Dynamics of the 1054 UT March 22, 1979, Substorm Event: CDAW 6

R. L. McPherron

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

R. H. Manka

National Research Council, Washington, D.C.

Center for Space Physics, Rice University, Houston, Texas

The physical processes involved in the transfer of energy from the solar wind to the magnetosphere, and release associated with substorms, have been examined in a sequence of Coordinated Data Analysis Workshops (CDAW 6). Magnetic storms of March 22 and 31, 1979, were chosen to study the problem, using a data base from 13 spacecraft and about 130 ground-based magnetometers. This paper describes the March 22 storm, in particular the large, isolated substorm at 1054 UT which followed an interval of magnetic calm. We summarize the observations in the solar wind, in various regions of the magnetosphere, and at the ground, synthesizing these observations into a description of the substorm development. We then give our interpretation of these observations and test their consistency with the reconnection model. The substorm appears to have been generated by a southward turning of the interplanetary magnetic field associated with a current sheet crossing. Models of ionospheric currents derived from ground data show the substorm had three phases of development. During the first phase, a two-celled convection current system developed in the polar cap as synchronous spacecraft on the nightside recorded an increasingly taillike field and the ISEE measurements show that the near-earth plasma sheet thinned. In the second phase, possibly triggered by sudden changes in the solar wind, a one-celled current system was added to the first, enhancing the westward electrojet. During this phase the synchronous orbit field became more dipolar, and the plasma sheet magnetic field turned strongly southward as rapid tailward flow developed soon after expansion onset, suggesting that a neutral line formed in the near-earth plasma sheet with subsequent plasmoid ejection. In the third phase, which occurred after interplanetary magnetic field turned northward, the magnetospheric current systems decayed as the plasma sheet expanded and the flow turned earthward. The data from this event support the notion that substorms include two major processes of energy dissipation: one directly driven by the solar wind and one driven by release of energy stored in the geomagnetic tail. The near-tail data suggest that one or more neutral lines formed earthward of the ISEE spacecraft. However, all the signatures of plasma flow and energetic particles can be explained only by postulating a complex series of events. While this reconnection picture represents the interpretations of many of the CDAW 6 participants, it is not a consensus viewpoint.

1. INTRODUCTION

The Energy Transfer Problem

The primary goal of the Coordinated Data Analysis Workshop (CDAW 6) is to trace the flow of energy from the solar wind through the magnetosphere to its ultimate dissipation in the ionosphere. Magnetospheric substorms play an essential role in this energy transfer and as yet are not completely understood. A major question related to substorms is the relative importance of energy dissipation directly driven by the solar wind and energy dissipation driven by the release of energy stored in the geomagnetic tail. Related questions are which solar wind, magnetospheric, or ionospheric parameters control geomagnetic activity and, quantitatively, what is the functional relation between these parameters and various measures of geomagnetic activity? Physically, we need to know which processes are responsible for the energy transfer across the magnetopause, and which processes transfer or release this energy within the magnetosphere. Field-aligned currents play an important role in energy transfer within the magnetosphere, but details of the global current systems and their temporal development during substorms are not yet completely known. Other important questions are the role of the ionosphere as a source of plasma, and the effects of this plasma on the substorm process, as well as the role of ionospheric conductivity.

CDAW 6 was organized by a number of researchers within the space physics community in an attempt to answer some of these questions. It consists of an ongoing sequence of workshops to define the questions, contribute data, discuss and analyze the data, present papers at scientific meetings, and finally, contribute papers to this collection. Facilities for this workshop have been provided by the National Space Science Data Center (NSSDC), the Lockheed Palo Alto Laboratories, and the European Space Operations Center. NSSDC has provided the computer resources necessary to assemble the diverse data required by the study in a common data base, and to display these data in a coordinated manner.

A study of magnetospheric substorms requires data from a global distribution of magnetic observatories, and an appropriate distribution of spacecraft within the magnetosphere and solar wind. The assembly of such a data set requires cooperation of many individuals from many different countries. The International Magnetospheric Study (IMS, 1976-1979; data analysis phase, 1980-1985) has provided an ideal data base from which to begin. One of its primary goals was the accumulation of data useful in studies of the solar wind interaction with the magnetosphere. Major components of the IMS include the magnetometer networks in North America, Europe, and Asia, ionospheric radars, and a comprehensive suite of observations in the solar wind.
newly dedicated and already existing spacecraft such as ISEE 1, 2, 3, GEOS 1, 2, and others launched by Japan and the Soviet Union.

The Substorms of March 22, 1979

The first step in the CDAW 6 workshop sequence was to choose substorm events for which all of the major IMS spacecraft were operational and conveniently situated for studies of substorms. It was also required that major magnetometer networks be appropriately located and that the substorms be well defined and tractable. Initially, a number of candidate events were considered in order to determine whether they satisfied the multiple selection criteria. Eventually, two events were chosen, the first with North America in the midnight sector and the second with Europe at midnight. For both events the ISEE 1 and 2 spacecraft were approaching the earth through the tail in the vicinity of the plasma sheet. The first period, 0600–2000 UT on March 22, 1979, is a moderate, well-defined magnetic storm preceded by a day of quiet conditions in the solar wind and magnetosphere. The three major features of the storm are as follows: (1) At 0826 UT a sudden storm commencement (ssc) (or perhaps better called a sudden impulse, si) occurred, because of a shock in the solar wind; the shock was most likely caused by a solar flare on March 19 [Tsurutani et al., 1984]. (2) At 1054 UT the onset of the first substorm expansion, the primary topic of this paper as well as the CDAW 6 analysis to date, began. This is an excellent example of an isolated substorm following an interval of magnetic calm. This substorm was associated with a 70-min interval of moderate, but fluctuating, IMF. This event is not discussed in this paper.

