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ISEE-3 observations of a viscously-driven plasma sheet: magnetosheath mass and/or momentum transfer?

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Abstract. A statistical analysis of data from the ISEE-3 distant tail campaign is presented. We investigate the mechanism driving slow, tailward flows observed in the plasma sheet. The possibility that these slow flows are driven by mass and/or momentum transfer across the distant tail magnetopause is explored. We establish that 40% of these flows could be driven by the transfer of approximately 4% of the magnetosheath momentum flux into the magnetotail. Current understanding of the Kelvin-Helmholtz instability suggests that this figure is consistent with the amount of momentum flux transfer produced by this mechanism. We also consider the possibility that these flows are solely driven by transferring magnetosheath plasma across the magnetopause. We find that there is sufficient mass observed on these field lines for this to be the sole driving mechanism for only 27% of the observed slow flows.

Key words. Magnetospheric physics (magnetotail boundary layers; plasma convection; plasma sheet)

1 Introduction

The structure of the distant magnetotail plasma sheet (X $< -60R_e$) has been examined in detail by both the ISEE-3 and Geotail spacecraft. These missions have established that the distant tail is a structured region, similar to the near-Earth tail. In particular, the spacecraft encountered a central plasma sheet region surrounding the cross-tail current layer and bordered by a plasma sheet boundary layer. Further still from the current layer are the north and south lobe regions. Many models (e.g. Coroniti and Kennel, 1972, 1973; Cowley, 1980, 1984) have been proposed for a hot plasma sheet formed by reconnection in the centre plane of the tail. However, observations have suggested that, at times, even the distant plasma sheet consists of closed flux tubes slowly flowing tailward (Slavin et al., 1987; Richardson et al., 1989). Global MHD models of the magnetotail under prolonged northward IMF have been used to suggest that a tail flank boundary layer may be formed resulting from near-simultaneous reconnection of field lines poleward of both north and south cusps (Berchem et al., 1995; Raeder et al., 1995). This, they suggest, may lead to a broad layer of closed flux tubes flowing slowly tailward. It is not clear at present how likely, or frequent this process may be. However, observations made by the Geotail spacecraft have shown that there is a slow flowing, cold boundary layer plasma in the near-Earth magnetotail (Fujimoto et al., 1998), which is reported to fill a substantial portion of the tail. It contains magnetosheath-like ions and anisotropic, heated, bi-directional electrons. The flow speeds are low, and it is suggested that this boundary layer is directly supplied by plasma from the magnetosheath through the flank magnetopause.

The proportion of the ISEE-3 distant tail plasma sheet encounters in which observed plasma conditions were consistent with expectations based on models of magnetic reconnection has been quantified at ∼50% (Mist and Owen, 1999). In the remaining cases, the observed tailward flow speeds were either significantly below the predictions of reconnection models (Cowley, 1980; Cowley and Southwood, 1980; Owen et al., 1991), or the observed densities were lower than the neighbouring lobe density. These models implicitly assume that the local lobe properties are similar to those at the acceleration site. While this is not necessarily the case, the general trend in the magnetotail is for the magnetic field magnitude to drop and the lobe density to increase with distance from the Earth (Slavin et al., 1987). These effects combine to produce a predicted reconnection-associated flow speed which declines with downtail distance from the acceleration site. Thus, for these tailward flows it is likely that an analysis based on local lobe parameters overestimates the speed of reconnection flows accelerated close to the Earth. For example, a tailward moving plasmoid, formed by a near-Earth neutral line, may be moving significantly faster than the local conditions would predict. Thus, on this basis Mist and Owen (1999) may have underestimated a subset of the predicted reconnection flow speeds, and hence, their statistical analysis

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Correspondence to: C. J. Owen (cjo@mssl.ucl.ac.uk) actually overestimated the number of observations that are consistent with reconnection.

In this paper, we will examine the nature of the non-reconnection plasma sheet flows observed by ISEE-3. We determine the proximity of the observations to the magnetosheath and investigate whether these flows could be driven by mass and/or momentum transport across the distant tail magnetopause. Our results are compared to our current understanding of the Kelvin-Helmholtz instability, which has often been suggested as a means of transferring momentum, and possibly mass, across the magnetopause (e.g. Miura, 1992; Chen et al., 1993; Fairfield et al., 2000; Otto and Fairfield, 2000). We consider whether this mechanism can transfer sufficient momentum to drive the observed flows. In the next section, we consider a method of calculating what proportion of the observed magnetosheath mass and/or momentum flux would need to be transferred across the magnetopause in order to drive the observed plasma sheet flows. We then discuss the database used in this survey and detail the means of categorising each event. We then present the analysis of these data. Finally, we discuss whether the data support driving of plasma sheet flows by transferring mass and/or momentum across the magnetopause.

2 Magnetosheath mass and momentum transport

Owen and Slavin (1992) consider the proportion of mass and/or momentum flux that would need to be transferred from the magnetosheath to be consistent with plasma flow speeds on apparently closed field lines in the distant plasma sheet. If a small amount of mass and/or momentum is transferred, the field line tension will dominate the plasma, and the field line will retreat earthward (although at a slower rate than if no energy was being transferred). There will be a balance point where the amount of mass or momentum being added to the field lines exactly balances the magnetic tension and the field line remains stationary. Finally, if significant mass and/or momentum is transferred, the closed field lines may be driven tailward. This approach is independent of any particular model of viscous transfer, and can be used to put limits on the efficiency of such processes.

