July 29, 1977, Magnetospheric Studies: Impulsive Waves, Global Dynamics and Geomagnetic Indices

MARGARET G. KIVELSON

Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California
Los Angeles, California 90024

This paper concludes the initial series of reports on the CDAW (Coordinated Data Analysis Workshop) study of the events of July 29, 1977. The primary purpose of this presentation is to point out interrelations among other papers in the series and to show how they increase our knowledge of how the magnetosphere operates. The day in question included intervals of intense geomagnetic activity, with an initial impulsive response to an interplanetary shock followed by numerous substorms. The latter half of the day was of special interest because the activity was limited to high latitudes in the northern polar cap, where it was substantial. Problems of magnetospheric physics addressed with the CDAW study are herein grouped into several general areas. The immediate response of the magnetosphere to changes in the solar wind (shock or other) was considered in studies of impulsive waves, which were traced through the magnetosphere to the ground and interpreted in terms of fast-mode wave propagation. The geometry and microstructure of the magnetopause, following the arrival of an interplanetary shock, were analyzed with data from near-geostationary satellites. The global magnetic geometry was modeled for the entire day. Plasma sheet convection was monitored at low and high altitudes. A model of particle convection during the first quarter of the day gave important evidence that the convection electric field penetrated to small radial distances for extended intervals. A large substorm at midday was unusually well documented with data from geostationary spacecraft and ground observatories. In reviewing those data this paper addresses the question of control of the local time of substorm onset. A model is presented that relates the local time of substorm onset to the sector of the tail earliest stressed following the onset of dayside reconnection. The late-day data provided evidence of lobe magnetic field reconnection when the solar wind magnetic field was pointing north. This paper marshals the evidence for different reconnection patterns and introduces an alternative pattern not previously considered. Remarks on the way in which the day's observations bear on several indices of geomagnetic activity end the summary.

INTRODUCTION

The papers of this series [Baker et al., Fennell et al., King et al., Knott et al., Manka et al., Nopper et al., Olson, Olson and Pfitzer, Reiff, Wilken et al., Wolf et al., and Zanetti et al.] provide exceptionally complete observations of the magnetosphere-solar wind system on a day of extremes. The solar wind density, for example, ranged from <2 ions/cm³ to more than 100 ions/cm³ [King et al., this issue]. In response to an interplanetary shock whose arrival coincided with that of a corotating density enhancement [Gosling et al., 1980; King et al., this issue], the magnetopause moved inward to a near-record minimum distance [Hoffman et al., 1975; Russell, 1976], probably within 6.1 RE [Knott et al., this issue] or 6.3 RE [Wilken et al., this issue]; later the magnetopause moved out, possibly to 15 RE [Olson and Pfitzer, this issue], and the bow shock may have moved out beyond 32 RE [King et al., this issue]. Other anomalies of solar wind properties on July 29, 1977, were reported in an earlier study by Gosling et al. [1980]. They measured an anomalously large He⁺/He²⁺ ratio of 0.3 for about 1 hour, approximately 12 hours after the passage of the interplanetary shock. The He⁺ enrichment occurred shortly after the proton temperature dropped from ~10⁶ K to 1.4 x 10⁶ K. Gosling et al. [1980] suggest that the cool He⁺-enriched plasma, which they believe to be solar gas driving the shock wave, was material ejected from an eruptive filament on the sun.

The north-south geocentric solar magnetospheric (GSM) field was pointing north. This paper marshals the evidence for different reconnection patterns and introduces an alternative pattern not previously considered. Remarks on the way in which the day's observations bear on several indices of geomagnetic activity end the summary.

Copyright 1982 by the American Geophysical Union.

Paper number 2A0330.
0148-0227/82/002A-0330$5.00

An interplanetary shock was observed at IMP 7, 32 RE upstream of the earth near the noon meridian at 0020 UT [Knott et al., this issue]. Soon thereafter (0026:37 UT) the GEOS 1 spacecraft near 7.1 RE and 1300 LT recorded a step-function increase in magnetic field magnitude and subsequently the magnetopause moved inward of the GEOS 1 spacecraft and approached but did not cross the ATS 6 spacecraft at 6.6 RE near 1500 LT. By 0030:45 UT the shock had reached the IMP 8 spacecraft near the dusk meridian, also about 32 RE from the earth [Wilken et al., this issue].

