JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. A3, PAGES 2425-2431, MARCH 1, 1987

Field-Aligned Currents Associated With Substorms in the Vicinity of Synchronous Orbit 1. The July 5, 1979, Substorm Observed by SCATHA, GOES 3, and GOES 2

T. NAGAI,[1] H. J. SINGER,[2] B. G. LEDLEY,[3] AND R. C. OLSEN[4]

Magnetic field topology and field-aligned current signatures in the vicinity of synchronous orbit are examined for a substorm on July 5, 1979. Changes from taillike to dipolar field geometry propagate earthward near the midnight meridian during the substorm. The major field-aligned currents producing a negative D perturbation at and around synchronous orbit are downward currents flowing into the auroral ionosphere on L shells greater than the synchronous spacecraft L shell. Although these currents are located initially on higher L shells, they shift toward the lower L shells as the change from taillike to dipolar fields propagates earthward. There may exist upward field-aligned currents located on smaller L shells in the limited longitudinal region near the meridian where mid-latitude D perturbations change their sign.

INTRODUCTION

It has been known that field-aligned currents play an important role in the magnetosphere-ionosphere coupling during magnetospheric substorms. Synchronous spacecraft observe a transient perturbation in the D component (azimuthal) of the magnetic field during substorms, which can be attributed to substorm-associated field-aligned currents [e.g., *Coleman and McPherron,* 1970, 1976; *McPherron and Barfield*, 1980; *Kokubun and McPherron*, 1981; *Nagai*, 1982b]. The D perturbation observed during substorm expansion phases is normally a positive deflection on the duskside of midnight and a negative deflection on the dawnside of midnight. Observed features of the D perturbations, however, depend strongly on spacecraft longitudinal position. Magnetic field configuration changes, such as a change from a taillike to a more dipolar geometry, are associated with substorms in the vicinity of synchronous orbit. The field changes can be quite localized [*Singer et al.,* 1983]. Characteristics of the D perturbations are closely coupled with these field changes. Although these results have been derived mainly by observations using a single spacecraft, several case studies using two longitudinally separated synchronous spacecraft have complemented them [Nagai, this issue] (see also *Arnoldy and Moore* [1983] and *Singer et al.* [1985]). In addition to two synchronous spacecraft, *Singer et al.* [1985] used SCATHA at a slightly greater radial distance to examine magnetic variations during substorms in the vicinity of synchronous orbit. However, the emphasis of that paper was on explaining longitudinal variations of the substorm signature. Thus we have a "longitudinal view" of substorms at synchronous orbit, but simultaneous observations at different L shells are highly desirable for studying further the nature of the substorm associated field-aligned currents as well as that of the field changes during substorms.

[1]Meteorological Research Institute, Tsukuba, Ibaraki, Japan.
[2]Space Plasmas and Fields Branch, Space Physics Division, Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts.
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland.
[4]Department of Physics, University of Alabama in Huntsville.

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

In this paper we report on one substorm event observed by three spacecraft at and around synchronous orbit. The expansion phase of the substorm starts at around 0927 UT on July 5, 1979. Locations of the spacecraft are presented in Figure 1. The synchronous spacecraft GOES 3 and GOES 2 are located with approximately 2 hours local time separation. Fortuitously, the near-synchronous spacecraft, SCATHA, is located about 1 R_E tailward of GOES 3. At the expansion phase onset, SCATHA and GOES 3 are almost lined up near the midnight meridian, and SCATHA is located at a slightly higher magnetic latitude than GOES 3. This is the best case of SCATHA-GOES conjunctions in surveying 1 year's data for our purpose. GOES provides magnetic field measurements [*Grubb*, 1975], and SCATHA provides particle measurements from the University of California at San Diego (UCSD) charged particle experiment in addition to magnetic field measurements [*Stevens and Vampola*, 1978]. The present case study sheds light on spatial structure of the field-aligned currents and their relationship to the local field changes.

SUBSTORM ACTIVITY BASED ON GROUND OBSERVATIONS

The magnetic field data from the Air Force Geophysics Laboratory (AFGL) Magnetometer Network for the substorm interval are presented in Figure 2. Locations of six AFGL stations are given in Table 1 along with locations of two standard stations and information on the spacecraft. Pi 2 pulsation signals are found after -0927 UT at all AFGL stations. They are seen clearly in the D component data, where the data are high pass filtered with a cutoff at about 5-min period (Figure 3). It is difficult, however, to determine the onset time of the Pi 2 pulsation more precisely. Although a mid-latitude positive bay is less well defined because of a pre-existing magnetic disturbance starting around 0705 UT, an initiation of a positive change is clearly identified in the H component data in association with the Pi 2 pulsation. It is most evident at the western station LOC. The positive H change starts at 0927 UT at LOC, and it is delayed at the eastern stations. The D component shows a positive (east-ward) trend at all AFGL stations after -0840 UT. At 0927 UT a sudden negative (westward) change in D starts at all stations except for LOC. These data indicate that 0927 UT is the most probable time for the onset of a substorm expansion phase.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. A3, PAGES 2425-2431, MARCH 1, 1987

