical analyses. Two of these results are reviewed here.

In the first analysis, $G(\theta)$ was assumed to be equal to $\sin^4(\theta/2)$, i.e., as in the formulation of ε . By using Eq. (1) with $F = M_A^{-2\alpha} G(\theta)$, and by manipulating the equation to solve explicitly for α , BARGATZE *et al.* used their large data set described previously (BARGATZE *et al.*, 1985) to solve explicitly for α in a large number of cases. The number of occurrences of a given value of α is shown in Fig. 10. As may be seen, there is a broad distribution of occurrences, but the most probable value of α is ~ 0.5 .

As shown in BARGATZE *et al.* (1986) a value of $\alpha = 1.0$ (in their formulation) implies

$$P_i \propto VB^2 G(\theta)$$

ALPHA' OCCURRENCE HISTOGRAM -- AL INDEX

Fig. 10. The number of occurrences of α' is plotted versus the magnitude of α' (Note that α' is equal to $1.0 - \alpha$). These results summarize the MHD coupling analysis of BARGATZE *et al.* (1986).

which is closely akin to the ε parameter (PERREAULT and AKASOFU, 1978; KAN and AKASOFU, 1982). On the other hand, $\alpha=0.5$ implies

$$P_i \propto VBG(\theta)$$

which is closely akin to the VB_s parameter. The analysis of Fig. 10 strongly favors a VB_s -type of interaction.

As a separate analysis, BARGATZE *et al.* (1986) also examined the $G(\theta)$ form explicitly. To do this analysis they again performed a statistical study using measured values in Eq. (1), but this time holding $\alpha=0.5$ (in keeping with Fig. 10 results). The "best" values of $G(\theta)$ were determined for broad θ -groupings of data and the results are plotted in Fig. 11. For comparison, two functional forms ($\sin^4\theta/2$ and $\cos\theta$) are also shown. The data are replicated quite well by the $\sin^4(\theta/2)$ curve. Hence, Bargatze *et al.* found that the ε -like gating function was most consistent with the data.

In summary, the dimensionally-constrained analysis results suggest that the MHD coupling exponent, α , is equal to 0.5 ± 0.1 . If α is equal to 0.5, the rate of energy transfer is given by $\rho V^3 k l_{CF}^2 M_A^{-1} G(\theta)$, where $k = \text{const}$. This function is proportional to $(\rho V^2)^{1/6} VBG(\theta)$ where, ρV^2 is the solar wind dynamic pressure. Thus, the results suggest that P_i is closely related to the strength of the solar wind motional electric

SUMMARY OF AL-G(THETA) RESULTS

Fig. 11. Empirical estimates of the gating function, $G(\theta)$, are plotted versus the IMF clock angle, θ . Two functions, $\sin^4(\theta/2)$ (upper solid curve) and $U(\theta) \cos(\theta)$ (lower solid curve), are shown for comparison. The empirical $G(\theta)$ -values were normalized such that they approach 1.0 for $\theta=180^\circ$, and an "error" baseline was subtracted before normalizing the $G(\theta)$ -values (from BARGATZE *et al.*, 1986).

field. Since P_i depends upon the solar wind dynamic pressure, the scale length of the magnetosphere (which is inversely proportional to ρV^2) also plays an important role in determining the rate of energy transfer. These conclusions differ from the conclusions reached by KAN and AKASOFU (1982) who found that $P_i \approx \varepsilon$.

The results of the gating function analysis suggest that $G(\theta)$ is best represented by a rectifier function such as $\sin^4(\theta/2)$ which is used in the definition of ε . BARGATZE *et al.* used the term “leaky” since a function like $\sin^4(\theta/2)$ allows for a small amount of energy input when the IMF is northward. In contrast, the half-wave rectified function like that used in the definition of VB_s does not allow for any energy input when the IMF is northward.

4. Total Magnetospheric Energy Output

Much of the correlative and other statistical work cited above has relied on one basic, simple parameter to measure magnetospheric response, viz., the AE (or closely related AL) index. In its usual form, AE is determined from only 12 auroral zone stations, but even in its much more detailed form of $AE(57)$ or $AE(70)$, this index is admittedly an imperfect measure of total magnetospheric response (see AKASOFU, 1981; KAMIDE *et al.*, 1983). At a minimum of concern, the AE and AL indices simply measure auroral electrojet currents and only by a variety of assumptions can one argue that these indices are a measure of major magnetospheric energy dissipation rates (e.g., BAUMJOHANN, 1986).

For the above reasons, it has proven desirable to develop and test continuous parameters which measure the total magnetospheric energy dissipation rate. PERREAULT and AKASOFU (1978) identified three terms as comprising the total energy dissipation rate:

$$U_T = U_R + U_J + U_A .$$

In this equation (each term of which is an explicit function of time), U_R is the ring current energy injection rate, U_J is the Joule heat production rate in the ionosphere, and U_A is the auroral particle energy flux. Although these three terms are the dominant ones in the inner magnetosphere (see also AKASOFU, 1981), there may be important missing components such as terms due to plasmoid escape (BAKER *et al.*, 1983).