Owen and Slavin (1992) apply the stress balance conditions appropriate to a one-dimensional current sheet (e.g. Owen and Cowley, 1987) to the closed field lines in the distant plasma sheet. They determine the amount of magnetosheath mass that would need to be scattered onto a field line in order to balance the field line tension and to drive it tailward at the observed flow speed. They assume that particles are scattered onto closed plasma sheet field lines with no loss of energy and derive an expression for the minimum density, n_{PSmin}, required in the plasma sheet if mass transport from the magnetosheath is driving the field line motion:

$$n_{PSmin} = \frac{(B_L^2 + B_{PS}^2)}{2m_i\mu_0(V_{SH} - V_{PS})^2}, \tag{1}$$

where B_L is the lobe magnetic field, B_{PS} is the plasma sheet magnetic field, V_{SH} is the magnetosheath flow speed and V_{PS} is the plasma sheet flow speed. Note that this is a lower estimate of n_{PS} since any pre-existing plasma on the field lines would increase this estimate.

Another possibility is that the flows are instead driven by some anomalous momentum transfer mechanism. Owen and Slavin (1992) also derive an expression for the minimum fraction of the magnetosheath momentum flux that would have to be transferred into the magnetosphere in order to drive the observed flows in the plasma sheet. They consider that a proportion (K) of the magnetosheath momentum is transferred to plasma sheet particles flowing towards the current sheet. Using the 1-D current sheet approximation, Owen and Slavin (1992) find the fraction, K, is given by

$$K = \frac{n_{PS}}{2n_{SH}}.\frac{(V_{PS} + V^*)^2}{{V_{SH}}^2}, \tag{2}$$

where n_{SH} and V_{SH} are the magnetosheath density and velocity, respectively, n_{PS} is the plasma sheet density, V_{PS} is the plasma sheet flow speed and V^* is given by

$$V^* = \left[\frac{(B_L^2 + B_{PS}^2)}{2n_{PS}m_i\mu_0}\right]^{0.5}. \tag{3}$$

Owen and Slavin (1992) applied the result to a single ISEE-3 encounter of a slow flowing plasma sheet. They found that for this interval (08:30–11:30 UT, 6 July 1983), the minimum plasma sheet density required to drive the flows is $n_{PSmin} = 3\,\mathrm{cm}^{-3}$, which exceeds the observed density of $0.5\,\mathrm{cm}^{-3}$ by a factor of 6. In the case study considered in their work, $K = 0.06$, at least 6% of the magnetosheath momentum would need to be transferred into the magnetosphere in order to drive the observed flows. Miura (1992) showed that up to 4% of the magnetosheath momentum flux may occasionally be transferred by the Kelvin-Helmholtz instability, which is close to the value required in this single observation.

Here, we broaden this study by conducting a statistical survey of the distant tail plasma sheet using the ISEE-3 data set. We compare the observations made by ISEE-3 during its deep tail phase with the Owen and Slavin (1992) parameters (Eqs. 1 and 2).

3 Data selection

We are concerned with mechanisms that may drive plasma sheet flows that are inconsistent with a reconnection interpretation. These flows must first be identified in the plasma sheet data set. The ISEE-3 data was used to identify four main regions that are found in the deep tail data; the north/south lobes, the plasma sheet boundary layer (PSBL), the plasma sheet and the magnetosheath. The definitions of these regions are described in detail in Mist and Owen (1999). In summary, however, the plasma sheet magnetic field strength is depressed from the lobe values (the average lobe magnetic field strength is 9.2 nT (Slavin et al., 1985)), and approaches zero at a central current layer. The magnetic field also varies in strength and direction (Bame et al., 1983). The plasma density is 0.1–1.0 cm^{-3} and the electron temperature is of the order of 100–1000 eV (Zwickl et al., 1984; Slavin et al., 1985). A large database containing all the ISEE-3 plasma sheet encounters has been created (Mist and Owen, 1999). This contains 754 plasma sheet encounters (each with a duration of >5 mins) between $X_{GSE} = -60$ and -240 R_E. In our previous work (Mist and Owen, 1999), we compared the observed plasma sheet velocity with the velocity predicted by reconnection models.

Of the 754 events, 677 were also closely located in time with a lobe encounter, such that the plasma sheet velocity could be reasonably predicted from reconnection models. These plasma sheet encounters are divided into the four categories (see also, Mist and Owen, 1999), as detailed below.

Events for which $n_{PS} < n_L$ are identified. Such events are not consistent with the reconnection models used to predict the plasma sheet flow speeds, since plasma sheet field lines formed by reconnection must have a density in excess of the surrounding lobe region.

The second category contains all the observed earthward flows with $n_{PS} > n_L$. Mist and Owen (1999) found that none of the earthward flows observed in this data set were consistent with the reconnection models. Particles mirrored at the Earth and returning to the deep tail will affect the stress balance calculation in the tail plasma sheet. Since these particles have not been explicitly included, the reconnection models may only accurately predict the plasma sheet speed for tailward flows.

The above categories leave only tailward flows with $n_{PS} > n_L$. Mist and Owen (1999) established that the observed tailward flux transport is not consistent with the applied models of reconnection when $-0.6 < V_{obs}/V_{PSout} < 0$, where V_{obs} is the observed velocity in the plasma sheet and V_{PSout} is the plasma sheet outflow speed predicted by the reconnection models. Hence, the remaining data were split into the final two categories: reconnection-like and non-reconnection-like (or slow) observations.

In order to study the transfer of mass and/or momentum flux from the magnetosheath using the ISEE-3 data set, it is desirable to further restrict the events chosen to those close to the magnetosheath. Due to small changes in external solar wind conditions, the distant magnetotail may move up to its full width, in any direction normal to its axis. Hence, on a case by case basis, we cannot use models of the average magnetosphere to indicate the location of the spacecraft with respect to the magnetopause. However, with a large data set, such as this, there are two alternate statistical measures of the spacecraft's proximity to the magnetopause. First, we can consider, on a statistical basis, events that are close to the average position of the tail magnetopause. Alternatively, we can statistically consider those events that are close in time to observations of the magnetosheath. In this paper, we will utilise and compare both these approaches.