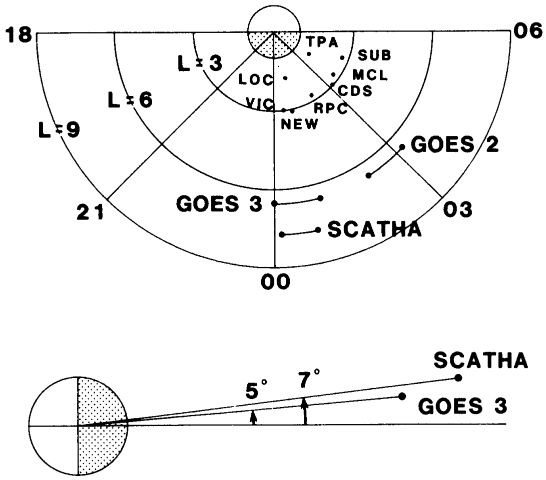

Fig. 1. (Top) Locations of spacecraft in L shell-magnetic local time. Locations are shown at 0900 UT and 1000 UT. Longitudes of ground stations at 0927 UT are also indicated. (Bottom) SCATHA and GOES 3 in radial distance—magnetic latitude.

At substorm onset at mid-latitudes the ground D component has in general a positive perturbation in the western sector and a negative perturbation in the eastern sector, and a positive H change is most evident near the local time meridian where the D component changes its sign [e.g., *Clauer and McPherron*, 1974]. This meridian is tentatively defined as the demarcation meridian for the ground D sign. In the substorm examined here the negative D perturbation is evident at RPC and other eastern stations, as described earlier. At LOC the continuing positive trend is seen in the D component around 0927 UT. The standard magnetic stations Newport and Victoria are located west of LOC (Table 1). There is a positive change in the H component at these stations around 0927 UT, although it is difficult to determine its onset time precisely in normal run magnetograms. The D component at these stations show a continuing positive trend around 0927 UT which is similar to that in the D component at LOC. Honolulu (25° west of Victoria) does not show any clear D signature. *Lester et al.* [1983, 1984] have shown that the Pi 2 polarization pattern over a wide longitudinal span can locate the demarcation meridian for the ground D sign. We made Pi 2 pulsation hodograms between 0929 and 0933 UT (not shown here). The major axis of the polarization ellipse points northwest at RPC and north at LOC. According to the results of *Lester et al.* [1983, 1984], the demarcation meridian for ground D sign is probably located west of RPC, near LOC. This result is consistent with the D signatures. As presented in Table 1, GOES 3 is almost in the Victoria meridian, and GOES 2 is between RPC and CDS. We find that GOES 3 is close to, but probably west of, the demarcation meridian for ground D sign, whereas GOES 2 is east of it at and just after the 0927 UT expansion phase onset.

Before we proceed to present magnetic field observations in space, we examine magnetic disturbances in the auroral zone. The magnetic activity is quiet during the period 0000-0900 UT on this day (hourly AE is less than 115 nT). Figure 4 shows traces of the H component from three stations. A sharp negative excursion of H with an amplitude

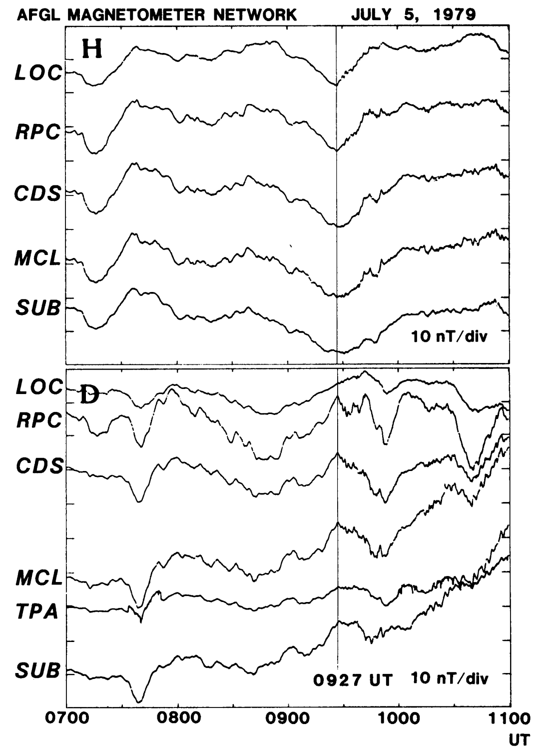

Fig. 2. The H and D component data from mid-latitude AFGL magnetometer observation.

of 200 nT starts around 0936 UT at Yellowknife (69.2° geomagnetic latitude, 296.0° geomagnetic longitude). The International Magnetospheric Study chain stations near Yellowknife also show a sharp negative H excursion after the same time. College (37° west of Yellowknife) shows only little disturbances. A gradual development of a negative bay is seen at the eastern station Fort Churchill (68.7°, 325.7°). The more eastern station Great Whale River (66.4°, 350.0°) detects a gradual negative bay after 0800 UT, which is probably a precursory disturbance in the morningside auroral zone [e.g., *Nishida and Kamide*, 1983]. The negative bay at this station is developing quite gradually around 0927 UT. Although no clear onset signature is found around 0927 UT, the auroral zone features are consistent with the mid-latitude signatures.