In spite of possible intrinsic deficiencies in U_T , this parameter has been commonly used and compared with various solar wind input parameters (e.g. AKASOFU, 1981; BAKER *et al.*, 1983; AKASOFU *et al.*, 1985). In its current formulation, U_T is explicitly computed in terms of the Dst and AE indices:

$$U_R = 4 \times 10^{20} \left(\frac{\partial \overline{Dst}}{\partial t} + \frac{\overline{Dst}}{\tau_R} \right)$$

$$U_J = 2 \times 10^{15} \cdot AE$$

$$U_A = 1 \times 10^{15} \cdot AE .$$

Here, $\overline{Dst} = Dst - (aP^{1/2} - b)$ which is a dynamic pressure-corrected value of the Dst index and AE is specified in nT. With these conventions, U_T is determined in units of ergs/sec and may be compared directly with such input parameters as ε (discussed above).

In nonstorm intervals, U_T is poorly determined and is not very useful (BAKER *et al.*, 1983; AKASOFU *et al.*, 1985). On the other hand, during moderate to intense storm intervals U_T is completely dominated by the U_R term, i.e. by ring current effects.

In a recent paper, AKASOFU *et al.* (1985) used the method of linear prediction filtering to assess the relationship between ε and U_T . One of their primary findings is illustrated in Fig. 12(a). In determining the impulse response function for many intervals, Akasofu *et al.* found a strongly dominant filter peak in the first time step, i.e., at essentially zero lag time. This "zero-lag effect" was suggested by AKASOFU *et al.* (1985) to be consistent with a strong, or even dominant, directly driven component of geomagnetic activity. This point was made even more strongly by AKASOFU (1985) who argued that such a feature of the analysis was conclusive proof that the magnetosphere is primarily a driven system.

Now the existence of a zero-lag peak in the linear prediction filter elements is surprising and physically implausible for a variety of reasons. Firstly, it is necessary to time-shift the solar wind measurements from ISEE-3 (which was used in this study) to the earth: this involves shifts of typically 30–60 minutes with uncertainties of at least 10 minutes (which is broader than the zero-lag peak). Furthermore, there are finite information propagation times (Alfvén times) of several minutes from the dayside magnetopause to the ionosphere and at least comparable propagation times from the outer magnetosphere into the heart of the ring current region. Finally, there is empirical evidence from many of the earlier correlation studies cited that the auroral zone takes at least 10 min to respond to solar wind changes. All of these arguments suggest that the zero-lag peak in Fig. 12(a) is an artifact of the analysis method in some way.

ZWICKL *et al.* (1985) undertook an analysis of this problem to try to determine how the zero-lag effect arises. In their investigation, they dissected U_T into its several component terms to see how each is actually calculated and to determine which terms are dominant. From the several published accounts of U_T determination, Zwickl *et al.* found that typically during storm intervals the term $\overline{Dst}/\tau_R$ is the largest, where τ_R is the ring current lifetime. Furthermore, (see, e.g., AKASOFU, 1981), τ_R is *assumed* to be dependent on ε :

$$\begin{aligned}\tau_R &= 0.25 \text{ HR for } \varepsilon > 5 \times 10^{19} \text{ erg/s} \\ &= 0.50 \text{ HR for } 1 \times 10^{19} \text{ erg/s} < \varepsilon < 5 \times 10^{19} \text{ erg/s} \\ &= 1.00 \text{ HR for } 5 \times 10^{18} \text{ erg/s} < \varepsilon < 1 \times 10^{19} \text{ erg/s} \\ &= 2.00 \text{ HR for } 1 \times 10^{18} \text{ erg/s} < \varepsilon < 5 \times 10^{18} \text{ erg/s} \\ &= 20.00 \text{ HR for } \varepsilon \leq 10^{18} \text{ erg/s}.\end{aligned}$$

Thus, as ε increases or decreases, a step-like increment is introduced into the U_T value via $\overline{Dst}/\tau_R$.

Fig. 12. Linear prediction filtering results based on a comparison of U_T with ϵ . Panel (a) shows the results obtained by AKASOFU *et al.* (1985) for a period of 29 September 1978, including a large peak at zero lag time. Panel (b) shows the results obtained for the same period by ZWICKL *et al.* (1985).

Figure 13 is taken from ZWICKL *et al.* (1985) and shows the effects of the above steplike variation of τ_R . The upper panel of Fig. 13 shows the value of $\partial \overline{Dst}/\partial t$ computed throughout the day of 29 September 1978 and this is rather small at all times. The second panel, by contrast, shows $\overline{Dst}/\tau_R$ using the above formulation and the steplike changes of τ_R are quite evident. The sum of the first two panels gives the third panel, U_R . By multiplying the observed AE on this day by 3×10^{15} one gets $U_I + U_A$; this is shown in the fourth panel of Fig. 13 and it is mostly insignificant compared to U_R . The lower panel of Fig. 13 shows the total U_T computed by Zwickl *et al.* using the above-identified prescription.