Solar wind parameters observed at IMP 8 are compared with the AE index in Figure 2. Prior to about 0815 UT the solar wind was relatively quiet with a velocity of the order of 340 km/s and a density of 10 cm$^{-3}$. The GSM Z component of the solar wind magnetic field had been weakly southward on several occasions but related to little observable magnetic activity in the auroral oval. At 0747:23 UT an interplanetary shock passed ISEE 3, causing large increases in velocity, density and magnetic field strength. This shock reached IMP 8 at 0821:20 UT, and the dayside of the earth at 0826, where it caused a sudden increase of the low latitude magnetic field. Assuming propagation of the shock along the earth-sun line, these times imply a velocity of 697 km/s, which should be compared to the solar wind velocity of 320 km/s before the shock and 450 km/s behind. However, taking the distance between ISEE 3 and IMP 8 and projecting it along the shock normal, the required velocity is $n \cdot \Delta \tau / \Delta \tau = 480$ km/s, which is slightly faster than the postshock solar wind velocity (J. King, personal communication, 1983). At 0923 UT a second dis-
continuity in the solar wind passed ISEE 3, producing another increase in the interplanetary magnetic field strength and a slight enhancement in the velocity. Accompanying these changes was a decrease in density and a sudden southward turning of the magnetic field. These effects arrived at IMP 8 after 1008 UT, and about 16 min thereafter the \( \text{AE} \) index began to increase from a low baseline level as currents began to flow in the auroral oval.

The IMF remained southward at IMP 8 for 70 min and, at the earth, produced magnetic activity (as measured by the \( \text{AE} \) index) exceeding 1000 nT. At 1037 UT the field began to turn less southward at IMP 8, and by 1122 UT, \( B_z \) passed through zero to become northward. Magnetic activity in the auroral zone reached a maximum at 1135 UT. Before \( \text{AE} \) had returned to background, a second and longer interval of southward IMF began at about 1312 UT and lasted nearly 3 hours. During this interval the \( \text{AE} \) index attained even larger values (exceeding 1500 nT). Within the interval there was a second increase in density accompanied by a sudden northward fluctuation of the IMF. The arrival of these effects at IMP 8 was quickly followed by the onset of a major substorm expansion.

Variations in the IMF recorded by IMP 8 immediately in front of the earth are displayed in Figure 3. In addition to the \( Z \) component variations mentioned above, the \( X \) and \( Y \) components of the field show an important physical feature in the solar wind, namely that the initial southward turning of the IMF was correlated with a crossing of the solar wind current sheet. Prior to the crossing, the IMF had been predominantly outward from the sun, while afterward it was inward, as shown systematically in Figure 1. This situation persisted until 1436 UT when the northward fluctuation of the IMF mentioned above reached IMP 8 and the spacecraft passed back through the current sheet into the region of outward field.

**Ground Magnetic Activity on March 22, 1979**

The character of ground magnetic activity on March 22, 1979, is summarized in Figure 4 by plots of magnetic indices. The top two traces display \( A_U \) (eastward electrojet) and \( A_L \) (westward electrojet). Both indices began to change rapidly at about 1020 UT, shortly after the first southward turning of the IMF was observed at IMP 8. The gradual decrease in \( A_L \) was interrupted by the onset of a substorm expansion at 1054 UT. A second interruption occurred at about 1123 UT in conjunction with a major intensification. \( A_L \) reached its minimum value at 1133 UT, and thereafter increased until 1330 when the second interval of southward IMF caused it to decrease once again.

The \( D_{st} \) and \( A_{SYM} \) indices are plotted in the bottom two traces. After 0826 UT both indices were positive as a consequence of an enhanced solar wind dynamic pressure following the interplanetary shock. This situation persisted until around 1010 UT, at which time \( D_{st} \) began to decrease. A decrease in \( A_{SYM} \) began somewhat later at about 1047 UT. Both of these indices reached minimum values at 1212 UT, about 30 min after the minimum in \( A_L \). The \( A_{SYM} \) index recovered rapidly, reaching its baseline value by the start of the second substorm. The \( D_{st} \) index recovered more slowly, never reaching its baseline value before it decreased again in association with the second substorm.
The geographic locations of magnetic observatories used in the CDAW 6 study are plotted in Figure 5 (for detailed locations, see the report by Kamide et al. [1983]). The Braunschweig chain in Scandinavia and the Izmiran and Sibizmir chains in western USSR were located in the noon to afternoon sector. The Greenland east and west chains were located on the prenoon side of the earth, while the Churchill chain, the Alberta chain and the Alaska chain were located between dawn and midnight. In the North American sector the Air Force Geophysics Laboratory (AFGL) chain extended east-west at subauroral latitudes. At lower latitudes the mid-latitude chain encircled the globe between 20° and 50° magnetic latitude.

Effects of the IMF were observed in the polar cap soon after the southward turning passed IMP 8. Figure 6 presents the dawn-dusk and noon-midnight components of the equivalent current recorded at Thule, Greenland, close to the geomagnetic pole. At approximately 1020 UT there was a sudden increase in the sunward component of the polar cap equivalent current (dashed line in Figure 6). This disturbance indicates the onset of enhanced convection driven by the solar wind. Magnetic disturbances persisted in the polar cap until about 1210 UT, approximately 50 min after the IMF had become northward at IMP 8.

A second interval of enhanced convection began about 1310 UT, shortly after the IMF turned southward for the second time. As in the first interval, convection persisted in the polar cap 40 min after the IMF became northward.

The response of polar cap stations to the southward turning was not instantaneous, as demonstrated in high-resolution data plotted in Figure 7. Station NORD, located at the poleward end of the east Greenland chain, responded about 7 min
later than the end of the southward turning recorded at IMP 8. While this delay is longer than the transit time expected using the location of IMP 8 and the orientation of the IMF discontinuity, it does represent a relatively rapid coupling of energy from the IMF into the magnetosphere. In both intervals the end of polar cap disturbance occurs during the recovery of the auroral zone bays (compare Figure 4 with Figure 6).

Traces of the $H$ component from selected auroral zone stations are plotted in Figures 8 and 9. These traces reveal a number of important events during the 1054 UT substorm. First, the start of bay activity in the auroral oval occurred between 1020 and 1022 UT, the same time that it began in the polar cap. Second, an apparent "precursor" bay was observed in the auroral oval between 1024 and 1050 UT. Third, the sudden onset of a major substorm expansion occurred at stations near midnight at about 1054 UT. The end of this expansion, as evidenced by the beginning of recovery of the negative bays, was between 1132 and 1152 UT. The entire substorm was over by 1300 UT.

A stack plot of mid-latitude $H$ traces presented in Figure 10 also reveals several of the important events during the 1054 UT substorm. The first and most obvious is the si at 0826 UT which produced a large, transient increase at all stations. The second was at approximately 1030 UT, when stations in the dusk sector began to record a decrease in $H$. The third was at 1054 UT, when a positive bay began at Newport (NEW). The onset of this bay was observed slightly later at Boulder, Tucson and Tahiti. It reached maximum development at 1120 UT, about 15 min earlier than in the auroral zone.

