Recent Progress in Studies of Magnetospheric Storms and Substorms[†]

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We have made various degrees of progress during the last two years in the areas covered by Topic III-6, Magnetic Storms and Substorms, including Aurora-Magnetospheric Relations. The finding of the V -potential structure above the auroral oval was certainly an important milestone in the history of magnetospheric research. The relationship between field-aligned currents and ionospheric currents has become increasingly clear during the last few years. Extensive attempts have been made to understand how the solar wind couples its energy to the magnetosphere and to find the expression for the rate of input energy from the solar wind to the magnetosphere. On the basis of this progress, a new model of the solar wind-magnetosphere relationship has begun to emerge.

The interpretation of observed magnetotail phenomena is still very confusing. Some of the problems associated with this confusion are discussed. Decisive observations to identify the basic processes associated with the “injection” of ring current particles have not been made. However, the finding of O^+ ions in the ring current belt was an exciting event during the last two years.

1. Introduction

There is no doubt that magnetospheric substorms can be considered to be, in many aspects, the most basic dynamical process occurring in the magnetosphere-ionosphere system. This is clearly demonstrated in recent two books by AKASOFU (1977) and NISHIDA (1978) which present details of substorm processes and their physical interpretations. Over the last two years, which this review paper attempts to cover, there has been a considerable amount of work done in the areas of magnetospheric storms and substorms. In this report, we describe some of the highlights of our progress as well as some of the crucial problems which will hopefully be clarified during the next several years.

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2. Definition of Substorm

Perhaps the most exciting topic that must be mentioned is a small-group workshop held in Victoria, Canada in August of 1978. Nine magnetospheric physicists active in the area of substorm research met on campus of the University of Victoria for three days to attempt to reach a consensus on the definition of substorms.

To understand physical processes which are responsible for magnetospheric substorms, one must know the time sequence of various signatures associated with substorms. This timing is especially important for the establishment of cause-and-effect relationships among various complex phenomena occurring during substorm activity. One of the most basic goals of our study is to understand under what conditions a substorm begins.

The original definition of substorm onset was 'the sudden brightening of an equatorward aurora near midnight' by AKASOFU (1964). In extending this substorm concept, AKASOFU *et al.* (1965) showed that the polar magnetic signature of substorm onset was a sudden intensification of the westward electrojet right beneath that brightening auroral arc. It was then suggested that the sudden decrease of the auroral zone H component magnetic field near midnight can also be used as a signature of substorm onset. Later, other phenomena were also correlated with the H onset and found to undergo sudden changes as well. However, it has become clear, unfortunately, over this decade of research, that these different substorm manifestations do not always provide the same substorm timing. As a result, different groups have used different signatures to define the time frame of substorms. At the present time, many individuals and groups are involved in a study of processes which constitute magnetospheric substorms. One of the major problems in this research is to synthesize the relationship among these processes resulting from the solar wind-magnetosphere interaction.

However, there has been no agreed definition of a magnetospheric substorm. Further, many researchers are not familiar with the different techniques for timing and ordering various substorm phenomena. The intercalibration of the available signatures for substorms is urgently needed. The main purpose of the Victoria workshop was to alleviate these problems by summarizing what we have really established during the last twenty years of substorm research and by making clear what the source of the controversy is. The final document describing the decisions reached by all nine participants is published by ROSTOKER *et al.* (1980).

The agreed definition of a magnetospheric substorm is as follows: A magnetospheric substorm is a transient process initiated on the nightside of the earth, in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and in the magnetosphere.

This substorm concept was further extended to an operational definition in

terms of measured parameters commonly available to researchers, as follows: A substorm is an interval of enhanced energy dissipation during which the strength of the auroral electrojets increases from and returns to the background level. During this interval there may be a sequence of intensifications of the electrojet, each associated with the generation of a Pi2 burst and a westward traveling surge. As the substorm develops, the region of disturbed aurora near midnight expands poleward and westward, reaching eventually a maximum latitude and beginning to recover. This working definition differs somewhat from the original definition of the auroral substorm by AKASOFU (1964). He established the framework upon which the magnetospheric substorm phenomenon has been described to date.