SPACECRAFT OBSERVATIONS

Figure 5 shows magnetic field data from SCATHA, GOES 3, and GOES 2 for the 4-hour interval in the dipole VDH coordinate system. In this system, H is antiparallel to the earth's dipole axis pointing northward, D is orthogonal to H and a radius vector to the satellite (azimuthal east), and V completes the Cartesian coordinate system pointing nearly radially outward. One-minute averages are used for SCATHA to smooth ripples, which are caused by having inadequate knowledge to remove the effect of spacecraft motion. However, there are some ripples in the data. Values of 3.06 s are used for GOES. Instrumental noise is noted in the GOES 3 data, especially in the H component. To examine magnetic disturbances around the expansion phase onset, magnetic field parameters are presented on a time scale of 30 min in Figure 6. Inclination of the magnetic field

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. A3, PAGES 2425-2431, MARCH 1, 1987

TABLE 1. Names and Coordinates of Magnetic Stations and Information on Spacecraft

	Code	Geomagnetic Longitude, deg	Geomagnetic Latitude, deg
Station name			
Standard			
Victoria	VIC	295.3	54.4
Newport	NEW	302.4	55.2
AFGL			
Lompoc	LOC	303.1	41.4
Rapid City	RPC	320.2	53.3
Camp Douglas	CDS	335.6	54.4
Mount Clemens	MCL	345.0	53.3
Tampa	TPA	346.7	38.7
Sudbury	SUB	359.4	53.4
Spacecraft			
SCATHA (7.8 R_E)		295	7
GOES 3 (6.6 R_E, 134.8°W)		296	5
GOES 2 (6.6 R_E, 102.4°W)		328	9

Values are calculated using a centered dipole field with the north pole at 70.8°W and 78.8°N geographic (IGRL, 1980.0). Geomagnetic longitude for SCATHA is that at 0927 UT on July 5, 1979.

vector (INC) is defined as $\tan^{-1}$ (-H/V). The inclination increases as the field becomes dipolar. Total magnetic field (BT) is calculated from the three component values. In this figure, 15-s average values are used for SCATHA.

Before the expansion phase onset at 0927 UT, SCATHA and GOES 3 observe a gradual decrease in V. GOES 3 observes a decrease in H. These changes result from a more taillike field configuration, which is a well-known signature of the magnetic field preceding expansion phase onsets [e.g., *Walker et al.,* 1976; *Kokubun and McPherron,* 1981; *Nagai,* 1982a,b; *Baker,* 1984]. During the period when the field grows more taillike, the D component behavior at SCATHA presents a striking contrast to that at GOES 3. There is little variation in D until the expansion phase onset at GOES 3. This is common for periods preceding expansion phases [e.g., *Nagai,* 1982b, this issue]. SCATHA detects a negative D perturbation after 0840 UT. It steepens around 0858 UT and 0918 UT. The D component is approximately 10 nT lower than the quiet day level just prior to the expansion phase onset. This is a significant deviation [Nagai, this issue].

It is of great interest to compare the temporal evolution of the magnetic field changes at SCATHA and those at GOES 3 during the expansion phase (see Figure 6) because, except for a radial separation, they are so close together. At the expansion phase onset, SCATHA observes a sudden negative D excursion, although its amplitude is small. GOES 3 observes a negative D spike following the onset. Although it is difficult to determine the start time of the negative D perturbation unambiguously in the GOES 3 data, it appears to coincide with the start of the D excursion at SCATHA. There is a dip (a positive change) in the negative D excursion at SCATHA, which is almost coincident with the negative D spike at GOES 3. After the D spike, D remains at a new value about 15 nT lower than the preonset value until 0940 UT at GOES 3, while D rapidly recovers after 0931 UT at SCATHA. At the expansion phase onset, SCATHA observes a sudden increase in V (see Figure 5), resulting from a dipolarization of the field. An irregular disturbance, probably a broadband Pi 2 pulsation [*McPherron,* 1981], is observed in all field components at and after the same time in higher time resolution data (not shown here because of the larger ripples). Increases of protons and electrons are observed by the UCSD instrument on SCATHA at the same time. These are characteristics of field and particle signatures associated with expansion phase onsets at synchronous orbit [e.g., *Walker et al.,* 1976; *Nagai,* 1982a; *Nagai et al.,* 1983; *Baker*, 1984]. At GOES 3 there is no sudden change in H or V until 0929 UT, and the field inclination remains almost constant. H shows a further decrease after the expansion phase onset. The dipolarization probably starts with an irregular disturbance after 0929 UT (see Figure 6). This is supported by particle observations by the synchronous spacecraft 1979-053,