The magnetosheath and lobe events for use in the analysis were selected using the criteria developed in Zwickl et al. (1984). We required that the periods of observed lobe or magnetosheath were at least 5 min long. The magnetosheath and lobe properties were averaged over the observed interval, the length of which was restricted to less than one hour. The proximity to the magnetopause of the observed flows cannot be measured using one spacecraft. Instead, we have had to determine the spacecraft's distance from an average aberrated magnetotail cylindrical magnetopause. An average magnetotail width of 60 R_E has previously been determined using data from the ISEE-3 spacecraft magnetopause crossings (Slavin et al., 1985). In a statistical analysis of region dwell times, Fairfield (1992) determined the average magnetotail width to be 60 R_E. Using a width of 50 R_E, it is found that 60% of plasma sheet encounters were close or external to the average position of the tail magnetopause. Using a width of 60R_E, 50% of the plasma sheet encounters were found further than 30 R_E of the nominal tail axis in the Y-plane. In this study, we use 50 R_E as the width of the central tail. Only 16% of plasma sheet encounters were identified as located temporally close (within one hour) to an observation of the magnetopause. Each of the plasma sheet intervals in the database that satisfied one or both of the magnetopause proximity criteria were then split into periods of five minutes, and their properties averaged over these intervals.

We will also consider how the classes of flows are ordered in quiet and active times. We do this using the AE index. In this study, a data period is categorised as active when it has an AE index greater than 200 nT.

Having applied the above categorisation and selection procedures to the entire database, the events can be compared with the parameters K, the fraction of magnetosheath momentum flux required to drive the flows and n_{PSmin}, the minimum plasma sheath density we expect to observe if the flows are driven by mass transfer across the magnetopause.

4 Contingency analysis

In this study, we wish to determine whether the plasma sheet data are better ordered by their proximity to the average magnetopause, or by their temporal proximity to a magnetosheath observation. We also wish to work out whether each class of events is more likely to occur under high/low magnetic activity. To do this we undertake a contingency analysis of the data set and examine whether there are significant differences between the classes of flows observed under these conditions.

In order to proceed with this analysis, we have to determine whether the event categories are independent of each other. First, we compare how the observed data are distributed with respect to an expected data distribution. This expected distribution is determined in the following manner: for example, to calculate the expected number of slow flows close to the magnetosheath, assuming that the data are independent, the fraction of the total data set that is close to the magnetosheath is multiplied by the fraction of total data set

Table 1. Distribution of plasma sheet encounters with respect to $Y = Y_{GSM_{AB}}$, the aberrated Y_{GSM} coordinate

Category	$\|Y\| < 25\ R_E$	$\|Y\| > 25\ R_E$	Total
$n_{PS} < n_L$	484	726	1210
Reconnection	186	369	555
Slow	337	635	972
Earthward	181	99	280
Total	1188	1829	3017

Table 2. Distribution of plasma sheet encounters sorted by time from observation of the magnetosheath

Category	T > 60 min	T < 60 min	Total
$n_{PS} < n_L$	881	329	1210
Reconnection	444	111	555
Slow	754	218	973
Earthward	259	21	280
Total	2338	679	3017

that is flowing slowly. Then, the total number of events in the data set is multiplied by this combined fraction to give the expected number of events in a particular class.

We compare the expected and observed data distributions by calculating the chi-squared "goodness of fit" statistic for the data set. The chi-squared statistic is a measure of how much the observed data (*O*) differ from expected values (*E*). The chi-squared statistic is given by the sum of $(O - E)^2/E$ for each category in the analysis. The 5% upper-tail critical value of the chi-squared statistic for this data set is 7.85. The calculated chi-squared value is 92.09 for data ordered spatially and 53.37 for data ordered by time from the magnetosheath. These values then indicate whether the data are independent or not. In this case, since the calculated chi-squared values are significantly greater than the critical value, we find that the data are not independent, and that the classifications depend on their proximity to the magnetosheath. Thus, we can continue with the contingency analysis.

In order to compare whether there are more or less events in a particular class than might be expected, we compare the relative differences between the observed and expected frequencies for each category. The measure used here is the percentage contribution to the chi-squared statistic for the data set made by data in a particular category. We also include the sign of the observed minus the expected distributions (*O*–*E*), to indicate whether more or less expected events are observed. A value close to zero suggests that the number of events in a particular category reflects the expected value in that category.

4.1 Proximity to the magnetopause

First, we compare the results ordered by space and time to determine whether they are better ordered temporally or spatially. In Tables 1 and 2, we show how the 5 min data periods are distributed when organised by spatial and temporal proximity to the magnetosheath. Tables 3 and 4 show the relative differences from expected frequencies for the spatial and temporal ordering of the data. A value close to zero suggests that the number of events in a particular temporal or spatial category reflects the expected value in that category. We have indicated in bold where there is a strong deviation from expected values, although of course, there are also associated large negative variations in the opposite case.

Table 3. Relative differences from expected values with respect to $Y_{GSM_{AB}}$

Category	$\|Y\| < 25\ R_E$	$\|Y\| > 25\ R_E$
$n_{PS} < n_L$	0.1%	−0.1%
Reconnection	−5.3%	3.4%
Slow	−5.9%	3.9%
Earthward	**49.3%**	−32.0%

We see that in both spatial and temporal ordering of the data, earthward flows are significantly more likely to be observed in the central tail region than close to the magnetosheath. The next significant difference is only found in the data ordered by time from the nearest magnetosheath crossing. In this, we find that close to the magnetosheath there are more events with $n_{PS} < n_L$ than we might expect. We do not see any significant preference for the slow flows to be located close to the magnetosheath. Although when ordered with respect to Y, they are slightly more likely to be slow at locations closer to the nominal magnetosheath.