Wilken et al. time the arrival of the initial field magnitude
enhancement at several geostationary spacecraft within the magnetosphere as well as at ground stations, thereby obtaining the azimuthal and average radial propagation speeds. In their final figure they present a convincing picture of the propagation of the wave, which they identify as a fast hydromagnetic wave. They stress, however, that the wave propagates both azimuthally (910 km/s) and radially (600 km/s), with velocities somewhat slower than those expected for the fast mode in the outer magnetosphere [Nishida, 1978]. If the cold ion number density was nominal, the observed velocities are consistent with a 20% admixture of oxygen ions in the cold ion population.

Later in the day (1430 UT) a compressional wave was initiated by a sudden impulse (si) whose signature was a sharp change in the magnetic records of globally distributed ground observatories [Nopper et al., this issue]. In the absence of evident changes of solar wind parameters other than a brief density enhancement, Nopper et al. identify the density spike as the cause of the magnetospheric si. (They comment that in a private communication J. King has questioned the reliability of the MIT-IMP 7 plasma detector at very low densities, but Nopper et al. are unable to offer any alternative cause of the si.) The Nopper et al. paper suggests that discontinuities in the solar wind, which impinge on the magnetosphere at a rate of several per hour, may be important sources of excitation of dayside pulsations, an old idea that they suggest be revived and carefully reexamined.

The compressional wave initiated by the si at 1430 UT propagated from near noon to predawn at geostationary orbit with a velocity of 1500 km/s, substantially faster than the 910 km/s inferred for azimuthal propagation in the same spatial region during the event of 0027 discussed by Wilken et al. The reduction of the fast-mode velocity between two sets of observations separated by 14 hours requires that the plasma density decrease by a factor of $\sim 3$ near geostationary orbit. Marked changes of plasma density in the outer magnetosphere over time intervals of hours may readily be accounted for by changes of convection patterns [e.g., Wolf et al., this issue] or ionic composition resulting from changes in source strengths and precipitation losses. Similar decreases in the number densities of O$^+$ and H$^+$ at $L < 5$ are evident in Figure 9b of Fennell et al. [this issue], which displays low-altitude S3-3 measurements from early (0630 UT) and late (1830 UT) day passes separated by 12 hours. Density reductions are everywhere greater than factors of 2.

Associated with the wave generated by the shock early in the day were impulsive changes in particle fluxes. Wilken et al. comment on the anticorrelated intensity variations of the spin-averaged integral fluxes of energetic ions and electrons seen by GEOS 1 in the leading edge of the wave. The time scale of the intensity variations was of order 10 s, i.e., the time during which the electric and magnetic fields of the wave increased. Fennell et al. also comment on spikes of suprathermal particles (60 eV to 16 keV), seen briefly at 0026:44 and 0026:56 (their Figure 2) when the impulse passed over ATS 6. The relation between the impulsive wave and details of the particle flux variations has not been fully worked out. Wilken et al. do provide a qualitative description of how betatron acceleration in the wave front, followed by inward convection in the wave electric field, is consistent with the observed particle flux changes.

Finally, the properties associated with the fast-mode wave should be noted. It can propagate in any direction and must be invoked to explain the radially inward motion of the impulse (at an average velocity of $v_i = 600$ km/s [Wilken et al., this issue]). The wave carries only a transverse electric field, azimuthal if the propagation is radial. At GEOS 1 in the outer magnetosphere, the transverse electric field of the wave was $17$ mV/m [Knott et al., this issue], and the field-aligned perturbation magnetic field was $b_{hi} = 39$ nT. The local phase velocity of the wave can be estimated from $v_{ph} = E_i/b_{hi} = 440$ km/s. The difference between the local and average radial velocity of the wave is consistent with the nonuniform properties of the magnetosphere at different radial distances. What is somewhat perplexing is that the local phase velocity differs considerably from the mean 'azimuthal' velocity $v_a = 910 \pm 140$ km/s, found for wave propagation between GEOS and GOES in the outer magnetosphere [Wilken et al., this issue]. Both $v_{ph}$ and $v_a$ should be close to the Alfvén velocity for the outer magnetosphere, and the factor of 2 difference between them has not been explained.