The followings are some other items that are agreed by the nine authors:

1) There is no inherent difference between physical processes responsible for weak and intense substorms.

2) If the interplanetary magnetic field (IMF) has a significant northward component for an interval of time greater than several substorm time constants, the magnetosphere approaches a state of lowest activity; the probability of substorm occurrence approaches zero.

3) As the IMF turns away from this state, there can be an interval of enhanced convection prior to the first substorm expansion. Substorms can be triggered during periods in which the IMF has either a northward or a southward component.

4) Substorm onset is signalled by the brightening of an arc located near the equatorward boundary of the oval of discrete auroras.

5) For the present time magnetograms from auroral oval and low latitude observatories can be used to define substorm onsets, if used with caution.

It may also be important to note that the "Victorian Nine" agreed unanimously that a substorm is associated with diversion of the cross-tail current to the polar ionosphere.

3. Relationship between Substorms and Solar Wind Parameters

There have been a large number of studies which have attempted to correlate geomagnetic indices with solar wind parameters. Table 1 summarizes most of the past work of such correlation studies.

The general practice in this study has been (i) to choose or devise a particular geomagnetic index and (ii) to attempt to find a solar wind parameter or a specific combination of two or more of them. As the solar wind parameters, most workers have chosen the solar wind speed V and the density n , the interplanetary electric field E , the interplanetary magnetic field $B(B_x, B_y, B_z)$ and the variance (σ) of these quantities. As Table 1 shows, for a chosen geomagnetic index, there is a particular solar wind quantity or a combination of them which correlates with it.

Table 1. List of the correlation studies between geomagnetic indices and solar wind parameters.

Author(s)	Geomagnetic index (time resolution)		Relation with solar wind parameters
SNYDER <i>et al.</i> (1963)	$\sum Kp$	(24 hr)	$\sum Kp = (V - 330)/8.44$
OLHERT (1968)	$\sum Kp$	(24 hr)	$\sum Kp = (V - 262)/6.3$
BALLIF <i>et al.</i> (1969)	Kp	(3 hr)	$Kp = 9 \left\{ 1 - \exp \left(\frac{-\sigma B_{T,N} - 0.35}{7.70} \right) \right\}$
ARNODY (1971)	AE	(1 hr)	$AE = -0.26 (\sum B_s \tau)_0 - 0.91 (\sum B_s \tau)_1,$ $-0.33 (\sum B_s \tau)_2 + 0.12 P_0$
BROBOV (1973)	Kp	(3 hr)	$Kp = f(V, B_s, \Delta B_s)$
GARRETT <i>et al.</i> (1974)	ap, AE	(1 hr)	$ap, AE \propto C_1 + C_2 V \langle B_s \rangle + C_3 V \sigma$
MURAYAMA and HAKAMADA (1975)	AE	(1 hr)	$AE = C B_s V^2$
BURTON <i>et al.</i> (1975)	Dst	(2.5 min)	$\frac{d}{dt} Dst_0 = F(E) - a Dst_0$
CROOKER <i>et al.</i> (1977)	Ap		$Ap = 3.5 \times 10^{-5} B_z V^2 - 1.9$
SVALGAARD (1977)	am	(3 hr)	$am = 6.6 q(f, \alpha) \left\{ \frac{B V_0}{21} \right\} \left[\frac{n V_0^2}{105} \right]^{1/3}$ $\times \frac{1.157}{(1 + 3 \cos^2 \phi)^{2/3}}$
PERREAULT and AKASOFU (1978)	AE, Dst	(1 hr, 6 min)	$\bar{U}_T = V B^2 \sin^4(\theta/2) l_0^2$
MAEZAWA (1979)	AL, AU, am	(1 hr)	$AL \propto B^{0.85} V^{2.08} (\sin \theta)^{0.54}$ $AU \propto B^{0.67} V^{1.15} (\sin \theta)^{0.34}$ $am \propto B^{1.08} V^{2.34} (\sin \theta)^{0.37} n^{0.2}$
HOLZER and SLAVIN (1979)	AL	(1 hr)	Rate of erosion $\frac{d\phi_e}{dt} = 0.2(1.9 \times 10^{10} \text{ cm}) B_s V_{sw} \text{ (km/sec)}$ Rate of return $\frac{d\phi_r}{dt} = 1.8 \times 10^{10} AL \text{ (r)}$
MURAYAMA (1979)	AL	(1 hr)	$AL = 60(B_s + 0.5)V^2 \cdot F(X, B_s)n^{0.13}$