4.2 Geomagnetic activity

Table 5 shows the data ordered with respect to the AE index. In this paper, high activity is defined as having an AE index >200 nT, and low AE is defined as having an AE index <200 nT.

We repeat the contingency analysis carried out above on this data set (Table 6). Considering the greatest relative difference, we see that there are more slow tailward flows than expected during geomagnetically quiet times, and consequently, there are fewer observed during active times. The next most significant difference is that there are more reconnection flows observed during active times. We also note that earthward flows are more likely to be seen during low activity periods and that $n_{PS} < n_L$ events are more likely to be observed during active periods.

Table 4. Relative differences from expected values with respect to T from magnetosheath: earthward flows are more likely to be found in the centre of the magnetotail and flows with $n_{PS} < n_L$ are more likely to be found close to the magnetopause

Category	T > 60 min	T < 60 min
$n_{PS} < n_L$	−6.4%	**22.1%**
Reconnection	0.8%	−2.9%
Slow	0.0%	−0.0%
Earthward	15.2%	**−52.5%**

Table 5. Distribution of plasma sheet encounters with respect to the AE index

Category	$AE > 200$ nT	$AE < 200$ nT	Total
$n_{PS} < n_L$	768	442	1210
Reconnection	389	166	555
Slow	403	569	972
Earthward	106	174	280
Total	1666	1351	3017

4.3 Magnetopause proximity and geomagnetic activity

In Table 7, we split the data into four categories: $AE >$ and <200 nT, and T $<$ and >1 h. This table shows the relative differences from the expected values. In this table we see that the reconnection flows are more likely to be observed in the centre of the tail, during active times. Slow tailward flows are observed during quiet times, across the whole tail. Interestingly, earthward flows are also more likely to be observed during quiet times, in the centre of the magnetotail. Flows with $n_{PS} < n_L$ are more often observed during active times, at the edge of the magnetotail.

4.4 Down tail distance

For completeness, it is also illustrative to order the data into down-tail distance bins. We split the data into two sections: $X > -140\,R_E$ and $X < -140\,R_E$ (Table 8). Again, we conduct a contingency analysis in the same manner (Table 9). As might be expected, by far the greatest relative difference is found in the earthward flows, with significantly more than expected being observed for $X < 140\,R_E$. There is no significant difference for any of the other categories.

5 Mass and momentum transfer analysis

We now wish to consider whether the flows may be driven by mass and/or momentum flux transfer from the magnetosheath. Equations (1) and (2) can be used to estimate the minimum plasma sheet density and the proportion of magnetosheath momentum flux required to drive the tailward flows. For this, we need to select events that are close to the magnetosheath. It has been established above (Tables 3 and 4) that the data are ordered similarly with respect to distance and time from a magnetosheath encounter. For definiteness, we now consider the subset of events that were temporally located within 60 min of a magnetosheath encounter.

Table 6. Relative differences from expected values with respect to AE index: slow flows are more likely to be observed during quiet times, and reconnection flows are more likely to be observed in active times. Earthward flows are also more likely to be observed during quiet times, while $n_{PS} < n_L$ are more likely to be observed during active times

Category	$AE > 200$ nT	$AE < 200$ nT
$n_{PS} < n_L$	**7.8%**	−9.6%
Reconnection	**11.6%**	−14.3%
Slow	−17.4%	**21.5%**
Earthward	−8.0%	**9.8%**

Table 7. Relative differences from expected values with respect to AE index and T from magnetopause crossing: slow flows are more likely to be observed during quiet times close to the magnetopause, and reconnection flows are more likely to be observed in active times in the centre of the magnetotail

Category	$AE > 200$ nT		$AE < 200$ nT	
	T < 1 Hr	T > 1 Hr	T < 1 Hr	T > 1 Hr
$n_{PS} < n_L$	**13.1%**	0.4%	−1.5%	−5.6%
Reconnection	−0.3%	**13.5%**	−0.4%	−10.9%
Slow	−3.8%	−9.0%	**6.1%**	**10.3%**
Earthward	−10.2%	−0.9%	−1.5%	**12.7%**

The data shown in Fig. 1 are ordered with respect to V_{PS}, the observed flow speed. The panels on the left show the percentage of magnetosheath momentum flux required to drive the flows, and the panels on the right show the ratio of the predicted (n_{PSmin}) to the observed plasma sheet density (n_{PS}). In the upper panels, we show the data with $n_{PS} > n_L$ in the reconnection (a, e), slow tailward (b, f) and earthward (c, g) categories. The bottom two panels (d, h) contain the data with $n_{PS} < n_L$. The horizontal lines in Figs. 1a to 1d indicate where 1% and 4% of the magnetosheath momentum flux is required to drive the flows. In Figs. 1e to 1h, the horizontal lines show the line where $n_{PSmin}/n_{PS} = 1$.