**GLOBAL DYNAMICS**

**Magnetopause Location and Microstructure**

Several papers of this series describe the inward displacement of the magnetopause in response to the interplanetary shock at 0027 UT. Knott et al. find gratifying agreement between the inward speed estimated by timing and related geometric arguments and that obtained from the measured perpendicular electric field. The innermost displacement of the magnetopause is described by Wilken et al., and Fennell et al., who agree that the magnetopause moved within the orbit of GEOS 1 at 6.7 $R_E$ (1300 LT) and near but not past ATS 6 at geostationary orbit (1500 LT). These observations provide a test of various approximations to the magnetopause standoff distance and shape, which is satisfactorily predicted by the estimates of Formisano et al. [1979] or of Holzer and Slavin [1978]. The standoff distances obtained from field modeling by Olson and Pfitzer [this issue] also accord with the observations.

To understand the success of the model predictions of magnetopause position, it is useful to examine the relevant external and internal parameters in detail. The objective is to understand how the specific well-documented case of July 29, 1977, fits into statistically derived results. We follow the arguments of Holzer and Slavin [1978], which may be presented in two parts. A reference magnetopause position, applicable for cases in which the interplanetary magnetic field is northward and the ring current is close to its quiet time value, is first calculated. Corrected for the $-4\%$ abundance of He$^{++}$ in the solar wind during the early hours of July 29, 1977 [Gosling et al., 1980], the Holzer-Slavin nose distance is $R_N = 102(nu^2)^{-1/6}$ with $n$ the density in cm$^{-3}$ and $v$ the solar wind velocity in km/s. For $n = 100$ and $v = 410$, $R_N = 6.5$ $R_E$. The nose location is defined by the meridian plane parallel to the $4^\circ$ aberrated solar wind velocity. King et al. [this issue] indicate that the solar wind direction was $\sim 7^\circ$ east of the sun in the relevant interval, so a nose location $3^\circ$ duskward of noon is anticipated. With GEOS 1 at 1300 LT and ATS 6 at 1500 LT, the post-shock reference magnetopause locations are 6.6 $R_E$ and 7.0 $R_E$, respectively. The ring current was only slightly enhanced in relation to its quiet time level [Olson and Pfitzer, this issue; Wolf et al., this issue], but the interplanetary magnetic field had been
inclined southward for more than an hour prior to the shock [King et al., this issue; Manka et al., this issue; Olson, this issue]. Consequently, erosion of dayside flux by the southward-directed interplanetary field is expected to be the principal process that modifies the magnetopause position. Erosion moves the magnetopause inward in relation to the reference magnetopause location, probably by a fraction of an $R_e$. In this particular case the bracketing of the post-shock magnetopause by GEOS 1 and ATS 6 is consistent in detail with a statistically derived model that seeks to account for the important control mechanisms. Additional, equally well-documented cases would help to determine whether agreement was fortuitous, whether models are accurate closer to the flanks, and whether additional corrections are needed to account for solar-wind-dependent variations of viscous drag or pressure-dependent changes of boundary shape.

For most of the 1.5 hours after the magnetopause moved inward of GEOS 1, the satellite remained in the magnetosheath. Aspects of the microstructure of the boundary region are investigated by Knott et al. They provide compelling evidence for several encounters with regions of open magnetic field lines connected both to the earth and to the interplanetary medium; such field lines are characterized by $B_z < 0$ and strongly field-aligned ion flux. They also discuss possible entries into ‘magnetic islands’ of the tearing mode instability; such regions are characterized by arbitrary $B_z$ and isotropic ion pitch angle distributions.

The magnetosphere remained compressed for several hours subsequent to the SSC (storm sudden commencement). Olson and Pfitzer’s model showed the nose of the magnetopause near $L = 6$ until 0400 UT, after which it began slowly to move to larger $L$. The various boundaries (polar cap, plasmapause, plasma sheet inner edge) traced by low-altitude polar-orbiting spacecraft [Fennell et al., this issue] reached minimum latitudes near 0600 UT and then began moving to higher latitudes, generally in accord with the predicted positions of these boundaries in the model calculation of Wolf et al.