Note: For details of the expressions and definitions of each notation, see the referenced papers.

An important point to consider here is the *purpose* of such a study. One expects that the finding of a high correlation between a geomagnetic index and a solar wind quantity would lead to a better understanding of physical processes involved in the solar wind-magnetosphere interaction. If this is indeed the basic motivation of such a study, one must be clear about what the chosen geomagnetic index really represents. Let us take for example, the Kp index. What does this semi-logarithmic index, from 0 to 9, physically represent? This question may be more difficult to answer than to find the correlation. In fact, there are perhaps only a few workers who know exactly how the Kp index is produced. Similarly, what does the daily sum of eight semi-logarithmic Kp numbers ($\sum Kp$) represent?

Similar questions can also be raised to all correlation studies which choose the $C9$, Ap , am indices; note that these indices are derivative indices from the Kp index. The present reporters believe that these indices are intended to be a very qualitative measure of geomagnetic activity and are *not intrinsically compatible* with basic physical quantities, such as V , B , n , etc.

In this respect, the choice of the auroral electrojet indices AE , AL , and AU have an advantage compared with the Kp index, since it is the magnetic field intensity of the auroral electrojets. However, one must also be cautious in using these indices since the current intensity depends both on the electric field and the conductivity in the ionosphere. Therefore, even if a high correlation is obtained between the AE index and a particular combination of solar wind parameters, it is not necessarily a simple matter to find the chain of processes involved in the solar wind-magnetosphere interaction which relates the AE index with that particular combination of the solar wind parameters. As mentioned earlier, this may be a more difficult problem than finding the correlation. In dealing with a geomagnetic index, one should also be aware of its accuracy. The fidelity of the AE index as a substorm index is unlikely to be more than 70%, so that there is no reason to attempt to find a combination of solar wind parameters which provides more than 70% of correlation. The best way to learn about the fidelity of any index is to produce it oneself.

Different geomagnetic indices have a high correlation with different combinations of solar wind parameters (e.g., MAEZAWA, 1978). Those differences are not discrepancies or disagreements. The Kp and the AE indices are not the same measure of geomagnetic activity. It should be noted that BURTON *et al.* (1975) examined the relationship between the ring current production rate estimated from the Dst index and the interplanetary electric field E . This is certainly a better approach than a simple correlation study.

PERREAULT and AKASOFU (1978) attempted to correlate the total energy dissipated in the magnetosphere-ionosphere system with the IMF by taking somewhat a different way of estimating the energy rate from the others. They determined first the total energy consumption rate $\bar{U}_T$ (erg/sec) of the magnetosphere by using the Dst and AE indices. Here,

$$\bar{U}_T = \bar{U}_R + \bar{U}_J + \bar{U}_A$$

$$\bar{U}_R = 4.0 \times 10^{20} \left(\frac{\partial Dst}{\partial t} + \frac{Dst}{\tau_R} \right) \text{ erg/sec}$$

$$\bar{U}_J = AE(\gamma) \times 10^{15} \text{ erg/sec}$$

$$\bar{U}_A = AE(\gamma) \times 1.5 \times 10^{14} \text{ erg/sec.}$$

After determining the total energy consumption rate $\bar{U}_T$ (erg/sec), their problem was reduced to finding a combination of the solar wind parameters which has the dimension of (erg/sec). The simplest combinations are ρV^3 and VB^2 .