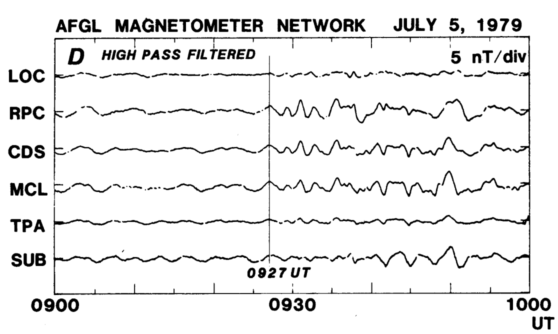

Fig. 3. The high-pass-filtered D component data from AFGL.

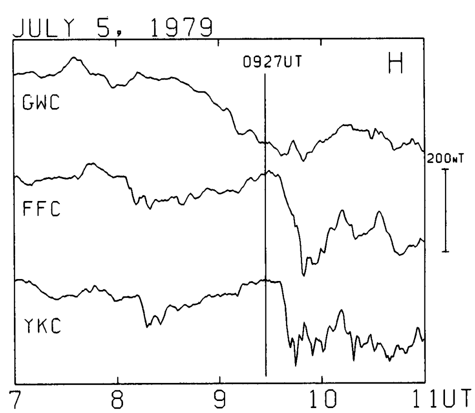

Fig. 4. H component magnetograms from Yellowknife (YKC), Fort Churchill (FCC), and Great Whale River (GWC) for the event on July 5, 1979.

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. A3, PAGES 2425-2431, MARCH 1, 1987

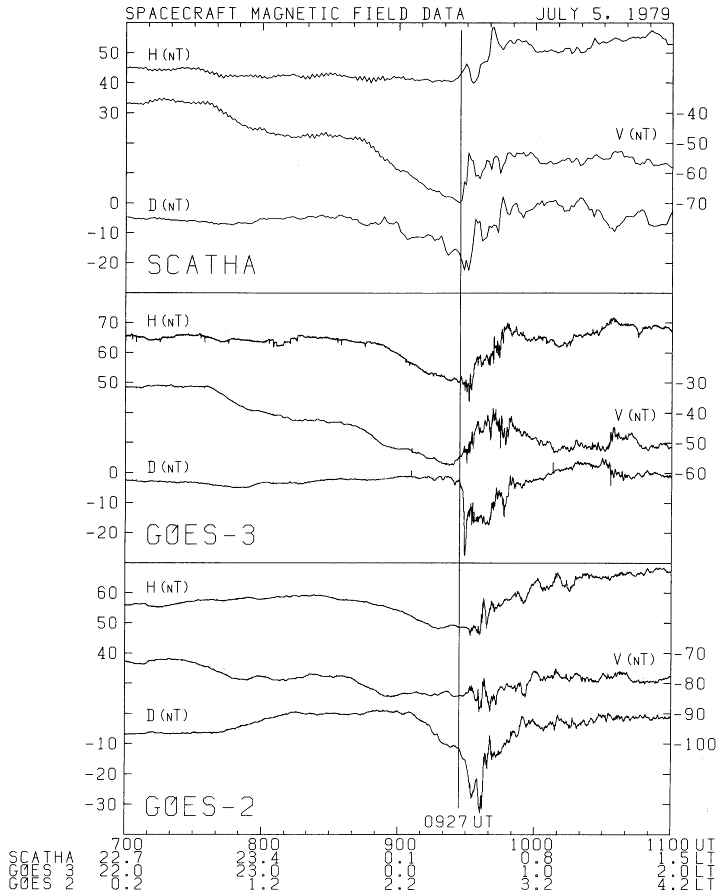

Fig. 5. SCATHA, GOES 3, and GOES 2 magnetic field observations. The data are presented in the dipole VDH coordinate system. H is roughly northward, V roughly radially outward, and D eastward.

located 0.7° east of GOES 3. Increases of energetic particles accompanying particle anisotropy changes are observed at 0929 UT, implying that a change takes place in the field configuration [e.g., *Baker*, 1984].

The field at GOES 2 also becomes more taillike prior to the expansion phase. D at GOES 2 starts to increase around 0740 UT, and it remains at a new value about 6 nT higher than its initial value. This is a prominent positive deflection in this local time region [Nagai, this issue]. D begins to recover around 0905 UT and turns negative after 0915 UT. Thus the temporal development of the D perturbation at GOES 2 is different from that at SCATHA. GOES 2 observes growth of the negative D perturbation after the expansion phase onset; however, the temporal development of the D perturbation is more gradual than that at GOES 3. There are two negative peaks in D at 0932 and 0936 UT. These are unique features at GOES 2. Although an irregular disturbance in all field components starts a little before the first D peak, a rapid dipolarization starts almost at the same time as the time of the second D peak. There is a time delay of the dipolarization at synchronous orbit relative to the positive H change on the ground in the same meridian (it occurs around 0930 UT at CDS, just east of the GOES 2 meridian). Time delays such as this are frequently observed [*Nagai*, 1982b; *Arnoldy and Moore*, 1983].