The expansion of the entire magnetosphere in the early afternoon of July 29, 1977, in response to a marked decrease in solar wind dynamic pressure [King et al., this issue], was less well documented, but there is evidence that magnetospheric boundaries moved outward and that ionospheric boundaries moved poleward. A bow shock situated beyond 32 $R_e$ for part of the afternoon is proposed by King et al. They argue that reduced plasma flow speeds at IMP 7 between 1503 and 1531 UT, and also between 1659 and 1728 UT, occurred when the spacecraft at 32 $R_e$ upstream entered the magnetosheath. There was no direct evidence of the bow shock crossings, but the anomalously large standoff distance is consistent with the small Alfven Mach number measured in the solar wind. (The paper of Gosling et al. [1980] provides no data between ~1500 and ~1900 UT and consequently sheds no light on possible bow shock crossings.) The magnetopause in the Olson and Pfitzer dynamic model receded to 15 $R_e$ at about 1700 UT. J. H. King (personal communication, 1981) cautions that the standoff distance may be overestimated. He emphasizes that the MIT-IMP 7 plasma densities must be used with care when, as at 1700 UT, the densities are lower than 4 cm$^{-3}$. King thinks the nose of the magnetopause may have remained inside of 12 $R_e$. Fennell et al. note that late in the day the active regions of auroral-type precipitations moved to very high latitudes consistent with the above-noted sunward excursion of dayside equatorial boundaries. In particular they state that at about 2200 UT the polar cap boundary moved above 85° magnetic latitude. Zanetti et al. [this issue] also note that the typical auroral zone and polar cap signatures were found to occur at increasingly high magnetic latitudes on successive passes of polar-orbiting satellites between about 1230 UT and 1430 UT. For the period from 2145 to 2250 UT they give evidence that the polar cap boundary moved up to invariant latitudes above 80°, and perhaps up to 83°. (Note in a dipole model where 72° invariant latitude corresponds to $L = 10$, 80° corresponds to $L = 33$. These numbers are not realistic, but they do give a sense of the extraordinary significance of displacement of the polar cap to 80° invariant latitude.)

**Convection of Plasma Sheet Ions**

Prior to the sudden commencement at 0027 UT on July 29, 1977, the magnetosphere had been quiet for some hours, although a weak substorm with onset at about 0013 UT was in progress [Manka et al., this issue]. Olson [this issue] notes that at 2330 UT on July 28, 1977, the IMF turned abruptly southward, and magnetospheric convection increased. From the appearance at $L = 5.4$ in the afternoon magnetosphere of structured Pc 1 events, he infers the presence of plasma ions freshly injected from the plasma sheet onto these field lines of the inner magnetosphere near the equator.

Fennell et al. also report on the location of the equatorward edge of plasma sheet ions, though with imperfect temporal resolution as they rely on infrequent data from polar-orbiting satellites. Their Figure 7 shows S3-3 data for the location of the plasma sheet boundary at dusk. A straight line used to join data points crosses $L = 5.4$ at approximately 0000 UT on July 28, 1977. Olson’s suggestion that newly injected plasma sheet ions appeared at dusk at $L = 5.4$, at about 2345 UT on July 28, 1977, is not incompatible with the limited data of Fennell et al., but there is no pass giving data close to the time of interest. The Rice model [Wolf et al., this issue] traces magnetospheric convection boundaries but only on a coarse temporal grid. Their input convection potential (see their Figure 2) does not reflect the southward turning of the field prior to the arrival of the shock at 0027 UT, and consequently their model shows inward motion of the plasma sheet only after the shock arrives.

Theories of the dynamical response of plasma sheet ions and electrons to storms and substorms were tested in a number of useful ways, using the CDAW data set. The Rice model [Wolf et al., this issue], applied to the first 6 hours of the day, demonstrated that the adiabatic response of the plasma sheet to enhanced convection electric fields can alone account for the storm-time ring current. No other mechanisms were needed to obtain plausible fits to the data, although Wolf et al. note that their results do not exclude contributions from other mechanisms. The point to be stressed is that the deep injection of the plasma sheet particles was modeled in a calculation that handled the convection electric field self-consistently. The model allowed for the imposed external field to be screened from the inner magnetosphere (shielding) by the convecting particles. The evidence that the convection field remained enhanced at low $L$ shells for several hours and that shielding was reestablished only after the plasma sheet had penetrated to low $L$ shells is of special interest; it runs counter to some
Theoretical arguments (see references in Wolf et al.) that require shielding in times that are short compared with an hour. Wolf et al. argue that the disruption of the Birkeland 2 current system is the major feature that allows the convection field to penetrate to low L shells. It should be noted that at low altitudes the predicted plasma sheet boundaries lie somewhat poleward of the observed boundaries (see Figure 7 of Fennell et al.), probably because an inadequate magnetic field model was used. The event-specific model of Olson and Pfitzer was not yet worked out when the Rice model was run at the CDAW workshop.