Since it has long been known that ρV^3 has little correlation with $\bar{U}_T$, the obvious choice is then VB^2 . PERREAULT and AKASOFU (1978) found that the following expression has a high correlation ($\sim 70\%$) with $\bar{U}_T$:

$$\varepsilon = VB^2 \sin^4 \left(\frac{\theta}{2} \right) I_0^2$$

where

θ = the polar angle of the IMF projected on the dawn-dusk meridian,

I_0 = constant ($\simeq 7 R_E$).

It is also important to note that KAN *et al.* (1980) showed that the above parameter ε can be identified as the dynamo power delivered from the solar wind to the magnetosphere. This identification not only provides a theoretical basis for the energy coupling function, but also constitutes an observational verification of the solar wind-magnetosphere dynamo theory. Moreover, it is interesting to note that the onset, expansive phase, the maximum epoch and the recovery phase of magnetospheric substorms may be much more tightly controlled by the solar wind than previously thought (see SWIFT, 1980).

AKASOFU (1979b) has shown by using hourly-value *AE* indices and solar wind parameters that there is a higher correlation coefficient between the *AE* index and ε than that between *AE* and just B_z . Some question has recently been raised by several workers about the results that substorm activity and substorm energy are proportional to VB^2 . By using a 10 years' data set of 3 hr averages of hourly values, MAEZAWA (1978) has shown statistically that the *AL* index is proportional to BV^2 while *AU* is proportional to BV . Since the *AL* magnitude is generally larger than the *AU* magnitude, the *AE* index ($=AU+|AL|$) is related mainly to BV^2 , not to B^2V . HAKAMADA *et al.* (1979) and MURAYAMA *et al.* (1980) have reached similar conclusions. Such differences are not discrepancies or disagreements. One can easily see that the quantity BV^2 has the dimension of current I_2 and that *AE* is proportional to I . Thus, *AE* should correlate best with BV^2 , while ε (erg/sec) should correlate with VB^2 (erg/sec).

It must also be noted, in attempting to evaluate the role of the reconnection theories in understanding substorm processes and the solar wind-magnetosphere coupling, that the dayside reconnection alone does not seem to couple the solar wind energy into the magnetosphere. In the region between the northern and southern cusps, the Poynting vector is directed outward across the magnetopause. The Poynting vector is directed inward across the magnetopause only on the downstream side of the cusps. Some of the recent ISEE/A and /B observations indicate that the basic process occurring on the magnetopause is transient in nature (RUSSELL and ELPHIC, 1979). It may well be that plasma instabilities at the magnetopause are so intense that the gyro-motions of solar wind particles and magnetospheric

plasma particles are almost always interrupted there. Therefore, the frozen-in-field concept may not be applicable in the magnetopause transition zone, nor perhaps in its immediate vicinity.

The last two years saw continued progress in the study of the role of the IMF in controlling the size of the auroral oval or the polar cap. During a prolonged period (>12 hr) of a large northward total field (i.e., a strong positive B_z), the auroral oval contracts asymptotically to its minimum size. This condition of the magnetosphere is called the 'ground state', and there is little substorm activity along the minimum size oval (KAMIDE *et al.*, 1977). This is the only period when the magnetosphere is in the steady state.

The auroral oval tends to expand immediately as soon as the IMF vector changes from almost a true northward-directed state (ZVEREV *et al.*, 1978; DANDEKAR and PIKE, 1978). HORWITZ and AKASOFU (1977) showed that the latitude of the dayside cusp shifts progressively equatorward after the B_z component becomes negative. Electric field variations in the vicinity of the auroral oval were examined by HORWITZ *et al.* (1978) who found that the southward turning of the IMF B_z component causes a rapid expansion of the auroral oval.

HOLZER and SLAVIN (1978) showed that the amount of magnetic flux transfer from the dayside magnetopause can be equated with the return flux measured in terms of the substorm AL index. It must be noted in this connection that EATHER *et al.* (1979) suggested that any erosion of dayside magnetic flux is not a direct result of southward turning of the IMF, but the cusp position is intimately related to substorm timing and intensity.