From Figs. 1a to 1d, we see that only slow, earthward flows (c) could be associated with momentum flux transfer <1% from the magnetosheath. However, from Fig. 1b, it is found that 40% of the slow tailward flows could be driven by transfer of <4% of the magnetosheath momentum. From Fig. 1d, it is found that 17% of the tailward flows with $n_{PS} < n_L$ could also be driven by up to 4% of the magnetosheath momentum flux. Note that in comparison, flows categorised as

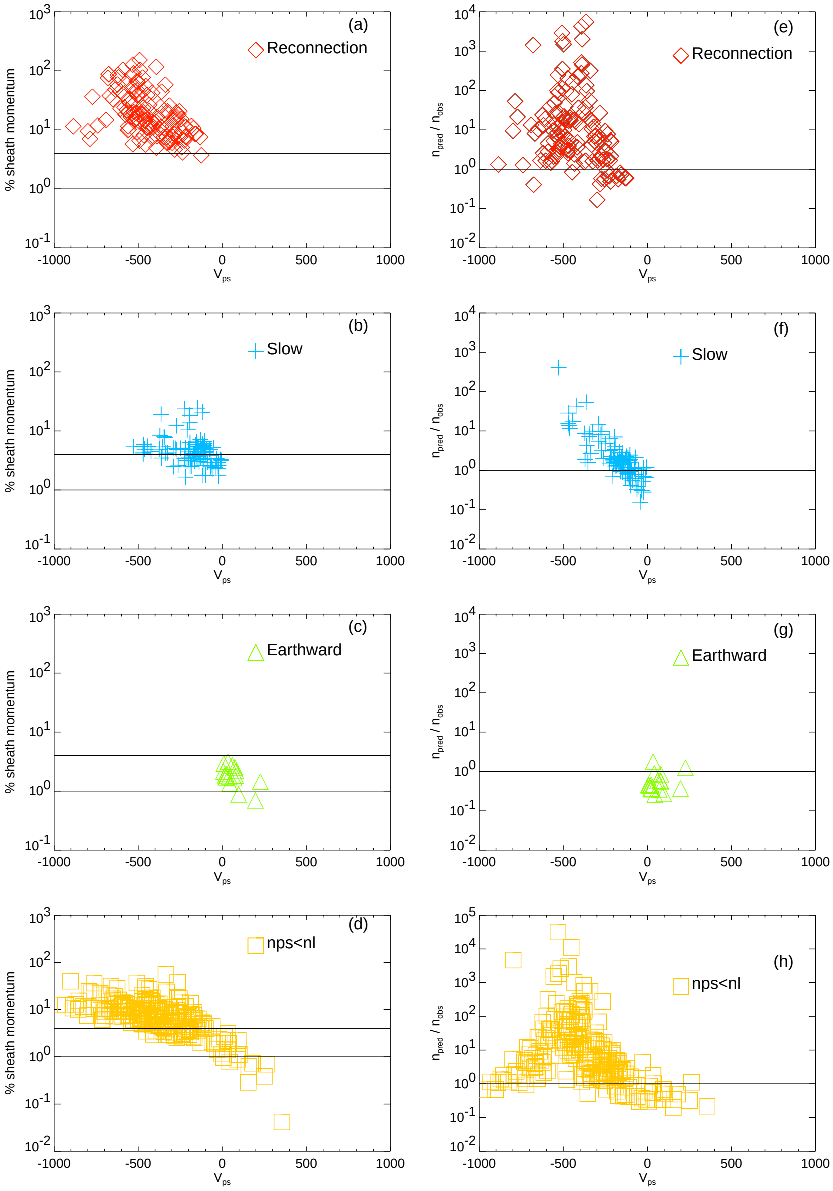

Fig. 1. **(a) to (d)** The average percentage of the magnetosheath momentum required to drive the observed flows. **(e) to (h)** The average ratio of the minimum predicted mass to the observed plasma sheet mass. The upper six panels contain the data where $n_{PS} > n_L$. The diamonds in Figs. 1a and 1e are the reconnection-like flows, the crosses in Figs. 1b and 1f are the slow tailward flows and the triangles in Figs. 1c and 1g are the earthward flows. The lower panels contain the data where $n_{PS} < n_L$. The panels are ordered with respect to V_{PS}. For the slow tailward flows, of the order of 4% of magnetosheath momentum (upper horizontal line in panels 1a–1d, the lower line is at 1%) is required to drive 40% the observed slow flows. However, the average mass density ratio is significantly greater than 1 (horizontal line in panels 1e–1h). This suggests that momentum transfer is more likely to be the preferred alternative mechanism driving slow plasma sheet flows.

Table 8. Distribution of plasma sheet encounters with respect to X_{GSE}

Category	X > −140 R_E	X < −140 R_E	Total
$n_{PS} < n_L$	240	970	1210
Reconnection	91	464	555
Slow	214	758	972
Earthward	152	218	280
Total	697	2320	3017

Table 9. Relative differences from expected values with respect to X_{GSE}: earthward flows are significantly more likely to be observed earthward of 140 R_E

Category	X > −140 R_E	X < −140 R_E
$n_{PS} < n_L$	−3.2%	1.0%
Reconnection	−6.2%	1.9%
Slow	−0.3%	0.1%
Earthward	**67.3%**	−20.2%

reconnection (1a) would require greater than 4% and, usually greater than 10% of magnetosheath momentum flux, to be transferred. We also find that considering all the flows, 17% of the tailward flows could be driven by the transfer of up to 4% of the magnetosheath momentum flux into the magnetosphere.

For mass transfer to be a viable means of driving the flow, the observed plasma sheet density must be at least the predicted density, such that $n_{pred}/n_{obs} < 1$. From Figs. 1e to 1h, we see that this is true for some of the events, including some of the reconnection-like flows. In particular, we note that it is true for some of the very slowest tailward flows. This effect could account for 27% of non-reconnection tailward flows (1f), 15% reconnection flows (1e) and 8% of the tailward flows with $n_{PS} < n_L$ (1h). All but two earthward flows (1h) could be consistent with mass transfer across the magnetopause.

