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Current sheet measurements within a flapping plasma sheet

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Abstract. Slow plasma flows perpendicular to the magnetotail neutral sheet and associated with flapping motions of the plasma sheet can occasionally exceed the sensitivity threshold of plasma instruments. This is the case in several events selected from 3 months of magnetotail observations by the three-dimensional plasma instrument on the AMPTE/IRM satellite. By comparing the ion flow in the Z_{GSM} direction and the correlated changes of the X_{GSM}-directed magnetic field, we estimate the current sheet flapping velocity to range from a few tens to a few hundreds of kilometers per second. Our measurements of the current sheet thickness (0.1-1 R_E) and current density (10-30 nA/m^2) were significantly different from estimates of these parameters based on magnetospheric models, suggesting a stretched field configuration. The observed events took place during geomagnetically disturbed periods. One of those periods was a 2-hour-long convection bay interval. The largest flapping flows were observed during the few events which also exhibited high-speed Earthward flows, but the flapping velocity was smaller during the more common, slow convection intervals. This observation, as well as the unexpectedly large flapping velocities seen as close as 12 R_E (i.e., close to the hinge point), suggests that flapping motions originate near the current sheet. Plasma sheet flapping tends to occur in conjunction with ground Pi2 bursts, but the exact onset times and the dominant periods of the two phenomena are generally different. Thus, although a common energy source of both phenomena may be intermittent current disruption/reconnection, the two phenomena are likely to couple differently to that free-energy source. We discuss the vertical structure of the plasma sheet parameters during flapping plasma sheet episodes.

1. Introduction

Flapping motions of the current sheet are common in the Earth's magnetotail. They can be distinguished from expansions/contractions of the plasma sheet in the event that the observing spacecraft crosses the center of current sheet and observes a polarity change of the magnetic field component in the X_{GSM} direction. Such flapping motions have been pointed out in many studies [*Speiser and Ness*, 1967; *Toichi and Miyazaki*; 1976, *Lui et al.*, 1978] but the morphology and origin of such motions have not yet been systematically investigated. Some authors have shown that flapping motions occur preferentially near substorm onsets [*Toichi and Miyazaki*, 1976], but their frequent occurrence during geomagnetically disturbed conditions in the absence of distinct substorm signatures was also noticed [*Fairfield et al.*, 1981].

One reason for such flapping motions may be the magnetotail's response to solar wind perturbations [*McComas et al.*, 1986, *Sanny et al.*, 1994], but it is also possible that some of them can be caused by internal processes like substorm activations. Solar wind-driven flapping motions are expected to have a larger amplitude far from Earth, because in the near-Earth magnetotail the current sheet is tied (hinged) to the magnetic equator. This tendency is confirmed by rare case studies that utilized the closely spaced ISEE-1 and ISEE-2 spacecraft. The flapping speed and excursion amplitudes were 100 km/s and 2 R_E at r~20 R_E [*McComas et al.*, 1986] but were only 10-20 km/s and 0.2 R_E, respectively, at r~11 R_E [*Sergeev et al.*, 1993].

The plasma sheet flapping motion can be a useful tool for probing the vertical structure of the current sheet if the speed of the sheet can be monitored. Using two closely positioned spacecraft separated in the Z_{GSM} direction, this can be done by assuming planar geometry and analyzing the time delays in the observations of the X_{GSM} component of the magnetic field. (GSM is the geocentric solar magnetospheric coordinate system.) Such studies [*McComas et al.*, 1986; *Sergeev et al.*, 1993; *Sanny et al.*, 1994] showed that occasionally a very thin current sheet (~0.2 R_E) is imbedded inside a thick (a few R_E) plasma sheet. Such thin current sheets have also been found in the near tail at the end of substorm growth phase using magnetic field modeling [*Pulkkinen et al.*, 1993] or other techniques [*Sergeev et al.*, 1990; *Lui et al.*, 1992]. Such thin current structures are potential sites of plasma instabilities leading to current disruption. Using a

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single spacecraft, it is difficult to measure the plasma sheet motions and deconvolve the current sheet thickness because of the large ion thermal speed relative to the flapping speed. In this paper we discuss fortuitous cases where it is, indeed, possible to infer the Z_{GSM} plasma velocity by calibrating it using the magnetic field variations. These cases occur when the current sheet is thin, such that even small flapping amplitudes can produce strong effects in the X_{GSM} magnetic field component. We estimate parameters of current sheets inferred from this technique and discuss the possible origin of the flapping motions and their relationship with substorms.

2. Analysis of Observations

2.1. Instrumentation and Methodology

We report on observations from the magnetic field and plasma instruments on the AMPTE/IRM satellite. The three-dimensional plasma instrument [*Paschmann et al.*, 1985] provided, in addition to the distribution functions at variable downlink rates, the moments of the distribution function for every satellite spin period (4.5 s). The ion distribution functions were measured in 3840 velocity space bins during each spin covering the energy range between 20 eV and 40 keV.

Figure 1 shows three examples of plasma sheet flapping observed on April 8, 1985. When the plasma sheet was moving northward, $V_Z > 0$, the X_{GSM} magnetic field component B_X was decreasing, and its time derivative was negative. In the case of a linear dependence of B_X on Z_{GSM}, which is true at least as a zero order approximation of the field in the vicinity of the neutral sheet, a positive correlation between dB_X/dt and $-V_Z$ is an expected signature of flapping. The first example (Figure 1, left) encompasses a rapid isolated crossing of the neutral sheet (north to south) at 2228:50 UT as well as two complete cycles of quasi-periodic neutral sheet oscillations with apparent period ~50 s between 2229:40 and 2232:20 UT. The isolated crossing was rapid but was not accompanied by a significant V_Z enhancement and thus does not qualify as a simple flapping motion. However, the quasiperiodic oscillations exhibit a high degree of anticorrelation (R=-0.84, as seen on top left graph of Figure 1) between the variations of V_Z and the time derivative of B_X. An offset in V_Z (~-30 km/s) is apparent at the beginning and at the end of this interval. This is also evident in the two other examples in Figure 1 and is present with the same magnitude and direction in other days examined.