4. Substorm Time Sequence

Geomagnetic data have provided valuable means in monitoring magnetospheric processes at remote locations on the earth's surface. The ground-based observations have several advantages over space observations by rockets and satellites. There are relatively a large number of observatories on the ground which continuously measure magnetic and electric fields and auroras, while only a few satellites are in the magnetosphere at any one time. Thus, for many magnetospheric physicists, it has increasingly become the common practice to use ground-based data in determining the onset time and the phases of magnetospheric substorms.

The timing of substorm sequence is not a trivial problem in establishing the cause-and-effect relationship among various phenomena occurring during the course of substorms. The use of ground magnetograms to determine the onset time of substorms was critically reviewed by MCPHERRON (1978). Since the sudden growth of the westward electrojet in the midnight sector is one of the dominant features of polar substorms, a sudden negative deviation near the auroral breakup can be an important tool of identifying the onset. However, this method requires

great care, particularly when data from a limited set of observatories are utilized. The pitfalls lie in the fact that the sudden onset thus determined at one station is often delayed 15–20 minutes relative to the onset at other stations. GUPTA and LOOMER (1979) have recently noted that the presently available *AE* indices may be in error at times 150 nT or more, since the present *AE* network of observatories does not have enough latitudinal width to monitor properly the electrojet activity. This means that one must be cautious in using the *AE* indices as the measure of the auroral electrojet.

Another tool which has been of frequent use in inferring the substorm onset time and the intensity of the auroral electrojet is the temporal change of the latitudinal profile of all three components as developed by Rostoker and his colleagues. By comparing observed profiles and model profiles, a number of characteristics of the substorm electrojet have been found. However, even though an accurate location of the electrojet is deduced from the latitudinal profiles, similar time delays are expected to occur in the east-west direction, since the electrojet expands and contracts in a very complicated fashion in the longitudinal direction. The network of the two-dimensional arrays in Canada developed by Gough and in Scandinavia by Untiedt have been used to monitor the distribution of the auroral electrojets as well as field-aligned currents, which represent the divergence of the ionospheric currents (BANNISTER and GOUGH, 1977, 1978; UNTIEDT *et al.*, 1978). Studies of magnetic and auroral data from several other IMS meridian chains are strongly desired.

The determination of the substorm onset on the basis of the *D* component magnetograms was made by SHIRMAN *et al.* (1978) who noted that although characteristic features in the *H* component do not apparently coincide along the meridian chain which they used, the *D* component is not subject to any timing difference. This may be explained by assuming that the main part of the *D* perturbations result from the field-aligned current flowing in a distant place, while the *H* component is influenced much more closely by local structures of the ionospheric currents than by the field-aligned currents.

Considerable attention has been given to magnetic positive bays in the *H* component in middle and low latitudes as a good indicator of the onset time and magnitude of substorms. It has been earlier suggested that such positive bays can be interpreted as the magnetic effect of the net field-aligned current flowing into and out of the polar ionosphere. We note in this respect that by this method, we can detect only intense substorms in which the mid-latitude effect is larger than several nT. The “Victorian Nine” agreed that insofar as identification of substorm onsets from middle and low latitude magnetograms is concerned, the *D* component generally provides the best indicator of the earliest detectable onset time. The *H* component signature depends on the position of the observatory with respect to the meridian of the auroral electrojet.

There are also several other topics of important findings which are associated with the onset of auroral substorms. First, PELLINEN and HEIKKILÄ (1978) reported observations of an auroral fading which occurs a few minutes before the main breakup. In a typical sequence referring to a meridian chain of all-sky cameras, an auroral backscatter radar and micropulsation activity, an auroral arc moves equatorward well before the substorm expansion, then fading comes just before the breakup. It was suggested that the fading phenomenon is an indication of the behaviour of the electric field in the magnetosphere, which is diminished locally in the vicinity of the fading arc. KAWASAKI and ROSTOKER (1979) have presented data from a magnetometer array with associated all-sky camera coverage and found that in the late evening sector, the sudden H decrease did not coincide with brightening of auroras. A significant enhancement of the westward electrojet near the Harang discontinuity occurred a few minutes prior to the development of the surge in the field of view of the array.