Observations at Synchronous Orbit

The locations of spacecraft within the magnetosphere are depicted in Figure 11. Six synchronous spacecraft were operational during the 1054 UT substorm. The SCATHA and GEOS 2 spacecraft were located just past noon. Spacecraft 1976-059 was near dawn, GOES 2 near 0400 LT, and 1977-007 and GOES 3 near 0145 LT. The ISEE 1 and 2 spacecraft

---

**Fig. 6.** Changes in the dawn-dusk polar cap magnetic field (courtesy of H. Kroehl).

---

**Fig. 7.** High-resolution plot of polar cap magnetic field response to southward IMF.

---

**Fig. 8.** Stack plot of auroral zone $H$ components. Traces are stacked by progressive west dipole magnetic longitude. LRV, Leirvogur; NAQ, Narssarsuaq; STJ, St. Johns; FSE, Fort Severn; BKC, Back; LYN, Lynn Lake.
06-20 UT March 22, 1979

NOW, Norman Wells; FSM, Fort Smith; CWE, Cape Wellen; CCS, Cape Chelyuskin; DIK, Dixon Island; KIR, Kiruna.

were on eccentric, inbound orbits in the 0200 LT meridian, about 14 Re behind the earth.

Observations made by GEOS 2 near local noon at 1054 UT are summarized in Figure 12. The H component plotted in the top panel is approximately parallel to the ambient field and recorded variations in the magnitude of the field. The most obvious feature in these data is the increase in field magnitude, following the sudden impulse, which corresponded to a major solar wind pressure increase and consequent magnetospheric compression. This began suddenly at 0826 UT, when the interplanetary shock passed the earth, and ended almost as suddenly at 1008 UT, when the pressure decreased in conjunction with the current sheet crossing and southward turning of the IMF. During the 1054 UT substorm there were no changes that obviously correlate with effects in the midnight sector. However, sudden decreases in magnetic field at 1140 UT and 1220 UT probably represent encounters with plasma injected earlier.

Magnetic observations recorded in the postmidnight sector by the GOES spacecraft are presented in Figure 13. The right panel of the figure display data from GOES 3, which at 1054 UT was located near 0145 LT. The radial component (V) shows that the magnetic field at this location began to grow more taillike almost immediately after the southward turning of the IMF. This growth accelerated rapidly at 1045 UT, with V reaching a maximum a little before 1054 UT. At 1054 UT there was a sudden change in the field, which then rapidly returned to a more dipolar configuration.

Changes in the synchronous magnetic field at a later local time were similar to those at 0145 LT, but considerably delayed. The left panel of Figure 13 indicates that the growth of a taillike field did not begin there until 1040 UT. Similarly, the dipolarization was also delayed, beginning at 1110 UT. The field at both locations returned to quiet levels by about 1240 UT.

The synchronous spacecraft 1977-007 was also located near 0145 LT and recorded changes in the field configuration similar to the GOES observations. Figure 14 displays time series of electron differential fluxes (30-300 keV), a measure of magnetic field orientation, and east-west gradient anisotropies for energetic protons (ions). The electron flux shows three distinct events. The first is a sudden dropout of energetic electron

Fig. 9. Continuation of H component stack plot. NOW, Norman Wells; FSM, Fort Smith; CWE, Cape Wellen; CCS, Cape Chelyuskin; DIK, Dixon Island; KIR, Kiruna.

Fig. 10. Stack plot of mid-latitude H components. Plotting conventions are the same as in Figure 8. SJG, San Juan; FRE, Fredricksburg; BOU, Boulder; TUC, Tucson; TAH, Tahiti; HON, Honolulu; WKE, Wake Island; GUA, Guam.
fluxes at 1035 UT. The second is the beginning of the recovery of electron fluxes a little before 1054 UT. The third is an injection of electrons beginning at 1103 UT. Changes in the orientation of the magnetic field calculated from the electron distribution function are similar to those at the nearby GOES 3 spacecraft, and gradient anisotropies show that particle fluxes (after about 1100 UT) engulf the spacecraft from altitudes greater than that of the spacecraft. Thus the injected particles come from outside synchronous orbit.

Observations in the Near Geomagnetic Tail

At the time of the 1054 UT expansion onset the ISEE 1 and 2 spacecraft were inbound in the plasma sheet in the 0200 LT meridian approximately 13 to 14 Rs behind the earth, as illustrated in Figure 11. The probable geometry of the plasma sheet shortly before the onset is depicted in Figure 15. Since this onset occurred within a few minutes of the time that the earth’s dipole axis was exactly perpendicular to the earth-sun line, it would be expected that the plasma sheet would be symmetric about the GSM equatorial plane. However, as we demonstrate below, the neutral sheet crossed both ISEE spacecraft even though they were located well below the equatorial plane (see bottom panel). As has been discussed by McPherron and Russell [1983], these crossings were a consequence of a southward directed solar wind velocity vector, and the plasma sheet was relatively thin at expansion onset. Based on this information the plasma sheet is represented as a relatively thin region dipping below the equatorial plane. At various times during the expansion phase the ISEE spacecraft were located close to one or the other of the plasma sheet boundaries.

Magnetic field observations at ISEE 1 are compared to solar wind and ground magnetometer data in Figure 16. A vertical dashed line drawn at 1055 UT designates the time of expansion onset. It is apparent that shortly after the southward turning of the IMF at IMP 8 the plasma sheet began to move downward across ISEE 1, causing the $B_z$ component to pass through zero and become positive pointing toward the earth. Subsequently, the spacecraft entered the boundary between the plasma sheet and the north lobe (suggested by the increase in field magnitude and confirmed by plasma observations [Paschmann et al., this issue] and by plasma probe measurements utilizing the Berkeley electric field detector [Pedersen et al., this issue]). At about 1050 UT the IMF turned northward at IMP 8, and 5 min later a major substorm expansion onset occurred. Effects of this onset were not seen in the ISEE 1 magnetic field until 1107 UT, when the neutral...
sheet moved upward across ISEE 1 and the field was observed to be pointing southward at the neutral sheet (negative $B_z$).