This offset is instrumental. Instead of modeling the instrument response to remove the offset, we avoid using the absolute values of V_Z and exploit the regression analysis between V_Z and dB_X/dt. To characterize the vertical gradient of the magnetic field (B_X), we use the linear regression between dB_X/dt and V_Z in the events where this correlation is large. Using the slope A_1 in the least squares fit $V_Z = A_0 + A_1 * dB_X/dt$ and with known lobe field B_L outside the current sheet, we then have the scale size (half thickness) of the current sheet as

$$h = B_L A_1 / \sqrt{(1 + k_1^2)}$$

In (1), k_1 is the regression coefficient between B_Y and B_X (i.e., $B_Y = k_0 + k_1 * B_X$). Its presence accounts for the fact that the plane containing the magnetic field lines does not coincide with the XZ plane. The equivalent lobe magnetic field is estimated from the total (plasma plus magnetic) pressure computed from spacecraft measurements. In addition to the vertical scale size of B_X, the

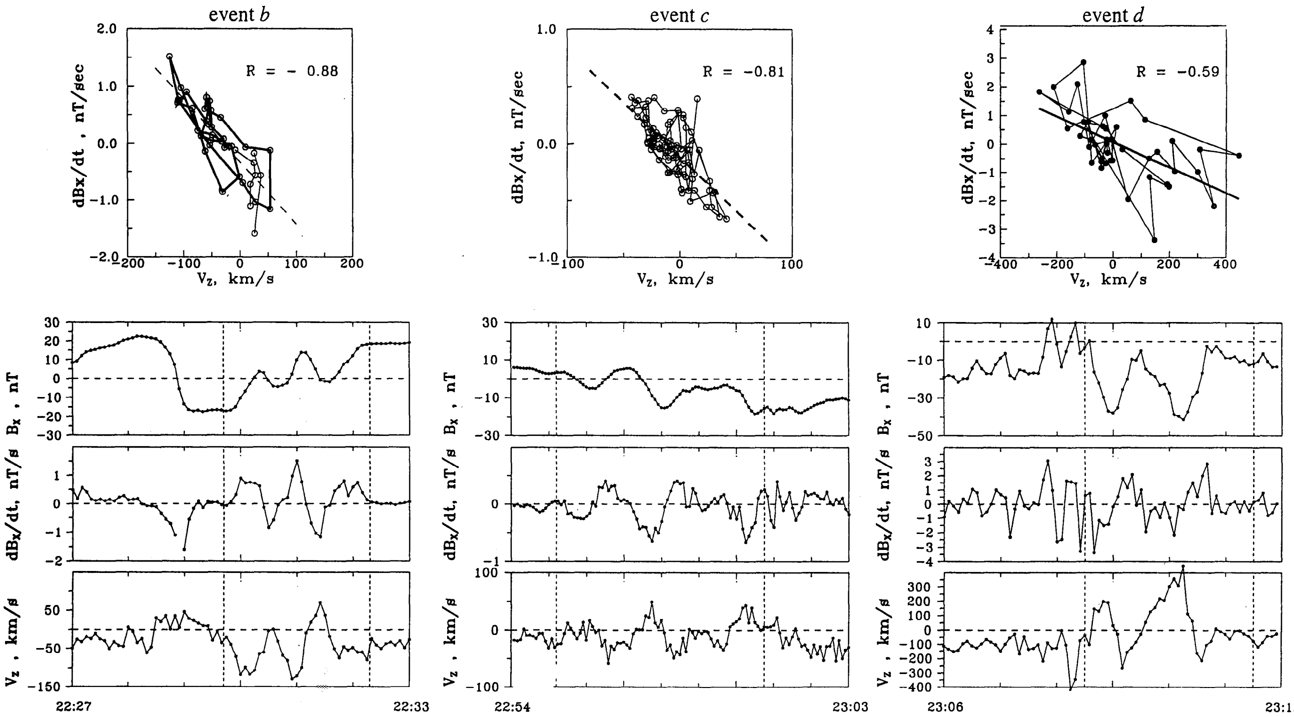

Figure 1. Comparison of magnetic variations in B_x component and vertical component of ion plasma flow for three periods of oscillating crossings of the neutral sheet on April 8, 1985 (these events are marked as b, c, and d in Figure 2). (top) Correlation plots between V_z and time derivative of B_x component are given. (bottom) The time intervals used for correlation are marked by the vertical lines on the parameter plots.

regression slope A_1 gives us the vertical magnetic field gradient, i.e., the value of current density, j, from the equation:

$$j[nA/m^2] = 796/(A_1(1+k_1))$$

if the velocity V_Z was measured in kilometers per second and, correspondingly, A_1 is given in kilometers per nanoTeslas. The technique assumes a planar current sheet geometry which is expected to be true if $B_Z << B_X$.

The presence of a V_Z offset prevents application of the technique to cases of single isolated neutral sheet crossings. Multiple crossings with alternating signs of V_Z and dB_X/dZ help define the offset better. Another limitation results from plasma convection. If the convection electric field is stable during the crossing, it may be computed and removed when applying regression analysis, since the convection-related V_Z flow component changes its direction with the change of B_X sign. However, if the convection is variable at a timescale comparable to that of the neutral sheet crossing, it produces a large ambiguity in the results when interpreting each single neutral sheet crossing separately. Convection is, indeed, variable on a minute timescale, especially during strong horizontal flow events in the plasma sheet, [e.g. *Angelopoulos et al.*, 1992]. The use of multiple neutral sheet crossings allows us to remove both the V_Z instrumental offset and possible effects of slowly varying convection. Therefore, although the procedure can be applied to single crossing as well, in the following we prefer to analyze periodic multiple crossings of the neutral sheet.

2.2. Survey of AMPTE/IRM Data Set

We surveyed the AMPTE/IRM measurements from the period March-May 1985 when the spacecraft was in the magnetotail and selected events showing multiple neutral sheet crossings on the basis of B_X that exhibited low-frequency oscillations about B_X=0. We excluded crossings during which the spacecraft measured small density (<0.1 cm^{-3}) to ensure better counting statistics. We scanned visually the plots to find crossings with noticeable variations of V_Z.

Figure 2 provides a survey of plasma sheet observations and ground-based activity between 2200 and 2330 UT on April 8, 1985, when IRM was at a geocentric distance of 14-15 R_E, at ~2300 magnetic local time (MLT) and near the nominal neutral sheet (dZ_{NS}<~0.1 R_E). The large-amplitude vertical flapping motions evidenced by the B_x oscillations started as early as 2100 UT. In all, between 2100 and 2320 UT there were 25 neutral sheet crossings with significant B_X change (at least, from -10 to 10 nT). We performed a cross-correlation analysis between V_z and dB_x/dt for each individual crossing. For eight cases the correlation was insignificant (correlation coefficient |R|<0.2). The remaining 17 events showed a negative correlation as expected from flapping motions. However, a large enough anticorrelation (R<-0.5) was found only in seven crossings. To improve the statistics we analyzed together the crossings which occurred within intervals shorter than 5 min and which have similar average plasma parameters, including the component velocities in the X_{GSM} and Y_{GSM} direction. The results of this study for groups and for isolated crossings which show large anticorrelation (R<-0.5) are given in Table 1. Two events, numbers 3 and 9, with smaller correlation are also included in Table 1; we will discuss those later. Some of the events, like events a, b, and c in Figure 2, exhibit short-period B_X waves (marked as "oscillating crossing" events in Table 1). These are most amenable to regression analysis and to studies of the current sheet structure. Other events exhibit close approaches to the neutral sheet but are mostly composed of measurements in the northern (or southern) halves of plasma sheet (marked as "partial crossing" events in Table 1). The characteristic vertical scale derived for most crossings was about 0.5 R_E, while the characteristic current density was approximately 10-20 nA/m^2. These values, as will be discussed later, are different from the average characteristics of the tail current sheet at this distance.