DISCUSSION

Following the expansion phase onset of substorms, a rapid relaxation of the stressed, taillike magnetic field configuration takes place in the near-earth magnetotail. This dipolarization is associated with an enhancement of energetic particles. At the expansion phase onset in the present case, which is determined by the ground magnetic observations, the dipolarization starts only at SCATHA. It is delayed about 2 min at GOES 3, located 1 R_E earthward of SCATHA. It is common that the start of a dipolarization at synchronous orbit is slightly delayed relative to ground onsets (within a few minutes or so) even near midnight [*Nagai,* 1982b, this issue]. We find that the start of the irregular disturbance is also delayed at GOES 3 relative to that at SCATHA. These observations suggest an earthward propagation of the "dipolarization process" near the magnetic equatorial plane in the near-earth magnetotail. The dipolarization is further delayed at GOES 2, located 2 hours east of GOES 3. The longitudinal development of the "dipolarization process" has been well established at synchronous orbit [*Nagai,* 1982b, this issue; *Arnoldy and Moore, 1983].* The start of the irregular disturbance also shows a progressive delay, although it precedes the dipolarization.

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

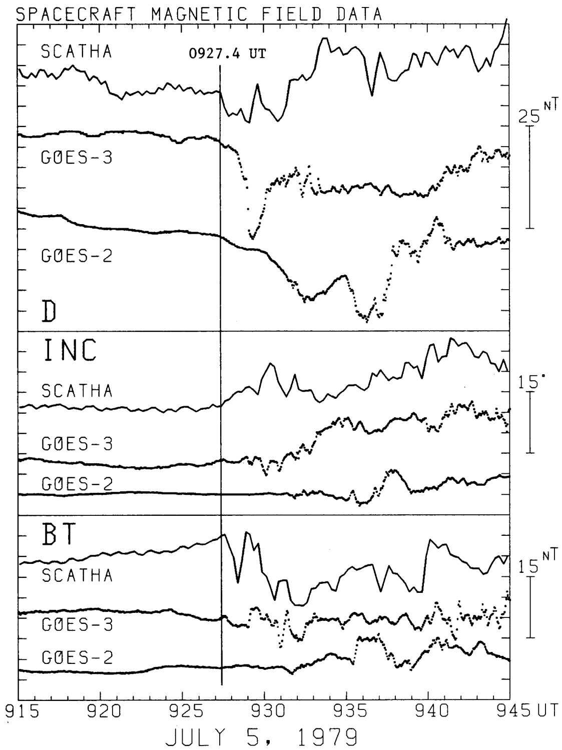

Fig. 6. Magnetic field parameters D, INC (field inclination), and BT (total magnetic field) at SCATHA, GOES 3, and GOES 2 in the interval from 0915 UT to 0945 UT.

Russell and McPherron [1973] reported a time delay of the magnetic disturbance observed by the ATS 1 and OGO 5 pair near the midnight meridian, similar to that reported here. They interpreted their event by an "inward moving field compression." Indeed, the total magnetic field increased at OGO 5 and later at ATS 1. The field compression is, however, not a common signature of the substorm effect off the magnetic equatorial plane at synchronous orbit [e.g., *Nagai,* 1982a]. In the present case the total magnetic field decreases during the dipolarization at SCATHA, and it remains almost constant at GOES 3.

We now speculate on the structure of the field-aligned currents just after the expansion phase onset. The newly formed or intensified field-aligned currents are detected at SCATHA and GOES 3. SCATHA detects a larger negative D perturbation than GOES 3 just after the onset. This indicates that the major field-aligned currents are those flowing into the ionosphere on L shells greater than the SCATHA L shell. Possible locations of the currents are depicted schematically in Figure 7b. During the negative D spike observed by GOES 3, SCATHA exhibits a dip in the negative D perturbation. This is probably caused by field-aligned currents flowing into the ionosphere between GOES 3 and SCATHA, in addition to those above SCATHA, as depicted in Figure 7c. As the substorm progresses, the D perturbation is reduced at SCATHA, though it remains at GOES 3. The major field-aligned currents exist probably in the vicinity of GOES 3, as shown in Figure 7d.