6 Discussion

In this work, we have considered the difficulties of conducting a survey of the plasma sheet close to the magnetosheath. It has been demonstrated that by restricting the data set to either those events temporally close to the observed magnetosheath, or spatially close to the magnetopause orders the data in a similar manner. By ordering in this way, we recover the previous results (Slavin et al., 1985) that earthward flows are more likely to be found in the centre of the magnetotail (defined here as $>$60 min from a magnetosheath encounter, or having an aberrated Y position within 25 R_E of the tail axis). However, from this proximity analysis, it was not clear whether reconnection flows are more likely to be found in the centre of the tail or whether slow flows are more likely to be found at the edge. The data do suggest that observations where $n_{PS} < n_L$ may be more likely to be found close to the magnetosheath.

We also investigated how the data were ordered with respect to the AE index. We find that the slow flows are more likely to be observed during quiet times, and reconnection flows are more likely to be associated with active times. This result is consistent with Slavin et al. (1987). These authors also investigated the nature of the distant plasma sheet during active and quiet times (defined as above or below 100 nT). During high magnetic activity, Slavin et al. (1987) showed that within $|X| = 90$ R_E ISEE-3 observed northward magnetic field and earthward flows, consistent with the spacecraft being located earthward of a neutral line. Further tailward, the flows were mainly tailward and had southward B_z. During quiet times, tailward flow was normally found beyond 80 R_E, and the magnetic field was northward nearly everywhere. The flow speed at these times is about half that during high activity. This analysis also suggests that closed field lines are being dragged tailwards during quiet times.

Combining the spatial and temporal categorisation methods, we found that earthward flows tend to be located in the centre of the magnetotail and observed during quiet times. This is consistent with a distant neutral line being active for longer periods, when the near-Earth neutral line is not, and suggests that the distant neutral line is more active in the centre of the tail. This result is also consistent with slow, tailward flows driven along the flanks of the magnetopause by some viscous mechanism, returning towards the Earth in the centre of the tail.

Reconnection-like flows are more likely to be observed during active times, and in the central tail region. This is consistent with previous observations, suggesting that reconnection preferentially takes place in the centre of the magnetotail (Slavin et al., 1985). The flows with $n_{PS} < n_L$ are also preferentially observed during active times, but close to the magnetopause. If the plasma sheet and lobes are not magnetically connected, i.e. if the lobe field lines in this region are not undergoing reconnection to form the plasma sheet, we would not necessarily expect them to contain similar plasma. Also, during active times, dayside reconnection may continuously take place near the subsolar point, leading to field lines being steadily pulled into the magnetotail and added to the lobes. These lobe field lines connect out into the solar wind along the length of the magnetotail, such that solar wind plasma may enter the magnetotail along these field lines to form a relatively dense and extensive plasma mantle. This enhancement in lobe plasma may result in $n_L > n_{PS}$ along the flanks.

During quiet times, however, the open lobe field lines continue to be stretched down the tail. Since no more field lines are being added to the magnetotail as a result of subsolar reconnection, the magnetopause near the Earth will become locally closed. Over time, this closed portion will extend further down the tail. Hence, unless mass transfer takes place across closed magnetopause, we might expect the lobes to become less dense. Therefore, it is not unreasonable for the plasma sheet to be statistically more dense than the lobes at these times. It is also possible that any mass transfer mechanism across a closed boundary is more efficient into the plasma sheet, when Bz is northward.

The slow, tailward, non-reconnection-like flows are most likely to be found during quiet times. This is again consistent with their being driven by some kind of viscous transfer mechanism which may be more effective during northward IMF. However, we do not find that they are preferentially located along the flanks. In this study, they are slightly more likely to be found in the centre of the magnetotail.

When the data are ordered with respect to distance down the tail, we find that earthward flows are more likely to be found in the mid-tail rather than the distant (< -140 R_E) region. This is consistent with previous results from ISEE-3 and Geotail, suggesting that the preferential location for the distant neutral line is $\sim$ 100–140 R_E (e.g. Zwickl et al., 1984; Slavin et al., 1985; Nishida et al., 1996).

The analysis carried out by Owen and Slavin (1992), considering the possibility of mass and/or momentum transfer across the magnetopause, has been extended to the full ISEE-3 deep tail data set. In this study, we have considered the 480 5-min plasma sheet intervals that were temporally close ($<$1 h) to the magnetosheath.

In Fig. 1, we have ordered the data with respect to the observed plasma sheet velocity and classed the flows as $n_{PS} < n_L$ and $n_{PS} > n_L$ and reconnection-like, slow and tailward or earthward. Consider first the magnetosheath momentum flux across the magnetopause (Figs. 1a to 1d). We have found that momentum flux transfer across the magnetopause, with a 4% efficiency, is able to drive 40% of the