Table 1 also includes results from 3 other days in 1985 (April 19, May 14, and May 25) when a significant anticorrelation between V_z and the time derivative of B_x was seen near the neutral sheet. Overviews of the plasma moments and magnetic field in the same format as that of Figure 2 are given in Figures 3 and 4 for two of these events (April 19 and May 25). Discussion on the inferred current sheet parameters for these events is deferred until section 3.

2.3. Vertical Structure of the Current Sheet

During neutral sheet crossings, B_X can be used as a proxy of the relative distance dZ_{NS} to the neutral sheet [*Bowling and Wolf*, 1976, *Sergeev et al.*, 1993], with the proviso that the relationship between two may occasionally be nonlinear. When analyzing individual crossings, it is difficult to interpret the time series measurements as due to either spatial or temporal variations. However, during multiple crossings of the neutral sheet like the ones studies above, repeated occurrences of the same features in the time series measurements most likely represent a spatial structure.

Figures 5 and 6 show examples of B_X, arranged profiles of plasma sheet parameters during neutral sheet crossings of an oscillating plasma sheet. Shown are only crossings through an "undisturbed" plasma sheet as determined by the slow flows and the low variability of parameters. North-south (N-S) crossings (V_Z negative, B_X increases) are shown in large circles whereas south-north (S-N) crossings are shown in small circles.

The current sheet profile on April 8 about half an hour before the substorm onset (Figure 5) shows a considerable negative B_y (about −3 nT) in the form of a persistent positive B_y shear. This B_y profile may differ considerably from the B_y profiles throughout other selected events: a negative B_y shear was observed repeatedly at the neutral sheet between 2254 and 2300 UT on April 8, 1985, and a correlated B_y versus B_x was seen at 2148-2151 UT because of the declined magnetic meridian in that case (spacecraft MLT is 21.7 hours). The B_y shear corresponds to a tailward (outward tail-aligned) current.

While the V_z hodogram shows a behavior expected from a flapping sheet (points corresponding to north-south crossings lay below the ones associated with south-north crossings), we could not find any trends in the hodograms of V_x and V_y, except on the last day (May 25, 1985, Figure 6) with Earthward flow in the central part (V_x~+50 km/s) and tailward flow in the outer part of plasma sheet (V_x~-50 nT). Note that the first episode on April 19, 1985, in Table 1 showed weak correlation between V_z and dB_x/dt. However, we included this event because (1) it shows a good coverage of current sheet, with B_z ranging up to lobe values, and (2) the generally small V_z variations (±20 km/s) relative to the offset value (-40 km/s) are in agreement with a small current sheet thickness expected from large B_x excursions.

3. Discussion

Multiple neutral sheet crossings are not uncommon in the AMPTE/IRM data set. The primary purpose of this paper is to

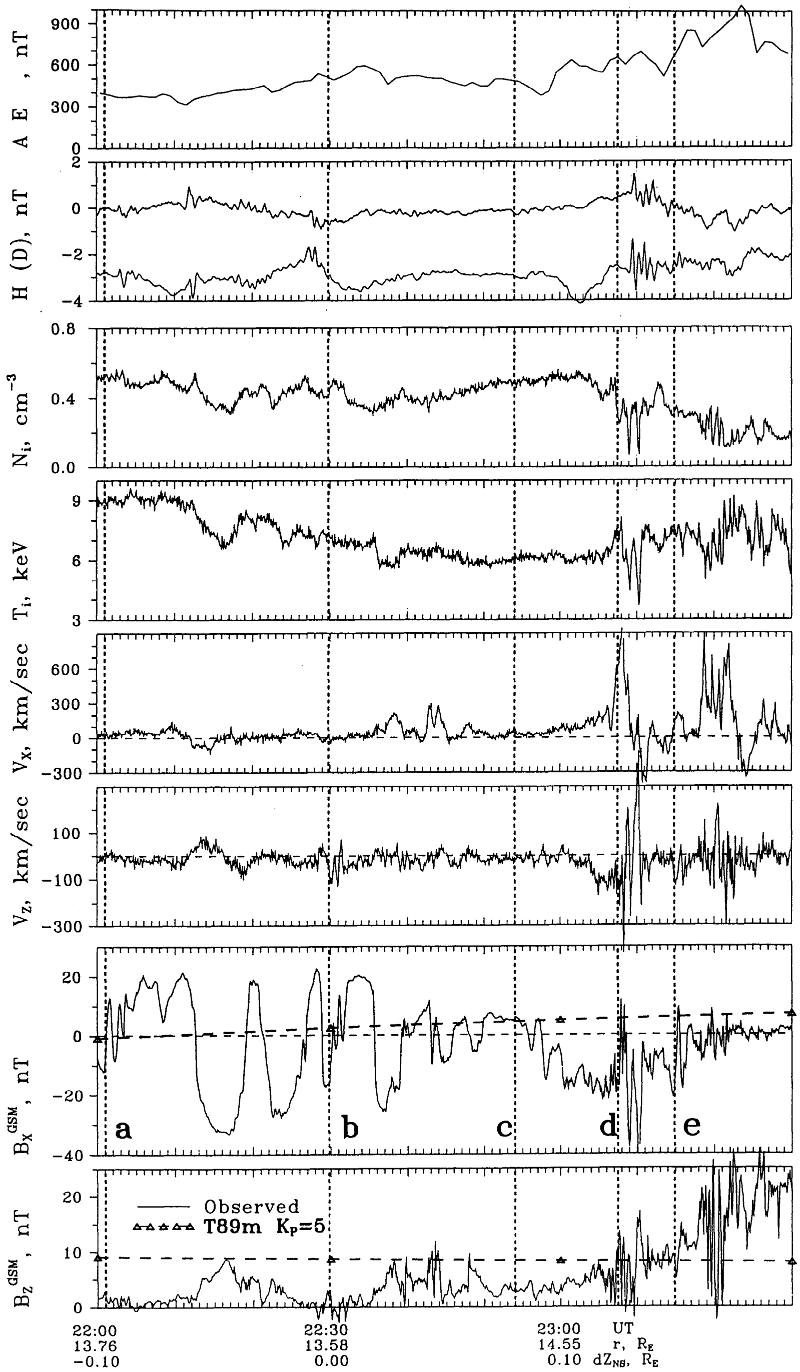

Figure 2. Summary plot of ground activity and plasma sheet observations at AMPTE/IRM on April 8, 1985. (top to bottom) *AE* index; recordings of induction magnetometer at Hermanus (H component, upper trace); plasma density, temperature, V_x, and V_z flow components; and B_x and B_z magnetic field components. The magnetic field values predicted by *Tsyganenko* [1989] Kp = 5 model are shown for reference on two bottom panels. Vertical lines mark the onsets of oscillating crossings of the neutral sheet.