The second topic of interest is the location of auroral arcs near substorm onsets. Using fortuitous polar passes of the ISIS-2 satellite which provides auroral imagery and particle data, LUI and BURROWS (1978) have suggested that the substorm triggering process occurs on closed field lines well within the outer and inner edges of the plasma sheet. This finding is very important in understanding of the substorm onset processes.

5. Magnetotail Observations

There have been a large number of conflicting reports on magnetic field variations and plasma flows in the magnetotail during magnetospheric substorms. The focal point of conflict is whether or not the present data set can confirm reconnection theories in the plasma sheet in conjunction with substorm onset. It is fair to say that the results are still controversial and very confusing. One of the problems in this topic seems to result from the tendency that only the B_z component was used to discuss the dynamics of the magnetotail associated with substorm processes. In fact, the two components (B_x , B_z) are not yet enough, and the B_y component is often as large as the other two components and is highly variable with time. After all, the magnetic field vector has the three components!

The past analyses of plasma flow have also been found to be inadequate. In the past, it was tacitly assumed that the flow was only an $(E \times B)$ drift motion in the magnetotail. It was LUI *et al.* (1977, 1978) who pointed out that a high speed flow has often a large component along magnetic field lines. If this is the case, the basic physics associated with motions of plasma along and perpendicular to magnetic field lines may be quite different.

Future studies of magnetotail data should be based on a careful analysis of the three components of $\mathbf{B}$ (B_x , B_y , B_z) and $\mathbf{V}$ (V_x , V_y , V_z), in addition to all basic

plasma characteristics. If such an elementary practice would be ignored in the future, the present confusion may continue even with high quality data from the ISEE satellites. Caution must be also exercised in identifying particular locations within the magnetotail where particular signatures for the substorm dynamics under study are observed. For example, magnetic variations in the tail lobe and near the neutral sheet within the plasma sheet are different even at the same L distance, and flow vectors of the tail plasma are variable depending on the location of the satellite observations.

It is also important to consider at this point what reconnection theories attempt to establish in the studies of magnetospheric dynamics. The acceleration of auroral particles is now found to take place mainly at a distance of 1.5–2.0 earth radii above the auroral oval. If the potential drop along the field lines there can really be as large as 5 keV, it may not be necessary to find major acceleration processes of auroral particles in the distant plasma sheet, although it seems likely that the reconnection process or disruption in the tail current in the plasma sheet relates to the generation of field-aligned currents.

6. Ring Current Formation

In spite of extensive studies in the past, the formation of the ring current belt has not been clearly understood. First of all, as WILLIAMS (1978) pointed out, we have not identified the positive ions which constitute the main part of the ring current belt, so far only the high energy tail and the low energy end of the spectrum. Secondly, there has been no decisive observation to indicate that those ions, as well as hot electrons, are “injected” from the plasma sheet or are “locally accelerated”, either along the geomagnetic field lines or in the equatorial plane. Therefore, the so-called “injection” process remains at present unveiled. This must be a frustrating experience for those who have worked in this particular area. Even if the dispersion observation is fully used, a single satellite observation would not be able to solve the problem. Well-planned, multi-satellite observations may be needed to reduce the large number of possibilities. A well-coordinated observation of plasma sheet particles and electric fields, at distances between 6 and 10 earth radii by more than two satellites, is needed to “trace” plasma particles. This effort should also be aided by modeling studies.

One of the highlights in the study of the ring current belt during the last two years is the finding of O^+ ions, both above the auroral oval (JOHNSON *et al.*, 1975) and in the ring current belt (BALSIGER *et al.*, 1979). At times, the flux of O^+ ions can be greater than that of protons. It is of great interest to examine the energy density of O^+ in comparison to the total energy density of the ring current belt. It is quite likely that O^+ ions are of ionospheric origin. The V -shaped potential structure can accelerate O^+ ions upward, in addition to the downward acceleration

of electrons. However, there are at least two problems to be solved in understanding the formation of the ring current belt of O^+ ions. First of all, O^+ ions must be trapped in the belt by changing drastically the initial pitch-angle distribution. Secondly, since the auroral field lines are expected to cross the equatorial plane at a geocentric distance of 10 earth radii or greater, one must find the transport mechanism for O^+ ions to be convected to a geocentric distance of 3–6 earth radii. A highly transient and large electric field may be required for the transport process.