The ISEE 2 spacecraft was situated somewhat lower than ISEE 1 and observed expansion effects somewhat earlier. Plasma observations from ISEE 2 are summarized in Figure 17. At 1058 UT a burst of plasma was observed flowing tailward at a velocity greater than 500 km/s. The velocity subsided to about 200 km/s until 1118 UT, when the flow direction reversed suddenly and strong earthward flow began. This flow persisted until about 1145 UT. During the interval of predominantly tailward flow there was a brief interval of earthward flow (1105 to 1107 UT).

Onset of 1054 UT Expansion Phase

A careful study of high-resolution data reveals that the expansion onset was more complex than suggested by the preceding discussion. Band-pass-filtered (30-200 s) flux gate magnetometer data from the AFGL magnetometer network displayed in Figure 18 indicate a $\pi$ 2 burst at 1055 UT. However, the data also show there was an intensification of the expansion at 1104 UT (also see Hughes and Singer [this issue]).

The earliest indication of the ensuing expansion onset was recorded at synchronous orbit by electron detectors on spacecraft 1977-007. As illustrated in Figure 19, electron fluxes began to increase at 1052 UT, suggesting that some change in the synchronous magnetic field began at this time. These data also demonstrate that injection of energetic electrons at this location was associated with the 1104 UT intensification of the expansion phase (also see Hughes and Singer [this issue]; Fritz et al., 1984).

The field-aligned current system associated with the 1054 UT expansion onset was centered at about 0300 LT. As illustrated in Figure 19, electron fluxes began to increase at 1052 UT, suggesting that some change in the synchronous magnetic field began at this time. These data also demonstrate that injection of energetic electrons at this location was associated with the 1104 UT intensification of the expansion phase rather than with the earlier onset (Hughes and Singer, this issue; Fritz et al., 1984).

The field-aligned current system associated with the 1054 UT expansion onset was centered at about 0300 LT. Figure 20 demonstrates this by a stack plot of the $D$ component from the subauroral zone AFGL chain of magnetometers. At Newport (NEW) the perturbation after 1054 UT is weakly positive, while at Rapid City (RPC) it is strongly negative. At stations Victoria and Sitka west of Newport (not shown), the perturbation was more strongly positive. Since the expected $\Delta D$ signature of the substorm current system is positive west of its central meridian and negative east, we conclude the central meridian was located just east of Newport, which was at 0300 LT.

The azimuthal location of the expansion onset in the auroral oval is somewhat harder to locate than its central meridian. Stack plots of the $D$ component from the Alberta and College chains (not shown here) suggest the westward surge formed west of Alberta (since the Alberta chain had no positive spike in the $D$ component), but considerably east of Alaska (a strong positive $D$ spike began after a 10-min delay). At Sitka a positive $D$ spike began nearly immediately after the expansion onset, suggesting the surge formed just east of Sitka. At this time, Sitka was nearly in the same local time meridian as the ISEE, GOES, and 007 spacecraft.

The latitude of the expansion onset can be determined fairly accurately from latitude profiles. Figure 21 summarizes results obtained from the Alberta chain. As indicated in the figure, the westward electrojet initially formed between 63° and 66° magnetic latitude. As time progressed, the equatorial edge of the electrojet drifted equatorward to about 60°, while the poleward edge remained fixed. As a result of this broadening, some of the more northern stations, e.g., Great Whale (GWC in Figure 8), observed an apparent recovery of negative $H$ perturbations. Stations farther south, however, observed steadily increasing negative $H$. At the time of the expansion onset, the center of the electrojet was located at about 63° magnetic latitude. Subsequently, its poleward edge expanded northward as shown in Figure 21. The equatorward edge continued to drift southward, reaching 57° at the end of the expansion phase (1120-1140 UT as defined by extrema in mid-latitude magnetograms of Figure 10, or in the AL index of Figure 4). After 1140 UT the poleward border again moved rapidly northward, reaching 74°, where it remained throughout most of the recovery phase.

A "poleward leap" [Pytte et al., 1978] of magnetic activity apparently occurred after 1140 UT as magnetic activity suddenly appeared at the highest-latitude stations in each of the three North American magnetometer chains. Figure 22 illustrates this phenomenon along the Churchill chain (bottom panel). The lowest-latitude station Whiteshell (WHS) began recovery at 1130, while a high-latitude station Baker Lake (BLC) suddenly began recording activity at 1137 UT. A simi-
lar phenomenon occurred on the Alaska chain where low-latitude stations began recovery about 1130 while the highest-latitude station (JOP) (not shown in the figure) began activity at 1135.

Figure 22 also illustrates the discrete nature of this substorm expansion. In addition to the onset at 1054 UT and the intensification at 1104 UT there was another at 1123 UT. This intensification is apparent along both the Alaska chain (top panel) and the Alberta chain (middle panel), where stations at intermediate latitudes recorded a sudden onset of activity.

3. SYNTHESIS OF THE OBSERVATIONS: SUBSTORM DEVELOPMENT AND MAGNETOSPHERIC DYNAMICS

As stated in the introduction, one major goal of this overview is to present the detailed time history of the first substorm on March 22, 1979, as determined from magnetic observations. In this section we describe this history in terms of a phenomenological model of the physical processes that appear to have taken place. Subsequent papers examine specific aspects of this and later substorms in greater detail; where relevant, we reference these papers to strengthen our arguments.

The chronology of events occurring during the 1054 UT substorm on March 22, 1979, is presented in Table 1. Significant magnetic activity on March 22, 1979, began when an interplanetary shock [Tsurutani et al., this issue] passed the earth. This shock compressed the magnetopause to about 7 $R_e$ at the subsolar point [Wilken et al., 1983], generating the initial phase of a magnetic storm which began with a sudden impulse at 0826 UT. The solar wind dynamic pressure remained high until about 1008 UT, when a decrease in density ended the initial phase and allowed the magnetopause to move outward again. Coincident with this decrease was a current sheet crossing and associated southward turning of the interplanetary magnetic field (IMF) which apparently initiated energy transfer into the magnetosphere via some process which applies a portion of the interplanetary electric field across the magnetosphere [Tsurutani et al., 1984]. The effect of energy transfer in the form of enhanced convection was observed throughout the polar cap and auroral zone shortly later [Kroehl and Kamide, this issue]. Also coincident with the southward turning of the IMF was a southward turning of the solar wind velocity vector [McPherron and Russell, 1983], which forced the tail downward beneath the GSM equatorial plane. This was observed in the near tail as apparent motion of the ISEE spacecraft toward and across the neutral sheet. At the same time, the tail current began to increase and move earthward, causing equatorward drift of the electrojets and an increasingly taillike field at synchronous orbit near 0200 LT [Baker et al., this issue; Barfield et al., this issue].