Fennell et al. remark that until 1200 UT, plasma sheet ions in the energy range 90 eV to 16 keV penetrated the outer edge of the plasmasphere. This feature is reflected in their Figure 7, which shows the measured plasmapause prior to 1200 UT at higher latitudes than the equatorward edge of plasma sheet ions. Later in the day, after the northward turning of the IMF, these two boundaries more typically coincide with each other. The penetration of plasma sheet ions within the plasmapause is familiar as a feature of steady state convection of moderate energy ions in the presence of an unshielded cross-magnetospheric electric field [e.g., Cowley and Ashour-Abdalla, 1976]. The convection paths within the plasmasphere create the ion distributions, called 'nose-events,' reported by Smith and Hoffman [1974] on the basis of Explorer 45 observations. The presence of moderate energy ions well within the plasmapause during the first half of the day, and their relative absence during the second half of the day, is consistent with the concept that enhanced convection electric fields were not excluded from low L shells pre-1200 UT for southward IMF. Convection electric fields were largely absent during the second half of the day when the IMF turned northward. The Rice model was not extended beyond 0600 UT because it does not include charge exchange precipitation and thus cannot simulate ring current recovery.

Steady convection models required modification to account for energetic particle injection to geostationary orbit during the 1230 UT substorm. Baker et al. [this issue] found it necessary to recognize the existence of a large induction electric field during the onset of the substorm expansion in order to explain the observed injection of particles with magnetic moments of several hundred mega-electron volts per Gauss. Their arguments are summarized in the discussion of the midday substorm in the next section.

**Substorms**

Several substorms occurred during the first half of July 29, 1977. An exceptionally thorough examination of the largest, at 1200 UT, was undertaken by Baker et al. Several well-instrumented geostationary spacecraft at local times near 0300 and 0700 provided data used for analysis. Some of the observed changes were shown to result from motion and distortion of the tail plasma sheet boundary, and others could be attributed to actual particle acceleration associated with tail field collapse. Unfortunately, no spacecraft data from the deep magnetotail were available.

The data supported a model of plasma sheet thinning in the near-earth tail coincident with the development of a taillike field geometry, a conclusion documented by analysis of energetic particle flux anisotropy. During substorm expansion, freshly accelerated particles appeared at the time the magnetic field became more dipolar. That energetic particles were responding nonadiabatically to the substorm expansion was confirmed by examination of changes in phase space density distributions. The injection and acceleration of particles up to mega-electron volt energies in less than 5 min could not reasonably be attributed to the action of a steady cross-tail electric field. Rather, the induction electric field that accompanies tail magnetic field collapse was invoked. For the observed rate of change of field magnitude (\(\Delta B = 100\) nT in approximately 5 min), a consistent explanation of both acceleration and convection suggested that an induction electric field of about 20 mV/m was briefly present over about 9 Re across the tail during the period of tail collapse. This induction electric field is an order of magnitude larger than the calculated fields of Olson and Pfitzer. Their calculated values are obtained from model fields evaluated only every 30 min, a procedure that necessarily underestimates the induced electric field associated with sudden changes of the magnetic configuration.

The freshly accelerated protons were observed as they drifted around the earth, and the dispersion of their arrival times was used to identify the location of particle injection. The first onset was found to have corresponded to an injection at 0200 UT.

Previous studies of substorm-produced, >300-keV proton pulses [Belian et al., 1978] have demonstrated that they are injected in a narrow longitudinal range 'which tends to be at, or somewhat before, local midnight.' Why, then, did the injections during the 1200 UT substorm commence well past local midnight? From the CDAW data set the IMF was found to lie mainly in the yz GSM plane with \(B_x < 0\) and \(B_y > 0\). At 1200 UT the dipole tilt was near maximum (35°) in relation to ecliptic north and tilted westward as viewed from the sun. This situation may well favor dayside reconnection at high northern latitudes.

A somewhat naive explanation of the local time of onset is suggested in the schematic diagrams of Figure 1, which show the field geometry. Stress builds up in the reconnecting field lines as they are convected downstream by solar wind flow. The stress will develop first on the shorter field lines, as emphasized by Crooker [1979]. This means that field lines flowing on the dawn side are earliest subject to stress, and the asymmetric stress in the tail may determine the local time of substorm onset. For the 1200 UT substorm the stress buildup occurred first on the dawn side of the tail, as illustrated in Figure 1a, and the substorm onset was at 0200 LT. Although the Crooker model is used to illustrate a possible reconnection geometry, the argument requires only that reconnection favor high northern latitudes for the relevant tilted dipole orientation.