7. Electric Field Observations

The electric field observations during the last two years have made the most remarkable progress, not only in terms of the elucidation of the large-scale convection pattern over the polar region, but also in terms of revealing the V -shaped potential structure.

It is noteworthy in particular that four different types of observations have contributed in revealing the V -shaped potential structure. They are direct electric field observation by the S3-3 satellite (MOZER *et al.*, 1979), auroral particle observations by the same satellite (MIZERA and FENNELL, 1977), Ba shape-charge injections by rockets (WESCOTT *et al.*, 1978) and TV observations of the shear motion of auroral arcs (HALLINAN, 1969). Thanks to those who contributed to these studies.

It has been suggested that this particular potential structure is a double layer. However, there are several different views among theorists about the role of the double layers in causing the potential drop. It has also been suggested that the potential drop is caused by an electrostatic shock and anomalous resistivity. Certainly, the finding of the potential structure has stimulated a number of theorists to work on this interesting problem. However, it is too early to identify the nature and cause of the formation of such a potential structure, except that it is quite likely that field-aligned currents are closely related to this phenomenon. Therefore, the generation mechanism of the field-aligned currents from the solar wind-magnetosphere dynamo is one of the most important future problems in magnetospheric physics.

The finding of the potential structure has profound implications in studying magnetospheric processes. First of all, one can no longer map magnetospheric electric fields to the ionosphere along geomagnetic field lines, or *vice versa*, by assuming that the field lines are equipotential lines. In fact, since the electric field associated with the V -shaped potential is very large (1 mV/m), compared with a typical ionospheric electric field (~ 20 mV/m), and cannot be seen in the ionosphere (but will be seen in the plasma sheet), one would expect that the electric field pattern in the magnetosphere is considerably different from what one would expect from the ionospheric field pattern. Thus, the coupling between the magnetosphere and the ionosphere is not perfect.

It is interesting to recognize that *the aurora is a manifestation of this imperfect coupling between the magnetosphere and the ionosphere*, since the potential drop accelerates auroral particles. Further, since there is an electric field parallel to the magnetic field, one can no longer identify motions of individual magnetic field lines. Thus, the frozen-in-field concept does not hold in the magnetosphere. Indeed, *the presence of the aurora is a manifestation of the breakdown of the classical frozen-in-field concept* which we have taken for granted for a long time.

It was mentioned earlier that the presence of a large potential drop of the order of 5 keV above the auroral oval indicates that the major portion of auroral particle acceleration takes place a little above the ionosphere, not in the plasma sheet.

8. Substorm Current Systems

During the last two years, good progress was made in the study of three-dimensional current systems during magnetospheric substorms, in particular, the relationship between field-aligned currents and ionospheric currents, the convection electric field, discrete and diffuse auroras and auroral electron spectra. Such a variety of observations have finally begun to converge in providing a self-consistent model of the magnetosphere-ionosphere coupling.

Numerical simulations of ionospheric electric fields and currents in relation to field-aligned currents have been conducted by several groups, such as NOPPER and CAROVILLANO (1978), NISBET *et al.* (1978), MAEKAWA and MAEDA (1978), and KAMIDE and MATSUSHITA (1979). These works proved the simulations to be a powerful tool in unveiling physical processes occurring during substorms in the ionosphere-magnetosphere system. This part will be reported in more detail in Division III, Topic 1 (ROSTOKER, 1980).

9. Summary

It may be worthwhile to describe briefly a newly emerging model of the solar wind-magnetosphere interaction on the basis of the progress made during the last two years.