show the possibility of estimating the flapping velocity and to study the plasma sheet structure based on measurements from one spacecraft. Therefore we concentrated on those closely spaced multiple N-S crossings or oscillating N-S events, which provide better statistics toward the estimation of plasma sheet parameters. The significant anticorrelation between V_Z and dB_X/dt that was observed shows that the flapping-related component of the measured vertical flow is substantial and that a meaningful estimation of the flapping velocity is quite possible using modern plasma spectrometers. This technique can be applied to measurements at Geotail, WIND, and the upcoming Equator S and CLUSTER spacecraft.

3.1. High Flapping Velocities in the Midtail Plasma Sheet

A principal result of our study is that rather large flapping velocities (several tens of kilometers per second up to a few

Table 1. Evaluation of Current Sheet Thickness and Current Density During Neutral Sheet Crossings Using V_Z versus d B_X /dt Correlation at AMPTE/IRM

Event	Neutral Sheet			Correlation Results									Activity
	UT, hhmmss	BL, nT	B_z, nT	V_x, km/s	V_y, km/s	Ni, cm^{-3}	Ti, keV	NN	R	A_1, km/nT	h, R_E	j, nA/m^2	
					April 8, 1985		*IRM at ~14 R_E and ~23 MLT*						
1	205100-	54	3.0	26	60	0.56	9.7	58	-0.65	-117	0.93	9.4	CB, ~400 nT
	205610	partial crossing											
2	212250-	53	1.8	-1	-5	0.66	9.7	38	-0.62	-116	0.91	9.3	CB, ~400 nT
	212505												
3	220045-	50	1.3	30	80	0.53	9.0	40	-0.45	-59	0.43	18.0	CB, ~400 nT
	220340	oscillating crossing, A											
4	222955-	40	-0.5	-10	-35	0.55	7.0	35	-0.84	-103	0.63	9.3	CB, ~500 nT
	223200	oscillating crossing, B											
5	225415-	35	3.0	41	37	0.53	6.1	70	-0.72	-118	0.64	8.1	CB, ~500 nT
	230020	oscillating crossing, C											
7	230740-	39	7.8	837	208	0.30	7.1	46	-0.50	-239?	1.88	4.0	SBS onset, ~700 nT
	230820	partial crossing, D at 2308,~700 nT											
8	231500-	40	9.9	182	170	0.32	7.4	18	-0.79	-82	0.50	9.7	SBS, ~800 nT
	231545	oscillating crossing, E											
					April 19, 1985		*IRM at ~12 R_E and ~22 MLT*						
9	214800-	57	1.9	32	61	0.78	7.7	30	-0.37	-51	0.42	22	SBS onset
	215100	partial oscillating crossing											+ CB, ~500 nT
10	220020-	53	1.9	192	85	0.48	5.9	38	-0.63	-96	0.74	12	SBS onset
	220405												
11	220530-	53	1.5	-58	9	0.56	6.0	41	-0.78	-64	0.49	18	SBS onset
	220930	partial crossing											
12	220900-	56	1.1	28	33	0.58	5.5	20	-0.84	-56	0.45	20	SBS onset
	221054	partial oscillating crossing											
13	221300-	56	4.1?	21	-5	0.27	7.6	21	-0.62	-109	0.88	10	SBS onset
	221500												
					May 14, 1985		*IRM at ~17 R_E and ~22 MLT*						
14	070600-	27	-1.9	64	32	0.50	2.7	35	-0.62	-67	0.25	19	~100 nT
	070920	partial oscillating crossing											
15	071000-	28	-1.2	32	39	0.51	2.7	38	-0.66	-107	0.41	12	onset at 0727 UT
	071340	partial oscillating crossing											
					May 25, 1985		*IRM at ~17 R_E and ~20 MLT*						
16	212920-	41	-2.1	40	-20	1.9	1.7	33	-0.76	-106	0.64	10	SBS ~300 nT
	213230	partial oscillating crossing											onset at 2112
17	213330-	40	-0.8	42	10	2.0	1.5	21	-0.88	-35	0.21	30	SBS ~300 nT
	213525	oscillating crossing											
18	213435-	40	-1.6	47	4	2.0	1.5	17	-0.74	-40	0.24	27	SBS ~300 nT
	213605	partial oscillating crossing											
19	213600-	40	0.6	-54	56	1.7	1.9	17	-0.76	-39	0.23	27	onset at 2112
	213750												second onset 2139

CB, Convection Bay; SBS, substorm.

hundreds kilometers per second) can be observed in the magnetotail as close to Earth as 12-14 R_E in the magnetotail. Flapping velocities of such a magnitude were previously seen only at distances of ~40 R_E and ~20 R_E [*Fairfield et al.*, 1981, *McComas et al.*, 1986]. Velocities of the order of tens of km/s were also reported at ~13 R_E for extremely disturbed solar wind conditions [*Sanny et al.*, 1994]. In our survey the strongest flapping velocities were measured in a locally active plasma sheet (V_X flows exceeding 400 km/s) during the expansion phase of a substorm. These velocities were about 300 km/s at ~15 R_E distance on April 8 (event d in Figure 2, at substorm onset, with peak V_X in excess of 1000 km/s) and about 200 km/s at ~12 R_E on April 19 (also during a substorm activation). In other events, without significant local horizontal flows the flapping velocity was always <100 kilometers per second. This difference suggests that flapping motions may originate at the location of plasma sheet activity in association with substorm intensification. The large magnitude of the flapping velocities found so close to the "hinging distance" of the tail current sheet (which is about 7 to 10 R_E in the *Tsyganenko* [1989] class of magnetospheric models) is an additional argument in favor of the internal origin of the flapping motions studied here.