It is important to note the ground D variations. The ground D component does not show any negative perturbation in the SCATHA–GOES 3 meridian just after the onset, although there exists a large negative D perturbation in space. The ground station LOC (8° east of the SCATHA—GOES 3 meridian) shows the continuous positive D trend until 0940 UT and then the negative D perturbation. Victoria shows similar variations. After 0940 UT the negative D perturbation is reduced at GOES 3. Therefore just after the onset, at the same time a negative D is observed in space at GOES 3, it is not observed on the ground in nearly the same meridian. This suggests upward currents on L shells interior to the GOES 3 L shell, canceling the effect on the ground of the downward currents above GOES 3 [see *Nagai,* this issue]. The suggested currents on L shells interior to the GOES 3 L shell are represented as the dashed lines in Figures 7b—7d. Near the GOES 2 meridian, the ground D component shows the negative perturbation. It is reasonable to suppose that the currents flowing into the ionosphere are located above GOES 2 during the expansion phase. The GOES 2 signatures are quite different from the signatures at SCATHA and GOES 3.

The magnetic bays and the Pi 2 polarization pattern observed by the AFGL stations suggest that the SCATHA—GOES 3 meridian is near the demarcation meridian for the ground D sign or near the center of a substorm current wedge, as discussed by *Gelpi et al.* [1985]. Further-more, AFGL ground magnetic data and Defense Meteorological Satellite Program images have been used by *Gelpi et al.* [1987] to show that this meridian is close to (about 1 hour east of) the head of a westward traveling surge in the auroral zone. Therefore it is likely that the field-aligned currents illustrated in Figures 7b-7d are longitudinally located near the demarcation meridian for the ground D sign and near or just to the east of a westward traveling surge (see also *Nagai* [this issue], *Samson and Rostoker* [1983], *Samson* [1985], and *Gelpi et al* [1987]). In this same region, *Samson and Rostoker* [1983] and *Samson* [1985] have shown overlapping field-aligned current sheets with downward currents at higher latitudes than the upward currents. Therefore the

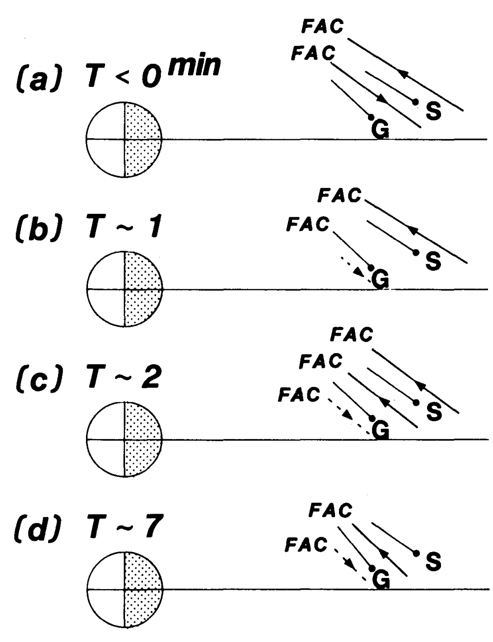

Fig. 7. Schematic illustration of locations of the major field-aligned currents (FAC) with respect to SCATHA (S) and GOES 3 (G) during the 0927 UT, July 5, 1979, substorm. Time is relative to the expansion phase onset. Magnetic field vector at each spacecraft is also presented.

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

oppositely directed field-aligned currents, which we infer from satellite data (Figure 7), are in agreement with the *Samson and Rostoker* [1983] model, since the ground-based observations locate the satellites near field lines extending into the region of the westward traveling surge.

The field-aligned current signature at synchronous orbit starts normally at the expansion phase onset of substorms [Nagai, 1982b, this issue]; however, it is sometimes observed prior to the onset, as seen in this case. This precursory field-aligned current signature is clearly identified in the 1054 UT March 22, 1979 (CDAW 6), substorm [*McPherron and Manka*, 1985; *Barfield et al.,* 1985]. For the CDAW 6 substorm, substorm onset signatures have been extensively examined, so that there is little doubt that no onset takes place before the 1054 UT onset. It is supposed that the currents are located near the outer plasma sheet boundary. There is evidence that many sheets of field-aligned currents exist near the outer plasma sheet boundary in the deep magnetotail during substorm expansion phases [*Frank et al*., 1981; *Elphic et al.,* 1985]. If the currents consist of a double sheet of oppositely flowing currents at the outer plasma sheet boundary, their effects can be confined into the region between the two current sheets. In the CDAW 6 substorm, GOES 2 first detected a negative D perturbation and then a positive D perturbation during the field change toward a more taillike configuration. The change in sign for precursory D perturbations is not uncommon [Nagai, this issue]. This suggests net field-aligned currents existing near the outer plasma sheet boundary. In the present case, SCATHA detects the precursory field-aligned current signature, but there is no corresponding signature at GOES 3. Nagai [this issue] has shown that the precursory field-aligned current signature is observed more frequently at the higher-latitude spacecraft GOES 2 than the lower-latitude spacecraft GOES 3 when the field is highly stretched. This is consistent with the present case, although the latitudinal difference between SCATHA and GOES 3 is only 2°. The longitudinal separation (less than 2°) between SCATHA and GOES 3 is negligible. Even when SCATHA is located exactly in the GOES 3 meridian around 0917 UT, only SCATHA detects the negative D perturbation. Therefore it is unlikely that these small latitudinal and longitudinal separations are the major factor in determining the differences in the D signatures.