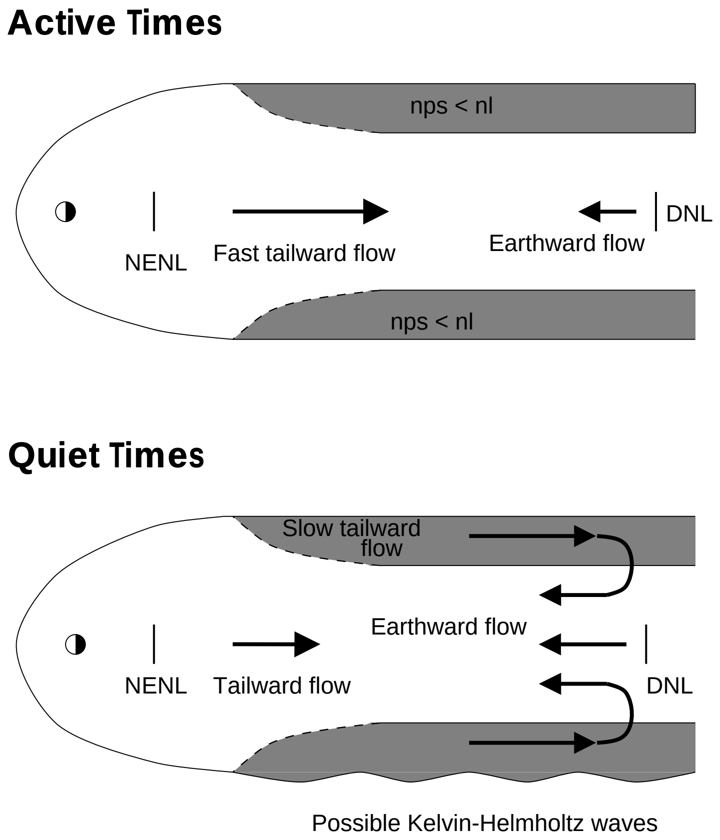

Fig. 2. Diagram of the magnetotail observed during geomagnetically active and quiet times. During active periods, reconnection takes place in the centre of the tail, earthward of 60 R_E. Along the flanks of the magnetosphere, $n_{PS} < n_L$, as would be expected if reconnection is not taking place in the plasma sheet in this region and if the magnetopause is open in the lobe region. During quiet times, earthward flows are seen more often, and we note they tend to be seen earthward of 140 R_E. Slow flows are seen across the tail. We find that 40% of the slow flows at the flanks could be driven by transfer of momentum across the magnetopause, by, for example, the Kelvin Helmholtz instability.

flows we have classified as slow. At higher tailward velocities, more magnetosheath momentum is required to drive the flows. Thus, the reconnection-like flows would clearly require any momentum transfer mechanism to be very efficient. These results extend the earlier results of Owen and Slavin (1992), where they found 6% of the magnetosheath momentum was sufficient to drive the flows observed in their case study. It has also been shown that up to 4% of magnetosheath momentum may occasionally be transferred by the Kelvin-Helmholtz instability (Miura, 1992). Many of the observations in our database are clearly within the range achievable by this mechanism. Therefore, it is possible that the Kelvin-Helmholtz instability could be a viable mechanism for driving the observed slow tailward flows. We also note that the slow flows were associated with lower geomagnetic activity. Low activity is also associated with northward IMF and the Kelvin-Helmholtz-like vortices are observed during prolonged periods of northward IMF on the dawn and dusk flanks (Chen et al., 1993; Seon et al., 1995; Fairfield et al., 2000). Although this is not strong enough evidence to link these observed slow flows with the Kelvin-Helmholtz instability, it does suggest that a more detailed investigation of boundary vortex observations in the deep tail could provide further information about momentum flux transfer across the distant tail magnetopause.

Consider now mass transfer across the magnetopause (Figs. 1e to 1h). Mass transfer is a feasible driving mechanism only for those observations in Figs. 1e to 1h that lie below the horizontal line, i.e. those with sufficient mass on the plasma sheet flux tubes. We find that the plasma sheet density observed during slow flow events is usually considerably lower than that necessary to drive the flows. Therefore, it is unlikely that the observed slow tailward flows in the distant plasma sheet are usually driven by a mass transfer mechanism.

Only the very slowest flows in our database satisfy the mass transfer criteria in the tail. This result is somewhat at odds with the suggestion by Fujimoto et al. (1998), that this is a viable mechanism for driving the slow flows observed in the near-tail. We also note that Fairfield et al. (2000) and Otto and Fairfield (2000) have suggested that mass may also be transferred across the magnetopause as a result of reconnection within the Kelvin-Helmholtz vortices. However, our analysis of the distant plasma sheet suggests that for the majority of slow plasma flows, momentum transfer is more likely to be the preferred driving mechanism. A study of the particle distributions observed in a large number of slow flow events will need to be carried out to conclusively answer this question.

In summary, the data presented here are consistent with a magnetotail structure dependent on activity level. In Fig. 2, we depict a diagram of the magnetotail, during active and quiet times. In active periods, reconnection takes place in the centre of the tail, in general earthward of 60 R_E. The flows close to the magnetopause during these periods tend to have $n_{PS} < n_L$, possibly due to reconnection taking place mainly in the central tail. The lobe and plasma sheet are not, therefore, magnetically connected in this region, but the open lobe-magnetosheath boundary may lead to enhanced $n_L > n_{PS}$. This also suggests that mass transfer into the plasma sheet does not take place across the magnetopause. Earthward flows are less likely to be observed, such that at these times, a near-Earth neutral line is dominant.

During quiet times, the picture is a little different. Earthward flows are now found in the central tail. This could be due to a quasi-steady distant neutral line tailward of the spacecraft and/or stirring from tailward viscous flows that would have to return earthward in the central tail where the viscous transfer mechanism is not strong enough to sustain the tension in the field lines. We also note that earthward flows are still found between 220 and 240 R_E, such that one, or both, of these processes must take place in the very deep tail.

Slow tailward flows are significantly more likely to be observed, both close to the magnetopause and in the central tail. It was seen that a substantial proportion (40%) of those on the flanks could be driven by the Kelvin-Helmholtz instability, whereas less than a third (27%) could be driven by a mass transfer mechanism. This suggests that the KHI is a more likely driving mechanism.

The diagram presented in Fig. 2 is different than that proposed by Nishida et al. (1998), who also discuss the configuration of the magnetotail in active and quiet times. They suggest that observations of tailward flows associated with the northward magnetic field in the distant tail, which appear consistent with tailward moving closed field lines, are, in fact, a consequence of tail twisting (Owen et al., 1995). Thus, these field lines could be open or connected at both ends into the solar wind. Although we agree that this is possible, we note that, particularly at the edge of the magnetotail, the observed flow speeds are significantly lower than reconnection predicts. Hence, although tail twisting may account for the apparent northward nature of some flux tubes, it does not explain their reduced flow speeds.