Two sets of events (April 8 and April 19) during which fast flapping was observed at small distances, correspond to rather

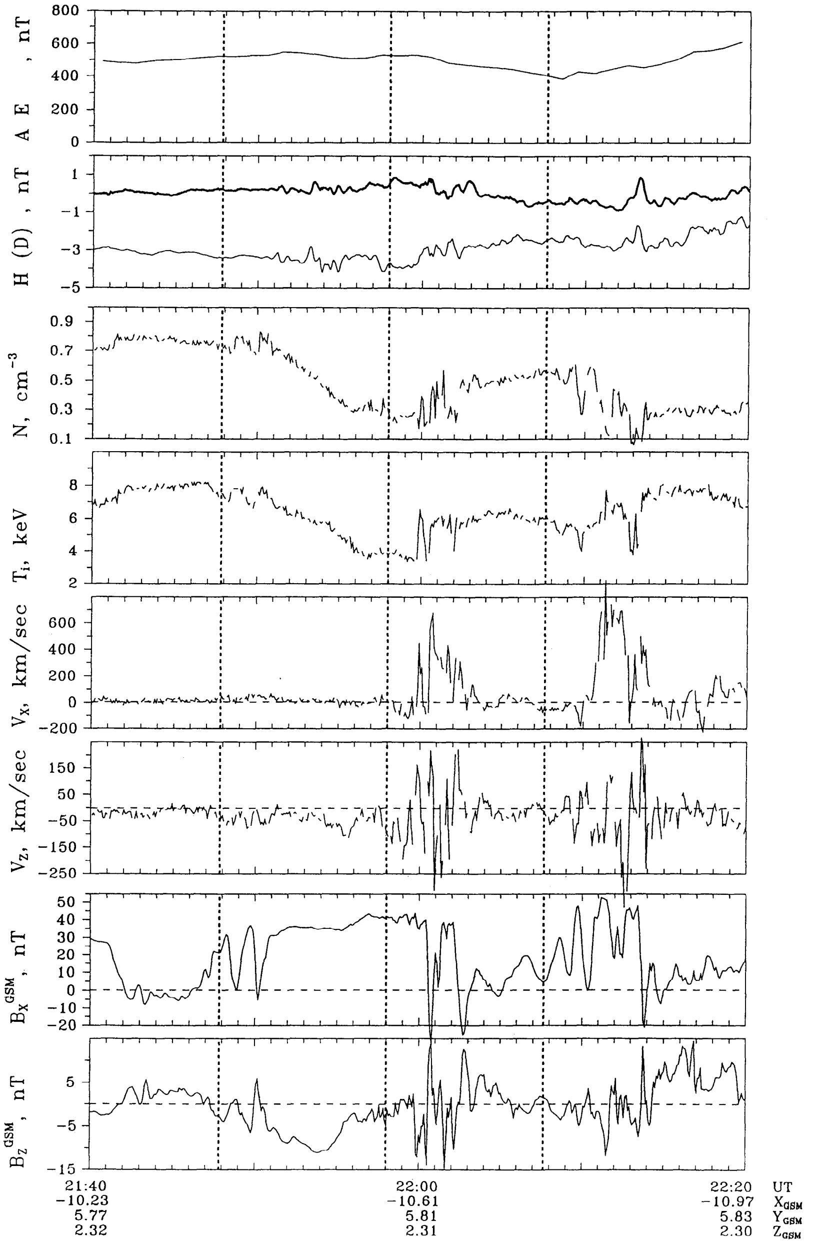

Figure 3. Same as in Figure 2 but for April 19, 1985 event.

disturbed conditions, with a Kp index that was large (5+ and 5 respectively). The estimated lobe field (see Table 1) was large relative to the T89 model. However the duration of the neutral sheet crossings was small so that the approximate amplitudes of the neutral sheet oscillatory motion was similar as in all of the other events (< 1 R_E and typically about a few tenths of an Earth radius). In the other two sets of events, IRM was situated farther away from the Earth (at 17-18 R_E), and Kp was 2- and 4+ (for May 14 and May 25 of 1985, respectively).

3.2. Current Sheet Parameters During Plasma Sheet Flapping Events

As seen from Table 1, in all (but one) cases the inferred scale height of the current sheet h was between 0.2 and 1 R_E and the most typical current density value was about 10-30 nA/m^2. For comparison, in the T89m model [*Peredo et al.*, 1993] for Kp=5 the vertical magnetic field gradient in the current sheet center at r = 14 R_E is dB_X/dt = 37.5 nT/R_E, and, correspondingly, the current density is 4.7 nA/m^2. This is 2-6 times smaller than the values estimated in our events. The broad current distribution predicted by the model is not surprising, taking into account the statistical approach used when constructing empirical models (for example, the flapping motions would artificially broaden the inferred vertical scale of the current sheet). Conversely, the vertical scale inferred by our analysis is rather an upper estimate of the actual current sheet scale size on account of the assumption of a constant current density over the plasma sheet thickness (linear B_X-Z_{GSM} relationship). In reality, the plasma sheet may contain a very thin current sheet in the central portion of plasma sheet [*McComas et al.*, 1986; *Sergeev et al.*, 1993; *Sanny et al.*, 1994]. If such a current sheet model were to be considered, the inferred scale size would have been smaller. Indirect confirmation