SCATHA is located approximately 1.2 R_E tailward of GOES 3. The Kp value is less than 2+ in the 24 hours preceding the substorm. The SCATHA particle observations show that the spacecraft encounters the inner edge of the plasma sheet around 0832 UT. This indicates that SCATHA detects the field-aligned current signature when it is inside the plasma sheet. Unfortunately, the spacecraft 1979-053, near GOES 3, observes only energetic particles (>30-keV electrons and >145-keV protons), which are probably trapped. Although information on plasma sheet particles is not available at synchronous orbit, it is possible that GOES 3 is not engulfed completely by the plasma sheet. Field-aligned currents flowing out of the auroral ionosphere are supposed to exist at the boundary of the inner plasma sheet near the SCATHA-GOES 3 meridian, and these currents probably cancel effects of the field-aligned currents flowing into the ionosphere near the outer plasma sheet boundary for GOES 3. Possible locations of the major field-aligned cur-rents with respect to SCATHA and GOES 3 prior to the expansion phase onset are presented in Figure 7a. In association with the expansion phase onset the inner edge of the plasma sheet probably moves earthward, and GOES 3 is deeply inside the plasma sheet. The positive D perturbation observed at GOES 2 prior to the expansion phase onset is quite exceptional [*Nagai,* this issue]. This perturbation might be related to the precursory auroral zone disturbance in the morning region (at Great Whale River).

SUMMARY

In the present case study we have used three spacecraft at and around synchronous orbit. SCATHA is located on an L shell greater than that at GOES 3 in almost the same meridian. The dipolarization in the field at SCATHA starts at the same time as the onset of the expansion phase recorded on the ground, but the dipolarization at GOES 3 is slightly delayed. This can be interpreted as the earthward propagation of the "dipolarization process." On the other hand, the field-aligned current signatures are detected at all spacecraft at the expansion phase onset. When the dipolarization starts initially near SCATHA, the major field-aligned currents producing the negative D perturbation at and around synchronous orbit are those flowing into the ionosphere on the L shells greater than the SCATHA L shell. When the dipolarization takes place around GOES 3, the downward field-aligned currents exist on the L shells between SCATHA and GOES 3. Upward field-aligned currents may exist on L shells interior to the GOES 3 L shell in the limited longitudinal region near the meridian where the mid-latitude D perturbations change sign. These oppositely directed field-aligned currents are consistent with field-aligned cur-rent sheets suggested by *Samson and Rostoker [*1983] and *Samson* [1985] near this location.

Acknowledgments. GOES magnetic field data were provided by Space Data Analysis Center, Institute of Space and Astronautical Science, originally by the National Geophysical Data Center, NOAA. We gratefully acknowledge the GOES data reduction assistance by J. Ishida. We thank C. E. Mcllwain for making available the SCATHA UCSD particle data. D. N. Baker kindly supplied energetic particle data from spacecraft 1979-053. Ground-based magnetograms from standard stations were provided by the World Data Center C2 for geomagnetism, Kyoto University.

The Editor thanks H. E. Spence and L. J. Zanetti for their assistance in evaluating this paper.

REFERENCES

Arnoldy, R. L., and T. E. Moore, Longitudinal structure of substorm injections at synchronous orbit, *J. Geophys. Res., 83,* 6213, 1983.

Baker, D. N., Particle and field signatures of substorms in the near magnetotail, in *Magnetic Reconnection in Space and Laboratory Plasmas,* edited by E. W. Hones, Jr., p. 193, AGU, Washington, D. C., 1984.

Barfield, J. N., C. S. Lin, and R. L. McPherron, Observations of magnetic field perturbations at GOES 2 and GOES 3 during the March 22, 1979, substorm: CDAW 6 analysis, *J. Geophys. Res.,* 90, 1289, 1985.

Clauer, C. R., and R. L. McPherron, Mapping and local time—universal time development of magnetospheric substorms using mid-latitude magnetic observations, *J. Geophys. Res., 79,* 2811, 1974.

Coleman, P. J., Jr., and R. L. McPherron, Fluctuations in the distant geomagnetic field during substorms: ATS 1, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 171, D. Reidel, Hingham, Mass., 1970.

Coleman, P. J., and R. L. McPherron, Substorm observations of magnetic perturbations and ULF waves at synchronous orbit by ATS-1 and ATS-6, in *The Scientific Satellite Programme During the International Magnetospheric*

Paper number 6A8709. 0148-0227/87/006A-8709$05.00

Study, edited by K. Knott and B. Battrick, p. 345, D. Reidel, Hingham, Mass., 1976.

Elphic, R. C., P. A. Mutch, and C. T. Russell, Observations of field-aligned currents at the plasma sheet boundary: An ISEE 1 and 2 survey, *Geophys. Res. Let., 12,* 631, 1985.