The simple argument given above leads one to speculate that substorms may quite generally be initiated in the local time sector first subjected to field-aligned stress. The tail sector that is earliest stressed after a southward turning of the IMF is determined by IMF orientation and the dipole tilt. The hypothesis that 'earliest stress' determines the LT sector of substorm onset satisfactorily explains why, under typical solar wind conditions, substorms are initiated on the dusk side of the tail. Consider what happens if the IMF is tilted only somewhat southward from a normal spiral field orientation. The schematics of Figure 2 show that in either a 'towards' or 'away' sector the downstream end of the interplanetary field line flows on the dusk side of the magnetosphere. Substantial stress on the dawnside field
Fig. 1. Schematic views of reconnection patterns for a field configuration with the IMF (dashed lines) in the yz plane (GSM), shown for an extreme tilt of the dipole. These conditions represent the IMF at about 1200 UT on July 29, 1977:
(a) Noon-midnight section with projected IMF field lines. Lines 1 to 1c actually flow on the dawn side of the tail, whereas lines 2 to 2c flow on the dusk side of the tail. Field-line tension represented by thicker lines is present along the magnetospheric portion of field lines 1b, 1c, and 2c but not along 2b. (b) A view of merging on the day side, adapted from Crooker [1979] for the case of a dipole tilted toward the sun. The tilt distorts the north-south symmetry of the reconnecting surface. A portion in the southern hemisphere is shaded to show that it is tilted too much to interact with the incident solar wind. The black curve connecting circled points represents the line along which the internal and unperturbed solar wind field lines are antiparallel. In Crooker’s model this curve is the locus of reconnection. The field line labeled 1-2 illustrates that the northern polar cap connects to field lines on the dawn side, whereas the southern polar cap connects to field lines on the dusk side. Field line 1 contains a short ‘kink’ that disappears quickly as tailward flow straightens it. Field line 2 must eliminate considerable slack before it can straighten and pull on magnetospheric field lines. Other dayside field geometries and merging laws could be used. Our arguments would be unaffected, provided merging occurs at high northern latitudes only.

Lobe Reconnection

The last half of the day, with the IMF strongly northward and the dipole tilt near maximum, provided an exceptional opportunity to observe the effects of possible lobe reconnection. Reconnection in a strictly northward IMF was first discussed by Dungey [1963]. In his picture, applicable to a closed magnetosphere, a strictly northward interplanetary field line reconnects simultaneously in the northern and southern hemispheres with a closed high-latitude ‘tail’ field line. (Closed (open) field lines have two (one) ends which cross the surface of the earth.) This reconnection leaves the topology of the field unchanged because a closed + interplanetary field line pair replaces the original closed + interplanetary field line pair. Some sunward convection of high-latitude flux tubes is required to restore the initial magnetospheric configuration, and that convection is symmetric in the two polar caps.

Russell [1972] pointed to the strong evidence that the magnetosphere is always open, i.e., that high-latitude tail field lines are not closed. This implies that a northward IMF can reconnect with the open field lines of the tail lobes. As it is improbable that a single interplanetary field line will connect neutral points on both lobes, especially if the IMF \( B_y \neq 0 \), Russell supposes reconnection to occur for different IMF lines in the two lobes. An interplanetary field line reconnecting with a northern lobe field line would replace an open + interplanetary field line pair with a topologically equivalent pair (see Figure 3c). Subsequent convective rear-
a) Reconnection with closed field lines—northern lobe only

b) Reconnection with open field lines—northern lobe only

Fig. 3. Alternate patterns of lobe reconnection for a northward oriented interplanetary magnetic field interacting with a tilted dipole. All diagrams represent projections into the noon-midnight meridian plane. Dashed curves represent some field lines connected to the earth but not participating in reconnection at the time illustrated. They are shown to emphasize the north-south asymmetry of the dayside fields. The most recently reconnected field lines correspond to the heavy curves. The symbols S and M identify portions of the reconnected field line originating in the solar wind and the magnetosphere, respectively. Numbers (1 and 2) are used to label particular field lines; single primes identify field line segments originating at southern locations and in (a) and (d) double primes identify segments from near the ecliptic plane. The processes producing the illustrated patterns (a-d) are identified below the corresponding diagrams.