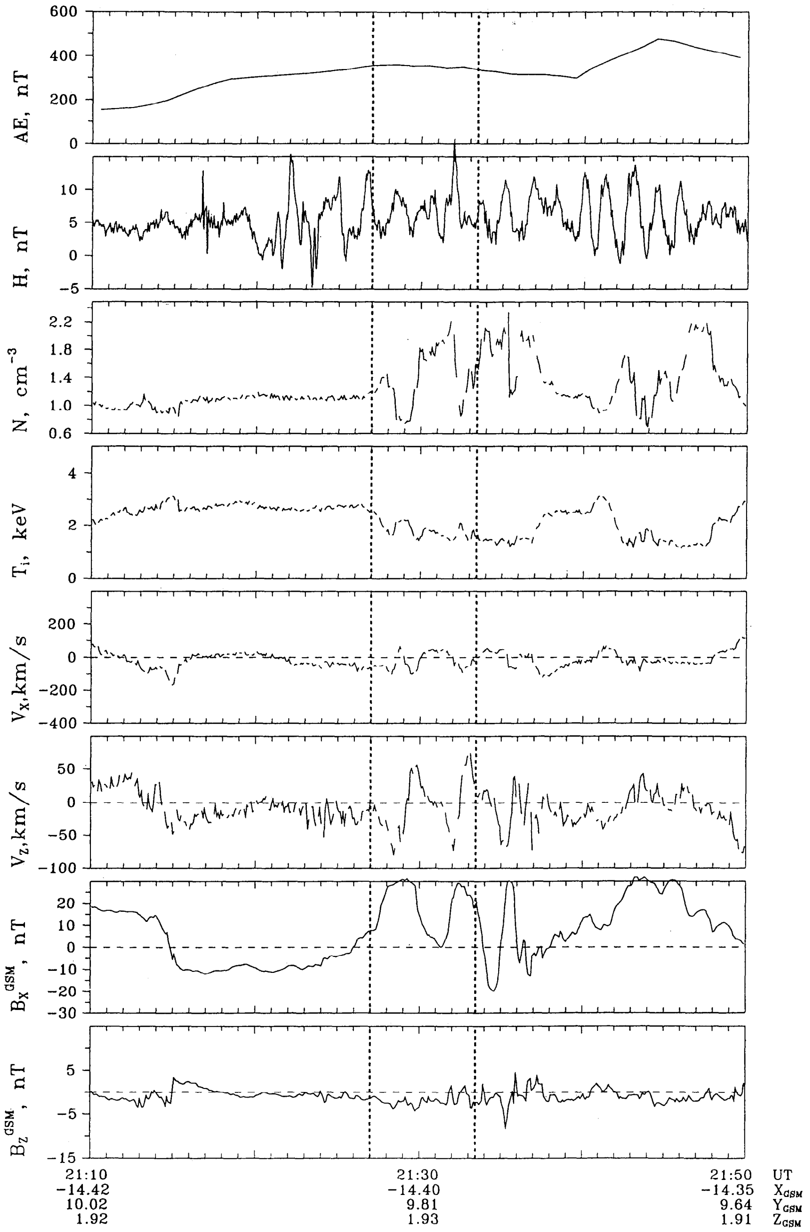

Figure 4. Same as in Figure 2 but for May 25, 1985 event.

that the plasma sheet is much thicker than the central current sheet probed follows from the fact that in no case did the spacecraft exit from the plasma sheet during the flapping motions as evidenced by the high plasma density. The actual current distribution cannot be deconvolved with confidence because of limitations of the technique used, arising from the contributions to V_Z from the variable convection and from the instrumental offsets. Both effects preclude the determination of the absolute part of the measured V_Z that contributes instantaneously to flapping.

Another important parameter, B_Z in the neutral sheet, is very small (about 1 to 3 nT) in all cases that exhibit small (<100 km/s) earthward flows (Table 1). The quiet (slow flow) thin current sheets therefore are typically quasi-neutral in a sense that $|B_Z| << |B_X|$. However, these sheets can also contain a net B_y (sometimes $B_y >> B_z$, see Table 1) as has been pointed out previously [*McComas et al.*, 1986, *Sergeev et al.*, 1993]. Increased B_Z values (approximately 10 nT) were observed together with strong horizontal plasma flows at substorm onset in the two last events of April 8.

An important characteristic of the current sheets studied is the persistence of quiescent thin current sheets (for intervals longer than 10 min) as follows from the observation of similar current sheet parameters during consecutive neutral sheet crossings (see Table 1). Ending this section, we would like to note that analyzed neutral sheet crossings with vertical scale 0.2-1 R_E may represent only a subset of all possible parameters. Some current thickness extrema (thick or very thin crossings) could not be resolved by this technique because of insufficient time and/or V_Z - amplitude resolution. Very thin current sheets of $h < \sim 0.2\, R_E$ could be missed because they are too short to be resolved at 5 s sampling rate. Conversely, if they are too long, the required V_Z

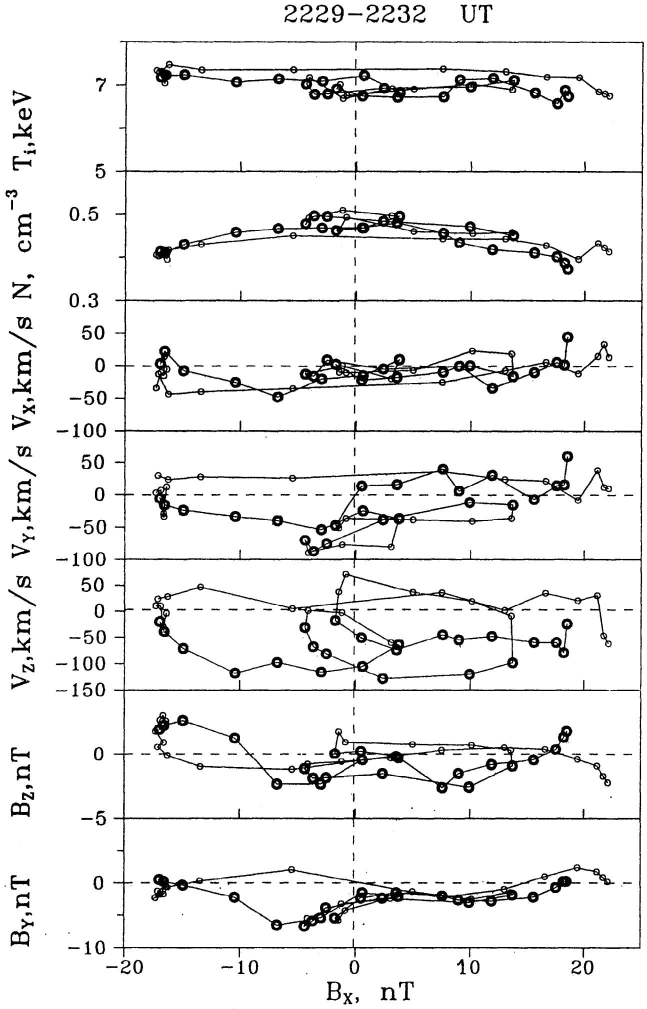

Figure 5. Hodogram of magnetic field and plasma parameters as a function of B_x component value for oscillating crossing b on April 8, 1985 (2229-2232 UT). Large (small) circles are used to distinguish the crossings from north to south (from south to north).