Let us consider the situation in which the solar wind-magnetosphere dynamo power increases from $\sim 10^{17}$ erg/sec to $\sim 10^{20}$ erg/sec. The magnetosphere is quite insensitive to $\varepsilon < 10^{17}$ erg/sec. As ε increases from $\sim 10^{17}$ erg/sec to $\sim 10^{18}$ erg/sec, the increased power generation is manifested by various phenomena, such as enhanced convection in the polar cap (thus enhanced field-aligned currents) and an enhanced magnetotail current. Note, however, that there is little energy accumulation in the magnetosphere by this increase, since the Joule heat production in the polar cap dissipates most of the generated power.

As ε reaches $\sim 10^{18}$ erg/sec, an auroral arc in the midnight sector suddenly brightens, indicating the onset of a magnetospheric substorm. It may be interpreted that an increasing intensity of field-aligned currents reaches the level that the resulting potential drop in the V -shaped potential structure becomes ~ 1 keV, so that the accelerated auroral particles can reach the E region of the ionosphere.

As ε increases further ($> 10^{18}$ erg/sec), the substorm intensifies. The power generated by the dynamo is now partly dissipated in the ionosphere by producing the Joule heat and also by auroral particles. Another part is consumed in building up the ring current belt.

An interesting phenomenon takes place as ε reaches $\sim 10^{19}$ erg/sec. The ring current begins to grow abnormally and the Joule heat production rate tends to level off. A further increase of ε does not increase significantly the Joule heat production rate.

It may be speculated that the potential drop in the V -shaped potential structure becomes large enough so that the potential difference across the polar cap can no longer increase. At the same time, the V -shaped potential structure accelerates a large number of O^+ ions toward the equatorial plane. These O^+ ions may become a significant part of the ring current particles.

As ε begins to decrease, the substorm intensity begins also to decline; the recovery phase begins. An important point is that there is a high correlation between solar wind parameters and substorm activity indicating that the solar wind is primarily responsible for gross features of both the growth and decay of magnetospheric substorms. It should be noted that this does not mean that the onset, expansive phase characteristics and the onset of the recovery phase, etc. may all not be determined by magnetospheric time constants. This is because the substorm time constants are less than 1 hour but most of the studies of the relationship between the solar wind parameters and geomagnetic indices are based on hourly average values, and because the growth and decay of substorms with finer time scale (like 5 minutes) cannot be expressed by any of the available indices.

10. Aiming toward the OPEN Era

A few comments may be in order in preparing us for the OPEN era which will be one of the major magnetospheric projects in the next decade.

10.1 *Magnetic tape output for the AE stations*

First of all, we must drastically improve the production procedure of the *AE* index. It is suggested that all *AE* stations be equipped with a magnetometer which can provide magnetic tapes as the output recording. We should start this conversion now, rather than all at once in 1985. Unless such an effort is made, magnetometers may become an obsolete instrument in magnetospheric studies (not

because the data are not useful, but because of time-consuming data handling).

10.2 New magnetometer networks

The IMS meridian chains of magnetometers have demonstrated that such a systematic data gathering is indeed a powerful tool in studying magnetospheric processes. A network of magnetometers should be carefully planned for the OPEN era; note that this does not necessarily mean an increase of the total number of magnetometers. It may also be necessary to construct unmanned stations in order to avoid serious gaps in the network. An international effort may be useful in this venture by gathering various experiences each group has had on the power supply, heating systems, etc.

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List of the publications in the area of Topic III-6 which are published during the last two years. The papers are classified under the following headings.

- I. General Reviews
- II. Substorm
 - a. Relationship with the solar wind
 - b. Onset and theories
 - c. Distant magnetosphere observations and their theories
- III. Plasma Injection
 - a. Ring current and plasmasphere
- IV. Aurora
 - a. Morphology
 - b. Field-aligned currents, ionospheric electric fields and currents, and magnetic disturbances
 - c. Acceleration process, precipitation, arc formation
 - d. Kilometric radiations
 - e. Radar aurora, absorption
 - f. Effects on the thermosphere

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