Accompanying the foregoing changes was an apparent thinning of the plasma sheet, which at 1030 UT caused energetic protons at synchronous orbit to begin to drop out. A complete dropout occurred 10 min later as the spacecraft GOES 3 and 1977-007 passed through a tailward directed current sheet into the tail lobe [Baker et al., this issue; Fritz et al., 1984]. ISEE 1 magnetic field observations [McPherron and Russell, 1983] also support the notion of plasma sheet thinning as the field magnitude increased dramatically (to $\sim 60$ nT), and the spacecraft moved into a low beta plasma [Lennarsson et al., this issue] near the northern boundary of the plasma sheet.

Coincident with the changes in the near-tail region, the currents in the polar cap developed into a convection-type, twin-vortex system [Clauer and Kamide, this issue]. As evident from the ratio of AU to AL (greater than 1) the late afternoon vortex was more pronounced than the early morning vortex [Kamide and Baumjohann, this issue].

As the westward electrojet increased in strength, its equatorward edge drifted southward (cf. Figure 22). This seems to have reduced the current over some stations, causing an apparent recovery of the negative bay. This recovery has been interpreted by some CDAW 6 participants as an earlier substorm. Careful examination of all available data shows that none of the usual indicators of expansion onset (Pi 2, sudden intensification, synchronous dipolarization, tail field decrease) occurred in conjunction with this portion of the event.

The expansion phase of the substorm may have begun as early as 1052 UT, as is suggested by the beginning of a recovery of particle fluxes at synchronous orbit. It definitely began by 1054 UT as a sudden dipolarization of the field had begun.
Fig. 15. Inferred geometry of plasma sheet prior to expansion onset at 1055 UT, March 22, 1979. Note that positions of ISEE spacecraft relative to the plasma sheet vary greatly through the event.

By 1055 UT, a Pi 2 burst and a sudden intensification of the westward electrojet were seen throughout the early morning sector. This onset may have been triggered by the northward turning of the IMF and solar wind velocity which began at IMP 8 at 1052 UT. Possibly the recovery of synchronous particle fluxes at 1052 UT was caused by the change in tail geometry brought about by the northward turning.

The current system associated with the expansion phase was distinctly different from the present earlier. As can be seen in the auroral zone stack plot, Figure 8, the eastward electrojet was decreasing in strength, e.g., at Tixie Bay (TIK), when suddenly the westward electrojet increased, e.g., at College (CMO). As shown by Clauer and Kamide [this issue] and also by Kamide and Baumjohann [this issue], the new system consisted of a single cell centered in the morning hours.

The westward surge associated with this expansion phase formed well into the morning sector, east of Sitka near 0200 LT, but west of the Alberta chain near 0300 LT. The central meridian of the expansion phase current system was at about 0300 LT, as can be seen from perturbations in the east-west magnetic field component at subauroral latitudes. The ISEE spacecraft and the two synchronous spacecraft (GOES 3 and 1977-007) were located nearly in the same meridian and were probably just west of the meridian of surge formation.

Recovery of the synchronous magnetic field to a more dipolar configuration occurred rapidly near the meridian of expansion onset. By 1057 UT, particle fluxes were back to predropout values, and the field inclination had decreased significantly. At this time the synchronous spacecraft 1977-007 (and presumably GOES 3) reentered the plasma sheet, since east-
west gradients in energetic protons show a maximum flux earthward of the spacecraft after this time (shown in bottom panel of Figure 14). The deviation in the east-west magnetic field component at GOES 3 indicates this as well, having nearly returned to its presubstorm baseline. At 1104 UT, a second Pi 2 burst was seen on the ground, and "dispersionless" particle injection began at 1977-007. Proton gradients indicate these new particles arrived on field lines above (or tailward of) the spacecraft. Subsequently, there was a negative perturbation in the D component, which if caused by currents on a boundary above the spacecraft, indicates field-aligned currents inward, toward the auroral oval.

In contrast to the foregoing, the field changes in the morning sector of synchronous orbit were considerably delayed. GOES 2 at 0412 LT observed a continuous increase in field inclination until 1110 UT, at which time it suddenly decreased. As suggested by Nagai [1982], this delay is probably a consequence of an expansion toward morning of the eastward edge of the substorm current wedge.

The first effects of the 1054 UT expansion onset were observed in the near tail at 1057:30 UT. At this time the neutral sheet passed upward over ISEE 2, and very rapid tailward plasma flow was seen [Paschmann et al., this issue]. This flow was accompanied by a strongly southward magnetic field [McPherron and Russell, 1983]. ISEE 1, which was above the neutral sheet, also recorded a tailward flow and field fluctuations. However, when the neutral sheet crossed ISEE 1 at 1107 UT, a southward field and tailward flow were present at ISEE 1 as well. As shown by McPherron and Russell [1983], the plasma sheet must have been extremely thin during the interval 1057-1107 UT, since the two ISEE spacecraft were in regions of lobelike magnetic field on opposite sides of the neutral sheet.

Effects of the 1104 UT substorm intensification were not observed in the magnetic field at either ISEE spacecraft. However, it may be noteworthy that a brief interval of moderate earthward plasma flow was seen at ISEE 2 between 1105 and 1106 UT (see Figure 17).

The recovery phase of the substorm in the near tail began about 1118 UT. At this time the plasma flow at both ISEE spacecraft reversed, becoming strongly earthward. Also, shortly after this time the stations at the equatorward edge of the auroral oval began to recover, and high-latitude stations recorded sudden intensifications. At 1124 UT there was a sudden decrease in the density of H⁺ and He⁺⁺ ions at ISEE 1, as simultaneously the density of O⁺ increased. Shortly thereafter, between 1128 and 1130 UT, the magnetic field strength decreased at both ISEE spacecraft, suggesting they were suddenly deep inside the plasma sheet. At 1134 UT a beam of oxygen ions was observed flowing outward from the ionosphere [Lennartsson et al., this issue]. These changes all suggest that the plasma sheet rapidly expanded after 1118 UT.