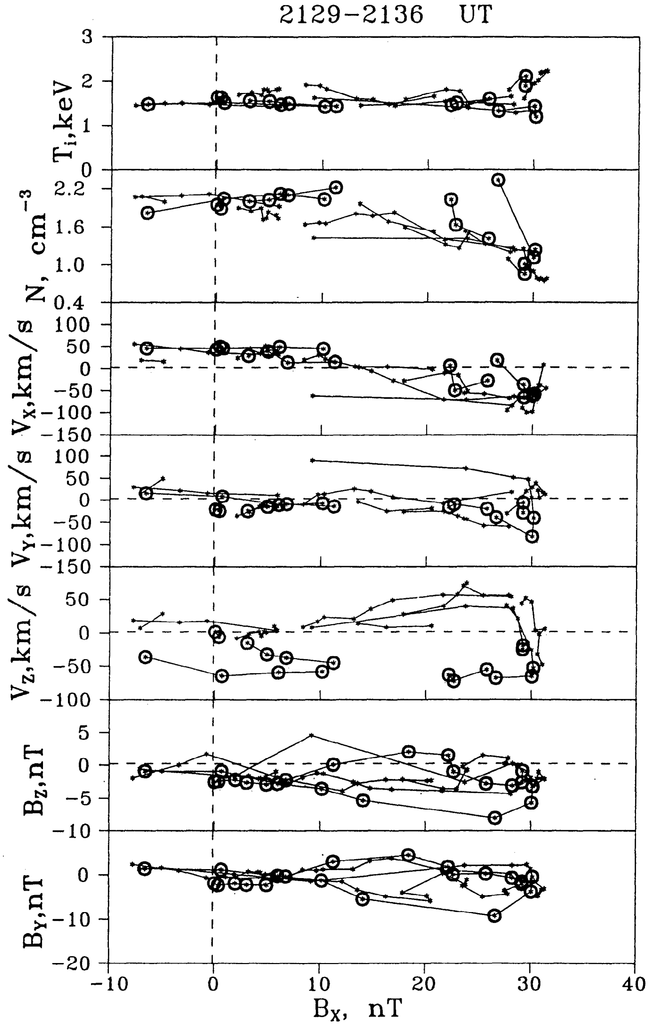

Figure 6. Same as in Figure 5 but for the oscillating crossings on May 25, 1985 (2129-2136 UT).

amplitude may be too small. In addition, in the case of broad current sheets the time required to cross them may be too long compared with changes of plasma flow and current sheet, and thus flapping may be masked by alternative sources of north-south flow. However, the analyzed crossings represent a significant fraction of all neutral sheet crossings observed during studied time intervals, and therefore they provide representative characteristics of the state of current sheet during these times. With that in mind we should note that the current densities inferred in our study (10-20 nA/m^2) at distances of 12-18 R_E are somewhat smaller than those inferred by *Lui et al.* [1992] just prior to substorm onset in the current disruption region at distances of 8-9 R_E. The difference in current density may explain the apparent stability of thin current sheets in the events analyzed here.

3.3. Vertical Structure of the Thin Current Sheet

Recently, *Pritchett and Coroniti* [1995] presented fully kinetic simulations to show that very thin (half-thickness less than a proton gyroradius) current sheets (TCS) may naturally form in the magnetotail neutral sheet in the transition region between dipole-like and current sheet regions (somewhere at 8-12 R_E). Formation of such thin current sheets is due to negative charging of the neutral sheet, so that the dominant contribution to the TCS density comes from the electrons. A prediction of this model is the presence of an electric field directed toward the neutral sheet or, equivalently, the existence away from the neutral sheet of a negative V_y convective flow. We checked all events but in no case did we find this V_y signature (e.g., Figures 5 and 6). Furthermore, the inferred current sheet half thickness (h in Table 1) was in all cases larger than the gyroradius of plasma sheet proton in the lobe field. Although we did not encounter thin negatively-charged current sheets in our limited survey at r>12 R_E in the plasma sheet, this does not contradict the Pritchett and Coroniti results. This is because charged TCS structures are expected in a limited range of distances along the tail, whereas further downtail the ordinary, relatively broad current sheet distribution should be typical. Our analysis places a tailward limit of 12 R_E on the distances where the charged TCS could be formed. Another reason why negatively charged thin sheets are not observed is that they may be discharged through the ionosphere. In that case one may expect to see the magnetic shear caused by the tailward (flowing upward from the ionosphere) field-aligned currents. The signature of such shear was possibly observed in one episode of an oscillating crossing at about 2230 UT (Figure 5 and number 4 in Table 1): on four neutral sheet crossings there was a systematic positive gradient $dB_y \sim 0.52\ dB_x$ in the central portion of current sheet (at $|B_x|<6$ nT). With the current sheet thickness taken from Table 1, this implies that the density of field-aligned current is ~ 4 nA/m^2 and that vertical size of field-aligned current region is about 0.2 R_E. Although there were neutral sheet crossings both preceding and following that event, a similar structure was not observed on those occasions, which means that the event has a short (a few minutes) lifetime.

3.4. Association of Flapping Motions With Substorms

Observations presented in our paper confirm previous reports of preferential association of neutral sheet flapping with high-activity conditions and substorm onsets. As we already mentioned, of the four broad time periods included in our analysis three were geomagnetically disturbed (Kp>= +4). In 14 out of the 19 events of Table 1 the flapping was observed near (within 10 min) substorm onsets or substorm intensifications. During the three broad time periods included in this study the sensitive induction magnetometer recordings from midlatitude station Hermanus (magnetic midnight at ~2330 MLT) were available to monitor Pi2 pulsation activity at the local time sector of AMPTE/IRM's ionospheric foot point. The traces of H and D components at Hermanus are shown in Figures 2, 3, and 4 (second from the top). The first five analyzed intervals in Table 1 for which no distinct substorms could be identified in the Pi2 or *AE* data occurred on April 8, 1985, during an event that has been previously analyzed by *Lopez et al.* [1994]. Overall, about 20 individual neutral sheet crossings occurred between 2050 UT and a substorm onset that took place at 2308 UT.

We analyzed all available monitors of substorm activity for the April 8, 1985, series of neutral sheet crossings, including auroral zone and midlatitude magnetometer stations, particle injections at geosynchronous orbit, and all-sky camera observations at the Syowa station (-66° corrected geomagnetic latitude, 2100-2300 MLT) and at Finnish station Kilpisjarvi (~66° corrected geomagnetic latitude, 0000-0002 MLT). On the basis of this survey we concluded that the plasma sheet flapping motions between 1900 and 2300 UT on April 8, 1985 took place during a convection bay event. Throughout this time interval the electrojet activity was steadily high (AE~400-500 nT, Figure 2). In agreement with findings by *Lopez et al.* [1994], throughout this period we found multiple, weak, short-duration (a few minutes) activations. The corresponding auroral breakups showed limited poleward expansion (less than 100-200 km in latitude), the associated magnetic disturbance was weak (less or about 150 nT), and the effects at different stations were typically uncorrelated (hence, localized in MLT). No significant plasma sheet flows (exceeding 400 km/s, which is a typical threshold for bursty bulk flows) were seen near the neutral sheet at AMPTE/IRM (Figure 2). These short-duration, local, and weak activations could be characterized as pseudobreakups, typically occurring during convection bays. One important conclusion of our study is the confirmation of the previous finding by *Sergeev et al.* [1994] of very stretched magnetic configuration in the near-Earth tail during steady convection events (convection bays). This is clear from both the high lobe field values (> 40-50 nT) and the small current sheet thicknesses inferred (h ~0.5- 0.9 R_E); see Table 1. Our case study extends similar previous results obtained near geosynchronous orbit to larger distances (~14 R_E). The extreme localization of the magnetotail and ionospheric phenomena during pseudobreakups but also the extreme stretching of the inner magnetotail field during convection bays are two alternative explanations to the one offered by *Lopez et al.* [1994] for the lack of a neutral sheet fast flow signature at AMPTE/IRM in correlation with the localized weak ionospheric activations.