On July 29, 1977, after the IMF turned strongly northward (1500 UT), ground records from all stations below the polar cap became extraordinarily quiet. At stations within the shrunken polar cap in the northern hemisphere, magnetic perturbations in excess of 500 nT were recorded, although the southern polar cap was quiet. Polar-orbiting spacecraft (TRIAD, S3-3, AE-C) confirmed the strong north-south asymmetry, with large currents present only in the northern polar cap [Zanetti et al., this issue]. Precipitating low-energy (<1 keV) particles with intensities comparable to magnetosheath levels were found at high latitudes (>80° invariant) in both polar caps. Localized bursts of >1 keV electrons and simultaneous ion flux decreases gave evidence of field-aligned electric fields above 80° invariant in both hemispheres.

Reiff [this issue] provided strong evidence for the presence of convection in both polar caps. A two-cell pattern, reflecting tailward motion near the edges and sunward motion near the centers of both northern and southern polar caps, is expected.

Zanetti et al. present two ideas to account for their observations. First, they propose that the tilt of the dipole strongly favors reconnection with open field lines of the northern lobe only (see Figure 3b). (Russell's [1972] picture, in which reconnection proceeds independently but simultaneously in both lobes, ignores the asymmetry arising from dipole tilt.) Next, they note that the conductivity in the two hemispheres is very different because only the northern polar cap is in sunlight; the conductivity differences enhance the current asymmetries. The symmetries in precipitating particles are attributed to their being on closed field lines.

Further data for the period of northward field are provided by Reiff [this issue]. She finds strong convection, with regions of sunward flow in both polar caps. Although conjugacy of the flow patterns cannot be established, the amplitudes are similar in both polar caps. Reiff argues that field lines from both hemispheres must participate in the reconnection. She supports the idea that hemispheric differences of electrical conductivity explain the asymmetric...
In the two hemispheres. In this model, too, field lines opened by reconnection with the IMF must close in the tail and return to the day side, flowing sunward across the polar cap. The convection patterns may differ little from those of the ‘reclosure’ geometry.

Thus far it has not been possible to choose cleanly among the proposed interpretations of the late day data, despite the extensive data available. All the interpretations rest on some form of northern lobe reconnection in the presence of a northward IMF [Dungey, 1963; Russell, 1972]. The fact that convective flows of similar strength were observed in both polar caps argues against the reconnection pattern of Figure 3b (reconnection with open field lines, northern lobe only) because such a pattern should not produce equally strong convective flows in both polar caps. The ‘reclosure’ pattern of Figure 3d can explain the observations but seems implausible for several reasons. It requires that individual interplanetary field lines systematically reconnect both in the northern and southern lobes. Reiff argues that the field geometry can accommodate two merging points on the interplanetary field lines. For the magnetic configuration of Crooker’s [1979] magnetopause, each lobe contains regions with magnetic fields strictly antiparallel to the observed interplanetary field, regions that are expected to permit reconnection. The consequences of dipole tilt are overlooked in Reiff’s argument. For a strongly tilted dipolar field the plasma properties will differ markedly at the loci of antiparallel fields in the two hemispheres. The pressure of flowing magnetosheath plasma normal to the magnetopause should be larger on much of the northern lobe than on the southern lobe; such a situation favors northern lobe reconnection. In addition it should be recognized that reconnection appears to be a sporadic process [Sonnerup et al., 1981] that rarely proceeds in a steady state. It seems unlikely that an intermittent process will systematically occur at two points of the same interplanetary field line, as required for ‘reclosure.’ Thus it seems improbable that the ‘reclosure’ pattern (Figure 3d) dominated the extended intervals of lobe reconnection on July 29, 1977.

The two remaining reconnection patterns (Figures 3a and 3c) seem to be consistent with the present evidence. Each implies convection and, by connecting both polar caps to the magnetopause, allows precipitation in both hemispheres. The north-south asymmetry of high-latitude currents may be controlled by effects other than the reconnection pattern as a consequence of differing ionospheric conductivities in the two hemispheres.

There seems little doubt that the evidence collected for July 29, 1977, gives substantial support to the view that lobe reconnection was observed. Additional analysis to test alternative patterns of reconnection may resolve the remaining ambiguities.