4. DISCUSSION AND INTERPRETATION OF THE EVENT IN TERMS OF A MODEL

There are several possible processes that might explain the energy transfer and release, and in fact this is one of the central problems of magnetospheric physics. The reader is invited
to use the material in preceding sections to draw his own conclusions. However, in this section of the paper we will discuss and interpret these data in terms of their consistency with one possible mechanism, reconnection on the dayside and in the tail region of the magnetosphere.

The observations summarized in the preceding section are well organized by a "three-phase" model of magnetospheric substorms [McPherron, 1979; McPherron et al., 1973]. In this model a southward turning of the IMF initiates a growth phase during which the solar wind drives a sequence of events culminating in an expansion phase. At the beginning of the expansion phase there is a sudden change in many of the processes initiated during the growth phase and a large increase in energy dissipation as measured by particle precipitation and Joule heating. The expansion phase is terminated by a sudden intensification of activity at high latitudes [Kisabeth and Rostoker, 1971] and the beginning of a recovery phase during which the various growth and expansion phase phenomena die away.

The various magnetospheric changes which occur during the growth phase can be interpreted as manifestations of a driven process [Akasofu, 1979; Baker et al., 1984; G. Rostoker et al., unpublished manuscript, 1984]. In a driven process, various phenomena are directly linked to the solar wind and respond to its changes. The fact that the process is controlled by the solar wind magnetic field suggests that reconnection between it and the earth's field may be responsible for the linkage [Dungey, 1961]. In the reconnection model of the driven process, magnetic flux from the dayside is transported to the nightside, where it reconnects and returns to the dayside. A fraction of the solar wind electric field is imposed across the magnetosphere as a result of dayside reconnection and drives a two-celled current system in the polar ionosphere. As discussed by Coroniti and Kennel [1972] and Akasofu and Kan [1973], there is no reason to expect a balance between the rate at which flux is transported to the tail and the rate at which it returns to the dayside. However, if these rates are not balanced, flux is eroded from the dayside and accumulates in the tail lobes. Other consequences include increased flaring of the magnetopause, an increase in the tail current, a more earthward location of the tail current, and plasma sheet thinning.

Most of these phenomena were observed in the 1054 UT substorm of March 22, 1979. As we demonstrated above, the southward turning of the IMF was quickly followed by the beginning of magnetic perturbations characteristic of a two-celled convection system. At the same time the auroral oval moved southward (accumulation of flux in the lobes), and the field at synchronous orbit became more taillike (strengthening and earthward movement of tail current). In addition, fluxes of particles at synchronous orbit disappeared (plasma sheet thinning). It is impossible for such a sequence to continue indefinitely, as the dayside would be completely eroded, or the nightside plasma sheet would be exhausted of closed field lines. Some process must occur which speeds up the return of flux to the dayside to bring the system into equilibrium. The various phenomena that occur during the expansion phase are apparently manifestations of this process.

It has been suggested [Russell et al., 1971; McPherron et al., 1973] that the expansion phase is caused by the sudden release of energy stored in the tail lobes. This process has been referred to as an "unloading process" [Akasofu, 1979]. In the unloading process, the release of energy drives additional currents in the westward electrojet and particle precipitation into the auroral oval. Some authors have suggested that the unloading process is brought about by the formation of a near-earth neutral line which reconnects the open flux accumulated in the lobes [Russell and McPherron, 1973; Nishida and Russell, 1978]. In one version of this model, the "plasmoid" model, the neutral line is initially of limited azimuthal extent and forms on closed field lines inside the plasma sheet. As discussed by Coroniti and Kennel [1972] and Akasofu and Kan [1973], there is no reason to expect a balance between the rate at which flux is transported to the tail and the rate at which it returns to the dayside. However, if these rates are not balanced, flux is eroded from the dayside and accumulates in the tail lobes. Other consequences include increased flaring of the magnetopause, an increase in the tail current, a more earthward location of the tail current, and plasma sheet thinning.

It is impossible for such a sequence to continue indefinitely, as the dayside would be completely eroded, or the nightside plasma sheet would be exhausted of closed field lines. Some process must occur which speeds up the return of flux to the dayside to bring the system into equilibrium. The various phenomena that occur during the expansion phase are apparently manifestations of this process.

It has been suggested [Russell et al., 1971; McPherron et al., 1973] that the expansion phase is caused by the sudden release of energy stored in the tail lobes. This process has been referred to as an "unloading process" [Akasofu, 1979]. In the unloading process, the release of energy drives additional currents in the westward electrojet and particle precipitation into the auroral oval. Some authors have suggested that the unloading process is brought about by the formation of a near-earth neutral line which reconnects the open flux accumulated in the lobes [Russell and McPherron, 1973; Nishida and Russell, 1978]. In one version of this model, the "plasmoid" model, the neutral line is initially of limited azimuthal extent and forms on closed field lines inside the plasma sheet. As discussed by Russell and McPherron [1973], this implies a connected pair of "x-type" and "o-type" neutral lines. Initially, reconnection cuts only the closed field lines forming a bubble

![Fig. 18. Pi 2 bursts recorded along the AFGL subauroral magnetometer chain, March 22, 1979 (courtesy of H. Singer). SUB, Sudbury; MCL, Mount Clemens; CDS, Camp Douglas.](image1)

![Fig. 19. Onset of expansion phase showed by electron flux at synchronous orbit, spacecraft 77-007, March 22, 1979.](image2)
of plasma (plasmoid) around the o-type neutral line. As described by Hones [1979a, b], this process will continue until open field lines defining the boundaries of the plasma sheet are reconnected (also see Hones and Schindler [1979] and Hones et al. [1973]). At this time the bubble of plasma is no longer connected to the earth, and tension in the newly merged field lines connected to the solar wind pulls the plasmoid downstream.

There are a number of expected consequences of the formation of a near-earth neutral line [Nishida et al., 1981]. First, in order to form the neutral line there must be a disruption of the sheet current across the tail. This can be accomplished by diverting a portion of the current into the ionosphere as a localized segment of westward current. Second, an x-type neutral line requires a region of southward magnetic field inside the plasma sheet tailward of the neutral line. In addition, the forces on plasma flowing into the neutral line from above and below are such that plasma will be ejected both eastward and tailward of the neutral line with high velocity. Movement of the plasmoid away from the earth leaves behind the x-type neutral line and a very thin plasma sheet [Fairfield et al., 1981]. Reconnection of open field lines in the tail lobes causes a decrease in field magnitude [Caan et al., 1978].