Let us now consider the oscillating crossings and their relationship with substorm activations. In a recent paper, *Bauer et al.* [1995] analyzed three time intervals of IRM observations showing intense oscillations of the neutral sheet. Referring to the model by *Nishida* [1979], they interpreted them as oscillations induced by the bouncing Alfven wave initiated by current disruption and suggested that the neutral sheet oscillates at the Pi2 frequency. Our study extends their investigation in a few ways. First of all, using the same data sets (two of their three events are the April 8 and April 19 events, shown in our Figures 2 and 3), we identified some more examples of oscillating crossings. For April 8, besides the strong oscillation *D* at 23:08 considered by *Bauer et al.* (exactly at substorm onset), one can distinguish three more events (a, b, c in Figure 2) showing well defined neutral sheet oscillations. All three occurred during the convection bay interval, that is, without any distinct current disruption and substorm onset. Nevertheless, in case a one may discern a pulsation train at the Pi2 frequency range recorded at Hermanus, which is delayed by 2 min after the apparent onset of the neutral sheet oscillation. In case b we also observe a Pi2 train at Hermanus, which starts ~3 min before the neutral sheet oscillation. The apparent oscillation period is similar (T~1 min) in both kinds of data. In case c the apparent period of the neutral sheet oscillation is larger (~100 s) but we can not see it on the ground. Furthermore, impulsive ground magnetic signatures at ~2212 and 2218 UT are not seen in spacecraft recordings. Finally, the strong flapping oscillations at the substorm onset starting at about 2306 UT with apparent period about 70 s corresponds to large-amplitude Pi2 train at Hermanus at the period about 40 s. Nearly the same picture occurs in two other events. On April 19 there was a clear neutral sheet oscillation at T~80 s (2248 UT), followed ~3 min later by a ground Pi2 pulsation of a smaller period. A clear enhancement of ground Pi2 pulsations had similar frequency (T~1 min) but was delayed by 1-2 min after the start of next neutral sheet oscillation (~2158 UT). The last, very distinct and strong NS oscillation (~2208 UT) had no ground counterpart until 2213 UT. Based on the above discussion, although there is definitely an association in the appearance of ground Pi2 and neutral sheet oscillations, this association is rather complex because the two phenomena do not appear simultaneously (one precedes or lags the other) and may have different oscillation frequencies. A clear illustration of this statement appears in the last event (Figure 4) where neutral sheet oscillations appear at 2227 UT, that is, ~8 min after the strong enhancement of Pi2 pulsations (2219 UT) and had about two times larger period than ground pulsations.

A possible explanation of the neutral sheet oscillations with the reconnection region as the likely driver of the waves may be the transient reconnection model of *Semenov et al.* [1992], which predicts Kelvin-Helmholtz type surface waves propagating away from the reconnection region [*Semenov et al.*, 1994; 1995]. Another possible explanation is the drift kink mode that is excited within thick current sheets and in combination with the tearing mode or interchange mode as discussed by *Zhu and Winglee* [1996], *Ozaki et al.* [1996], *Pritchett et al.* [1996], and *Pritchett and Coroniti*, [1997]. In the latter explanation the observed oscillations are not the consequence but an inherent part of the plasma sheet acceleration process. The details of the wave generation and propagation and the parameters controlling the period of oscillations are research topics promising to unravel important aspects of the coupling between local activations and global evolution.

4. Conclusions

We have shown that slow plasma flows directed perpendicular to the neutral sheet plane and associated with north-south flapping motions of the midtail plasma sheet may be large enough to exceed the sensitivity threshold of plasma spectrometers. The correlation of these slow flows with dB_X/dt during times of multiple plasma sheet oscillations can be used to separate the contribution of semipermanent convection to the total measured flow. Applying this method to multiple neutral sheet crossings during four broad time intervals selected from scanning through 3 months of AMPTE/IRM magnetotail data, we were able to extract estimates of the current density (j) and vertical scale height (h) of the current sheet. The estimates indicated a much more dense (j~10-20 nA/m^2) and thin (h~0.2-1 R_E) current sheet than predicted by magnetospheric models.

In our data set we found that thin current sheets at distances from 12 to 18 R_E were associated with substorm onsets but in most cases (15 from 19 events) in the absence of bursty bulk flows (defined to be near-neutral sheet flows with magnitude greater than 400 km/s). A large number of neutral sheet crossings occurred during a 2-hour-long time interval classified as a convection bay event, confirming previous evidence that during convection bays the near-Earth plasma sheet is characterized by a stretched magnetic field configuration. The current sheet densities observed were still smaller than reported values [*Lui et al.*, 1992] prior to current disruption, which explains the stability of the current sheet in our observations.

Our results showed that the largest flapping-related V_Z flows (200-300 km/s) have been observed in the presence of high speed Earthward flows whereas the flapping velocity is smaller (several tens of kilometers per second) in the slow-flow (nonactive plasma sheet) regions. This fact together with observation of large flapping velocities near the hinging distance (as close as 12 R_E) and the correlation of the plasma sheet flapping with high geomagnetic activity shows that flapping motions have a free-energy source related to near-neutral sheet activations observed at times of substorms.

By comparing appearance of neutral sheet flapping oscillations with ground Pi2 activity, we found that both appear nearly simultaneously, but the exact onset times as well as the dominant periods are generally different. Although a common free-energy source for both phenomena may be the broad spectrum of waves generated during the current disruption/reconnection process, different mechanisms may disseminate that energy to the observed phenomenon. Surface waves propagating toward undisturbed parts of the plasma sheet from the impulsive, localized acceleration sites observed during substorms [*Angelopoulos*, 1996], may be the mechanism that couples the free energy emitted locally in the tail to the global flapping motions of the plasma sheet. Alternatively, the observed waves may be the evidence of the drift kink mode that is excited in thin current sheets and in conjunction with tearing or interchange modes results in particle acceleration related to substorms as seen in recent computer simulations.

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