As should be quite evident from Fig. 13, defining the dominant term in U_T (the output parameter) in terms of ε (the input parameter) introduces a very strong correlation between U_T and ε . In fact, AKASOFU *et al.* (1985) used a slightly more refined and smoother relationship between ε and τ_R in their computations. Their results for ε and U_T during the period 0500–1800 UT on 29 September 1978 are shown in Fig. 14(a). Nonetheless, a high correlation between the two time series is enforced by the assumptions made in calculation U_T .

What then do these results mean regarding statistical comparisons of ε and U_T and, in particular, what do these results imply concerning the zero-lag effect of Fig. 12(a)? As should be clear from the above discussion, the present methods of calculating U_T more or less ensures a large, short time-lag correlation between ε and

Fig. 13. A demonstration of the relative contribution of various terms in the U_T parameter on 29 September 1978 as computed by ZWICKL *et al.* (1985).

Fig. 14. (a) The values of ϵ , U_T (computed) and U_T (predicted) for the period 0500–1800 UT on 29 September 1978 as determined by AKASOFU *et al.* (1985). (b) The same parameters determined by ZWICKL *et al.* (1985) using a different formulation for U_T .

U_T . A strong, step-like signal superimposed on an otherwise smoother and more random variation of one parameter with another will completely dominate a cross-correlation analysis (see BAKER, 1986 and references therein). Thus, any cross-correlation analyses between ε and U_T (as in BAKER *et al.*, 1983) must be regarded with extreme caution and such correlation analyses probably are almost entirely useless.

As made clear, for example, by CLAUER (1986), the linear prediction filtering method is basically a cross-correlation method also. Thus, the inherent correlation with ε introduced in the computation of U_T makes prediction filtering entirely unsuitable for assessment of the relationship of ε and U_T .

Figure 12(b) shows the linear prediction filtering results obtained by ZWICKL *et al.* (1985) using a single fixed value of τ_R ($= 1$ Hr) on 29 September 1978. As may be seen, most of the filter elements are similar to those in Fig. 12(a), but the large zero-lag peak has disappeared. Hence, Zwickl *et al.* conclude that the zero-lag effect is entirely an artifact of the assumed correlation between ε and U_T .

Figure 14(b) shows a computation of U_T (second panel) using $\tau_R = 1$ Hr. The third panel shows the predicted U_T using the filter of Fig. 12(b) convolved with ε (upper panel). Here U_T is much less similar to ε (compare Fig. 14(b) with Fig. 14(a). We conclude that, at present, a single τ_R , independent of ε , is more acceptable on physical grounds and it avoids the pitfall of a built-in solar wind dependence.

We would argue on the basis of the work of Zwickl *et al.* that the present formulation of U_T is very problematic. In particular, since it *assumed* that U_T depends on the level of ε , a very strong correlation is introduced *a priori*. Hence, cross-correlation analysis (e.g., BAKER *et al.*, 1983) and linear prediction filtering analyses (e.g., AKASOFU *et al.*, 1985) are not permissible methods of assessing the physical response of the magnetosphere (as measured by U_T) to variations in the solar wind (as measured by ε). Especially importantly, we would point out that the arguments of AKASOFU (1985) that the magnetosphere is quite dominantly a driven system are based strongly on the zero-lag peak in the prediction filters. This zero-lag peak is very much an artifact of the analysis.

5. Summary and Conclusions

We have reviewed several aspects of the evidence showing control of substorms by the solar wind and the IMF. Statistical studies over the past decade, or more, have elucidated this control and have left little doubt about the fundamental role that energy transfer from the solar wind to the magnetosphere plays. In this sense, magnetospheric activity is driven by the solar wind and IMF. However, it is also clearly revealed by these studies that internal magnetospheric instabilities play a vital role in substorms. In almost all cases, one can see evidence that the magnetosphere stores energy for substantial periods in the magnetotail prior to rapidly releasing this stored energy at substorm expansive onset. Hence, we have concluded in this review that the magnetosphere exhibits both a “driven” and an “unloading” response to the IMF-controlled solar wind energy transfer. These two facets of the interaction are intimately related and cannot be considered in isolation.

New case studies, and recent innovations in statistical analysis such as linear prediction filtering, demonstrate that the magnetosphere responds on two separate time scales. The driven response is relatively short, viz., 10–20 min. On the other hand,

the energy unloading timescale seems typically to be ~ 1 Hr. Direct in situ evidence supports the contention that energy is stored in the magnetotail lobes and that this energy is rapidly released due to instabilities in the near-earth plasma sheet. Recent *DE* polar imaging and ISEE-3 deep-tail data support these interpretations.

As illustrated by our discussion here of the “zero-lag” effect (Figs. 12–14), extreme caution must be used as one employs statistical methods to assess the magnetospheric response to solar wind influence. Built-in relationships can often be quite subtle, but can nonetheless completely invalidate statistical comparison methods.

Based on the rather significant limitations of the U_T parameter revealed by the ZWICKL *et al.* (1985) analysis discussed above, we would conclude by arguing that new, improved methods of estimating magnetospheric energy output are needed. In particular, a parameter like U_T , but one that is independent of the solar wind input, is badly needed. In the future, it would also be highly desirable to monitor continuously for other energy loss terms such as plasmoids in the distant tail.

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