Frank, L. A., R. L. McPherron, R. J. DeCoster, B. G. Burek, K. L. Ackerson, and C. T. Russell, Field-aligned currents in the earth's magnetotail, *J. Geophys. Res., 86,* 687, 1981.

Gelpi, C., W. J. Hughes, H. J. Singer, and M. Lester, Mid-latitude Pi 2 polarization pattern and synchronous orbit magnetic activity, *J. Geophys. Res., 90,* 6451, *1985.*

Gelpi, C., H. J. Singer, and W. J. Hughes, A comparison of magnetic signatures and DMSP auroral images at substorm onset: Three case studies, *J. Geophys. Res., 92,* 2447, *1987.*

Grubb, R. N., The SMS/GOES Space Environment Monitor System, *Tech. Memo. ERL SEL-42,* Natl. Oceanic and Atmos. Admin., Boulder, Colo. 1975.

Kokubun, S., and R. L. McPherron, Substorm signatures at synchronous altitude, *J. Geophys. Res., 86,* 11,265, 1981.

Lester, M., W. J. Hughes, and H. J. Singer, Polarization patterns of Pi 2 magnetic pulsations and the substorm current wedge, J. *Geophys. Res., 88,* 7958, 1983.

Lester, M., W. J. Hughes, and H. J. Singer, Longitudinal structure in Pi 2 pulsations and the substorm current wedge, *J. Geophys. Res., 89,* 5489, *1984.*

McPherron, R. L., Substorm associated micropulsations at synchronous orbit, in *ULF Pulsations in the Magnetosphere,* edited by D. J. Southwood, p. 57, Center for Academic Publications, Tokyo, 1981.

McPherron, R. L., and J. N. Barfield, A seasonal change in the effect of field-aligned currents at synchronous orbit, *J. Geophys. Res., 85,* 6743, 1980.

McPherron, R. L., and R. H. Manka, Dynamics of the 1054 UT March 22, 1979, substorm event: CDAW 6, *J. Geophys. Res., 90,* 1175, 1985.

Nagai, T., Local time dependence of electron flux changes during substorms derived from multisatellite observations at synchronous orbit, *J. Geophys. Res., 87,* 3456, 1982a.

Nagai, T., Observed magnetic substorm signatures at synchronous altitude, *J. Geophys. Res., 87,* 4405, 1982b.

Nagai, T., Field-aligned currents associated with substorms in the vicinity of synchronous orbit, *2,* GOES *2* and GOES *3* observations, *J. Geophys. Res.,* this issue.

Nagai, T., D. N. Baker, and P. R. Higbie, Development of substorm activity in multiple-onset substorms at synchronous orbit, J. *Geophys. Res., 88*, 6994, 1983.

Nishida, A., and Y. Kamide, Magnetospheric processes preceding the onset of an isolated substorm: A case study of the March 31, 1978, substorm, *J. Geophys. Res., 88,* 7005, 1983.

Russell, C. T., and R. L. McPherron, The magnetotail and substorms, *Space Sci. Rev., 15,* 205, 1973.

Samson, J. C., Large-scale studies of Pi *2's* associated with auroral breakups, *J. Geophys., 56,* 133, 1985.

Samson, J. C., and G. Rostoker, Polarization characteristics of Pi 2 pulsations and implications for their source mechanisms: Influence of the westward traveling surge, *Planet. Space Sci., 31*, 435, 1983.

Singer, H. J., W. J. Hughes, P. F. Fougere, and D. J. Knecht, The localization of Pi *2* pulsations: Ground-satellite observations, J. *Geophys. Res., 88,* 7029, 1983.

Singer, H. J., W. J. Hughes, C. Gelpi, and B. G. Ledley, Magnetic disturbances in the vicinity of the synchronous orbit and the substorm current wedge: A case study, *J. Geophys. Res., 90,* 9583, 1985.

Stevens, J. R., and A. L. Vampola (Eds.), Description of the space test program p78-2 spacecraft and payloads, *Tech Rep. 78-24,* Space and Missile Systems Org., Los Angeles, Calif., 1978.

Walker, R. J., K. N. Erickson, R. L. Swanson, and J. R. Winckler, Substorm-associated particle boundary motion at synchronous orbit, *J. Geophys. Res., 81,* 5541, *1976.*

B. G. Ledley, Goddard Space Flight Center, Greenbelt, MD 20771.

T. Nagai, Meteorological Research Institute, 1-1, Nagamine, Yatabe-Machi, Tsukuba-gun, Ibaraki-ken, 305 Japan.

R. C. Olsen, Department of Physics, The University of Alabama in Huntsville, Huntsville, AL 35899.

H. J. Singer, Space Plasmas and Fields Branch, Space Physics Division, Air Force Geophysics Laboratory, Hanscom AFB, MA 01731.

(Received August 21, 1986;
revised November 12, 1986;
accepted November 17, 1986.)

Paper number 6A8709. 0148-0227/87/006A-8709$05.00