Many of these phenomena were observed during the 1054 UT expansion phase [Fritz et al., 1984]. Subsequent to the expansion onset there was a rapid growth of the westward electrojet in the postmidnight sector. Simultaneously, the field at synchronous orbit became more dipolar as mid-latitude observatories detected the magnetic perturbations of field-aligned currents connected to this electrojet (diversion of tail current through the ionosphere). In the plasma sheet a high-velocity burst of tailward flowing plasma was observed in as-

Fig. 20. Stack plot of D components from subauroral zone AFGL chain, at 55° geomagnetic latitude, March 22, 1979.

Fig. 21. Location of the westward electrojet in Alberta as inferred from latitude profiles of magnetic perturbations (courtesy of G. Rostoker).
association with a very strong pulse of southward field (implying tailward motion of a plasmoid). In fact, from the Berkeley electric field data, in conjunction with the magnetic field and plasma data, there is clear evidence that a plasmoid passed ISEE at about 1058 UT [Manka and Mozer, 1984]. Subsequently, lower velocity and a more weakly southward field were observed for almost 20 min. Also, particle injection was observed at synchronous orbit. During this time the tail current sheet was extremely thin, and the central plasma sheet was not observed by either spacecraft (reconnection of lobe field lines by stable near-earth neutral line).

Unloading of energy from the tail lobes must eventually cease, or come into equilibrium with the rate at which energy is transported to the lobes by the solar wind. Otherwise, the tail lobes would vanish during the expansion phase just as the dayside or nightside closed field regions would vanish during the growth phase. The end of the unloading process apparently initiates the recovery phase. In the plasmoid model the recovery phase begins with sudden tailward motion of the near-earth neutral line. As the neutral line passes the near-earth spacecraft, there is a sudden reversal of flow direction and expansion of the plasma sheet as they move into the closed field region earthward of the neutral line [Forbes et al., 1981]. The tailward motion of the neutral line is projected onto the ionosphere as a rapid poleward movement of auroral and magnetic activity [Pytte et al., 1978]. Subsequently, activity dies away as the currents driven by the unloading and driven processes decay.

These recovery phase phenomena were also observed during the 1054 UT substorm, although not as smoothly as suggested by the model. A reversal of the plasma sheet flow at 1118 UT suggests the neutral line moved tailward of the ISEE spacecraft at this time. The intensification of magnetic activity at higher latitudes at 1123 UT supports this interpretation. However, the sudden appearance of magnetic activity at highest latitude did not occur until after 1135 UT, suggesting the neutral line made its final retreat to the deep tail at this time.

During the CDAW 6 workshop a number of problems with the foregoing interpretation were noted and alternative explanations considered. For example, Helkila [1983] suggested that the precursor bay (1024–1045 UT) is an indication of an earlier substorm expansion onset and that there was no growth phase before the 1054 UT expansion onset. However, as we have discussed above, this signature was probably pro-

### Table 1. Magnetic Chronology for Substorm Expansion at 1054 UT, March 22, 1979

<table>
<thead>
<tr>
<th>Time, UT</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0410-0425</td>
<td>Brief interval of southward IMF at ISEE 3.</td>
</tr>
<tr>
<td>0530-0540</td>
<td>Another southward interval.</td>
</tr>
<tr>
<td>0613</td>
<td>Isolated substorm at Great Whale River and AFGL PI 2.</td>
</tr>
<tr>
<td>0747</td>
<td>Interplanetary shock passes ISEE 3.</td>
</tr>
<tr>
<td>0821</td>
<td>Shock reaches IMP 8 (Δt = 35 min) (compare to 57 min at v = 440 km/s).</td>
</tr>
<tr>
<td>0826</td>
<td>SSF recorded on nightside by AFGL chain.</td>
</tr>
<tr>
<td>1000-1000</td>
<td>Equatorial edge of oval moves south 2°.</td>
</tr>
<tr>
<td>0923</td>
<td>IMF turns southward (− 20 nT) at ISEE 3. Simultaneous changes in solar wind flow.</td>
</tr>
<tr>
<td>1008</td>
<td>Southward IMF reaches IMP 8 (Δt = 54 min).</td>
</tr>
</tbody>
</table>

#### Growth Phase

- 1000-1020 | Density decreases from 35 to 10 cm⁻³. |
- 1010-1030 | Field decreases by 50 nT at GEOS 2. |
- 1010-1100 | Large amplitude E field oscillations; T = 240 s (not seen in B) at GEOS 2. |
- 1024 | Start isolated bay in morning oval. |
- 1025 | Neutral sheet crosses down over ISEE 1 (does not reach ISEE 2). |
- 1028 | Neutral sheet crosses up over ISEE 1. |
- 1034-20 | Neutral sheet crosses down over ISEE 1. |
- 1037 | IMP begins to turn northward. |
- 1038-40 | Neutral sheet crosses down over ISEE 2. |
- 1042 | Isolated bay reaches minimum and recovers. |
- 1050 | ISEE 1 appears to reach north lobe. |
- 1051 | IMF briefly rotates northward at IMP 8. |

#### Expansion Onset

- 1054 | Expansion onset, GOES 3 dipolarization. |
- 1055 | Begin ground PI 2 and positive bay at Fredricksburg. |
- 1055-1056 | Sudden intensification of negative bay at Meenook (east of NEW near 0230 LT). |

#### Expansion Phase

- 1057-30 | Neutral sheet passes upward over ISEE 2 (B₁ is southward below neutral sheet). Begin very strong tailward flow at ISEE 2. |
- 1059-30 | ISEE 2 near lower plasma sheet boundary, suddenly records a 55-nT southward B₂. |
- 1059 | ISEE 2 nearly enters south lobe. Tailward flow appears at ISEE 1 near upper plasma sheet boundary. |
- 1064 | Particle injection at spacecraft 1977-007. Surge appears to have reached College. |
- 1065-1107 | Brief interval of apparent earthward flow at both ISEE. |
- 1106-40 | Neutral sheet passes upward over ISEE 1 (B₁ is southward below neutral sheet). |
- 1107-30 | ISEE 1 near lower plasma sheet boundary. |
- 1110 | Dipolarization of field complete at GOES 3. B₂ begins to increase at both ISEE. |
- 1111 | Begin dipolarization at GOES 2. |
- 1115 | IMF begins to turn northward at IMP 8. |
- 1117-1118 | Earthward flow begins at ISEE 1 and 2. |
- 1122 | IMF becomes northward at IMP 8. |
- 1123 | Intensification along Alberta chain. ISEE 2 well inside of plasma sheet. |
- 1125 | B₂ reaches maximum at both ISEE. ISEE 2 temporarily in south lobe. |
- 1129 | ISEE 2 well inside plasma sheet. |
- 1131-1133 | Burst of strong earthward-downward flow. Maximum of mid-latitude positive bays. |