**Geomagnetic Indices**

In the final section of this summary, CDAW contributions to the analysis of geomagnetic indices are discussed. The index to which these papers have drawn most attention is the Akasofu epsilon index of solar wind power input [Perreault and Akasofu, 1978]. King et al., for example, organize some of their description of solar wind properties in terms of the Akasofu epsilon index. On the other hand, the question of how best to quantify the relation between the solar wind as a driver of magnetospheric processes and the magnetospheric...
response [Akasofu, 1979; Baker et al., 1981; Clauer et al., 1981] has not been dealt with in this series of CDAW papers.

By providing unusually well-documented data on the temporal evolution of the magnetosphere, the CDAW study has led to valuable advances in modeling the magnetospheric magnetic field [Olson and Pfitzer, this issue]. In particular, Olson and Pfitzer called attention to the importance of a modified $Dst$ index for quantifying the strength of the ring current. Because in an ssc the magnetopause moves markedly inward, low-latitude magnetic perturbations include effects directly attributable to changes in the magnetopause current systems in addition to ring current contributions. This point was originally made by Burton et al. [1975] in their study of the storm time ring current. In modeling the magnetic fields of July 29, 1977, Olson and Pfitzer first calculated the perturbations produced by the magnetopause currents alone. They then obtained a modified $Dst$ from the measured $Dst$ minus the calculated perturbations attributable to magnetopause currents. Modified $Dst$ was used to scale the ring current strength for their field model.

The model of Wolf et al. does not treat $Dst$ as an input parameter but relies on other measurements (solar wind velocity, density, magnetic field and the auroral AL index) and then calculates $Dst$. Both magnetopause currents and the ring current contribute to the predicted $Dst$, which reproduces observations with considerable success over the time interval modeled.

One final point worth noting is that the observed shock of the first hour of July 29, 1977, was embedded in a corotating stream interface [King et al., this issue]. It is of interest to note that despite the complexity of the solar wind behavior, the arrival of a stream interface region, and certain properties of the interplanetary field, would have been predicted from interplanetary data by use of criteria described by Rosenberg [1982]. The prediction is based on identifying an increase in solar wind number density by a factor of 1.7 over the previous day. When that condition is satisfied (as it was by 1700 UT on July 28, 1977, see Figure 1 of King et al.), Rosenberg finds it probable that the IMF will develop a substantial north-south component within half a day and that a geomagnetic storm will follow, as it did 7 hours after Rosenberg’s criterion was satisfied. (Rosenberg’s work suggests that a geomagnetic storm might have occurred even had the shock not triggered it.) In an earlier study, Rosenberg and Coleman [1980] suggested that an envelope of IMF $B_z$ in the stream region was quite sinusoidal, with a period of approximately 30 hours. On July 29, 1977, the IMF latitude [King et al., this issue] swung south to north with a ~24-hour period. Further investigation, using other data sets, is needed to test the merit of this method of prediction and especially to apply it to cases for which the solar wind variations do not include both a corotating stream and an interplanetary shock.

CONCLUSION

The study of July 29, 1977, through the approach of a coordinated data analysis workshop, has provided a remarkably complete data set for the investigation of the solar wind-magnetosphere system. This initial set of papers illustrates many important phenomena. New ideas, and old ideas never well tested, have been pursued and are presented for examination in this set of papers. The participants supported the proposal that the data should be available to all interested scientists. We hope that more good science will emerge from ongoing studies.

Acknowledgments. The hospitality of J. I. Vette and the members of his staff is gratefully acknowledged. R. H. Manka, whose persistence and enthusiasm motivated even government agencies, is to be commended. I should like to thank D. J. Southwood for enlightening discussions and J. H. King, C. T. Russell, and J. A. Slavin for useful criticism. This material is based upon work supported by the National Science Foundation under grant ATM 79-23586 and by the National Aeronautics and Space Administration under grant NGL-05-007-004.

The Editor thanks D. N. Baker and D. H. Fairfield for their assistance in evaluating this paper.

REFERENCES


Nopper, R. W., Jr., W. J. Hughes, C. G. Maclellen, and R. L.
Reiff, P. H., Sunward convection in both polar caps, *J. Geophys. Res.*, this issue.

(Received July 9, 1981; revised February 23, 1982; accepted February 26, 1982.)