#### Poleward Leap

- 1137 | Electrojet activity moves to high latitudes. |

#### Recovery Phase

- 1150 | End plasma sheet flows. |
- 1152 | Begin rapid recovery from negative bays. |
- 1210 | End polar cap convection. |
- 1215 | Begin recovery from positive bays. |
- 1300 | End all bay activity. |
duced by movement of a narrow westward electrojet equatorward of the normal auroral oval. G. Rostoker (personal communication, 1983) has suggested that the southward field in the plasma sheet at expansion onset was created by an outward line current emanating from a westward surge east of the spacecraft. Although this might explain the initial southward field, it does not explain its persistence. Ground data clearly show that the surge propagated westward, and one would expect to see a distinct reversal of the Z component as it passed over the ISEE spacecraft. In fact, the field remained southward for 15 min at ISEE 2, long after the surge had moved to midnight local times. Huang et al. (1983) noted that there was a brief interval of earthward flow during the interval of southward Bz (1105–1107) and this is incompatible with the proposal that a neutral line was earthward of the ISEE spacecraft until about 1118 UT. We note, however, that this event followed soon after the 1104 UT intensification which caused plasma injection at synchronous orbit and might have been caused by the formation of a second neutral line tailward of the ISEE spacecraft. Another problem noted by G. Parks (personal communication, 1983) is that the tail field turned northward somewhat earlier than the flow reversal. Such an association between northward field and tailward flow has been observed by others [Caan et al., 1979; Hayakawa and Nishida, 1982] and is seen in numerical simulations [Sato et al., 1983]. A possible explanation for this phenomenon is that the relative orientations of field and flow are very dependent on position relative to the center of a localized neutral line. Another problem discussed in some detail by Paschmann et al. [this issue] is that the timing of the flow reversal at the two spacecraft does not correspond to their assumed positions relative to a single neutral line. In our view, most of these difficulties can be eliminated by postulating a more complex scenario than the one given above. First, it is likely that the initial neutral line (1054 UT) was spatially localized, probably east of the ISEE spacecraft. With time, this region expanded westward to engulf the spacecraft (1057:30 UT). Then, an additional neutral line may have formed (1104 UT intensification), tailward of the spacecraft (earthward flow at 1105–1107 UT), and probably centered in a different meridian. While these changes were occurring, the entire tail was moving upward with waves in the neutral sheet as a result of the changes in the solar wind flow direction.

If a substorm behavior is as complex as suggested above, then it will be difficult given the limited observations available with current spacecraft to prove conclusively that a near-earth neutral line is the only appropriate description. Missions involving many identical spacecraft, in conjunction with high time and space resolution images of auroral development, can possibly resolve some of the ambiguities.

5. Summary

The objective of the CDAW 6 analysis is to better understand the transfer of energy, from the solar wind to the magnetosphere, and its release associated with substorms. Magnetic storms on two days, March 22 and 31, 1979, have been studied, though the analysis thus far has primarily concentrated on the first substorm (1054 UT) of March 22. The March 22 storm is characterized by consistent correlations between solar wind variations and magnetospheric response, both substorms having strong increases in magnetospheric currents following sustained intervals of southward IMF.

In this paper we have described the development of a relatively isolated substorm (1054 UT) in the context of the solar wind and magnetospheric conditions. The CDAW 6 data base with data from approximately 43 experiments on 13 spacecraft, 2 incoherent scatter radars, and more than 130 ground magnetometers provides an excellent resource for this study. The March 22 event was chosen so that ISEE 1 and 2 were in the tail and fortuitously were inbound through the plasma sheet and neutral sheet region just at the time of substorm onset, leading to the possible identification and analysis of what appears to have been a plasmoid ejection presumably associated with near-earth neutral line formation. As we have seen, the consistency with the general reconnection picture is quite good, the major drawback being the lack of a quantitative physical model which describes the reconnection region sufficiently well to predict its physical extent, the amount of energy transferred, and the resulting plasma and field properties.

Some of the significant areas of research in the CDAW 6 analysis include a detailed analysis of the solar wind shock and solar wind coupling to the magnetosphere; analysis of the ssc using ground-based and synchronous orbit data; quantitative analysis of the amount of energy coupled into the magnetosphere during the substorms; a numerical analysis of the global electrojets, and associated magnetic field variations and electric potentials as inferred from ground magnetometers by the Kamide-Richmond-Matsushita method; an analysis of the Joule heating in the ionosphere; a detailed study of the variation of the energetic particle population at synchronous orbit and in the tail; and a study of the highly dynamic (in space and time) region in the tail at about 12–14 Rs during substorm onset. The details of these studies will be presented in the following papers in this issue and in future publications.

Acknowledgments. The CDAW 6 sequence of workshops have been made possible by support from NASA through the National Space Science Data Center, J. I. Vette, Director. Data utilized in the workshop were acquired as part of the International Magnetospheric Study and have been funded by a variety of national agencies in various countries. The World Data Center A for Solar-Terrestrial Physics, J. H. Allen, Director, has provided a significant portion of the ground magnetic data; the computational resources used in modeling the magnetic data were provided by the National Oceanic and Atmospheric Administration and by National Aeronautics and Space Administration contract NAS 5-27564. The participation of R. H. Manka in CDAW 6 has been supported by the National Oceanic and Atmospheric Administration and by National Aeronautics and Space Administration grant NAG 1-172. The participation of G. Rostoker has been supported by National Science Foundation grant ATM 80-20376, Office of Naval Research grant ONR N00014-82-K-0031, and by National Aeronautics and Space Administration grant NGL 05-007-004. We would like to thank D. Baker, W. Baumjohann, G. Rostoker, and H. Singer for helpful comments on preliminary versions of this manuscript. This is IGPP publication 2265.

The Editor thanks D. N. Baker and W. Baumjohann for their assistance in evaluating this paper.

REFERENCES


R. L. McPherron, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

(Received June 25, 1984; revised September 11, 1984; accepted September 11, 1984.)