7 Conclusions

In this paper, we have investigated whether mass and/or momentum transfer across the magnetopause are feasible ways of driving the observed flows in the plasma sheet. The flows were categorised into 4 types: $n_{PS} > n_L$ and reconnection-like, slow and tailward, earthward or whether $n_{PS} < n_L$. In particular, we have considered whether these different types of flows are more likely to be driven by mass or momentum transfer.

In the distant tail, flows with $n_{PS} < n_L$ are observed more often close to the magnetopause during high geomagnetic activity. Earthward flows are more likely to be observed in the centre of the tail, during low activity and earthward of $-140\ R_E$. Reconnection-like flows appear to be found in the centre of the tail, during high activity periods. Slow, or non-reconnection tailward flows are more likely to be observed during quiet times. They are observed across the tail.

When we consider those flows observed temporally close to the magnetosheath, we find that the transfer of up to 4% of the magnetosheath momentum flux into the magnetosphere could drive 40% of the observed slow flows. We suggest that the Kelvin-Helmholtz instability, which may be capable of this degree of momentum transfer, could be responsible for driving these flows. We note that the slow flows have been associated with quiet periods of geomagnetic activity, which are, in turn, associated with northward IMF. The Kelvin-Helmholtz instability has also been associated with northward IMF. While magnetosheath plasma has occasionally been observed close to the magnetopause in the plasma sheet, we find that it could be responsible for driving $< 26\%$ of the observed slow flows in the distant tail. We suggest that if the non-reconnection-like tailward flows are indeed driven by a viscous-type transfer process, this is more often likely to be a momentum transfer process, such as the Kelvin-Helmholtz instability, than a mass transfer process.

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References

Bame, S. J., Anderson, R. C., Asbridge, J. R., Baker, D. N., Feldman, W. C., Gosling, J. T., Hones Jr., E. W., McComas, D. J., and Zwickl, R. D.: Plasma regimes in the deep geomagnetic tail: ISEE-3, Geophys. Res. Lett., 10, 912, 1983.

Berchem, J., Raeder, J., and Ashour-abdalla, M.: Magnetic-flux ropes at the high-latitude magnetopause, Geophys. Res. Lett., 22, 1189, 1995.

Chen, S. H., Kivelson, M. G., Gosling, J. T., Walker, R. J., and Lazarus, A. J.: Anomalous aspects of magnetosheath flow and of the shape and oscillations of the magnetopause during an interval of strongly northward interplanetary magnetic field, J. Geophys. Res., 98, 5727, 1993.

Coroniti, F. V. and Kennel, C. F.: Changes in the magnetospheric configuration during the substorm growth phase, J. Geophys. Res., 77, 3361, 1972.

Coroniti, F. V. and Kennel, C. F.: Can the ionosphere regulate magnetospheric convection?, J. Geophys. Res., 78, 2837, 1973.

Cowley, S. W. H.: Plasma populations in a simple open model magnetosphere, Space Sci. Rev., 25, 217, 1980.

Cowley, S. W. H.: The distant geomagnetic tail in theory and observation, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones Jr., vol. 30 of Geophys. Monogr. Series, 228–239, AGU, Washington, D. C., 1984.

Cowley, S. W. H. and Southwood, D. J.: Some properties of a steady state geomagnetic tail, Geophys. Res. Lett., 7, 833, 1980.

Fairfield, D. H.: On the structure of the distant magnetotail: ISEE3, J. Geophys. Res., 97, 1403–1410, 1992.

Fairfield, D. H., Otto, A., Mukai, T., Kokubun, S., Lepping, R. P., Steinberg, J. T., Lazarus, A. J., and Yamamoto, T.: Geotail observations of the Kelvin-Helmholtz instability at the equatorial magnetotail boundary for parallel northward fields, J. Geophys. Res., 105, 21, 159, 2000.

Fujimoto, M., Terasawa, T., Mukai, T., Saito, Y., Yamamoto, T., and Kokubun, S.: Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations, J. Geophys. Res., 103, 4391, 1998.

Mist, R. T. and Owen, C. J.: ISEE-3 observations of slow flows in the magnetotail plasma sheet, J. Geophys. Res., 104, 25 063–25 075, 1999.

Miura, A.: Kelvin-Helmholtz instability at the magnetospheric boundary - Dependence on the magnetosheath sonic Mach number, J. Geophys. Res., 97, 1, 1992.

Nishida, A., Mukai, T., Yamamoto, T., Saito, Y., and Kokubun, S.: Magnetotail convection in geomagnetically active times, 1, Distance to the neutral lines, J. Geomagn. Geoelectr., 48, 489, 1996.

Nishida, A., Mukai, T., Yamamoto, T., Kokubun, S., and Maezawa, K.: A unified model of the magnetotail convection in geomagnetically quiet and active times, J. Geophys. Res., 103, 4409, 1998.

Otto, A. and Fairfield, D. H.: Kelvin-Helmholtz instability at the magnetotail boundary: MHD simulation and comparison with Geotail observations, J. Geophys. Res., 105, 21 175, 2000.

Owen, C. J. and Cowley, S. W. H.: A note on current sheet stress balance in the geomagnetic tail for asymmetrical tail lobe plasma conditions, Planet. Space. Sci, 35, 467–474, 1987.

Owen, C. J. and Slavin, J. A.: Viscously driven plasma flows in the deep geomagnetic tail, Geophys. Res. Lett., 19, 1443–1446, 1992.

Owen, C. J., Cowley, S. W. H., and Richardson, I. G.: Properties of the geotail plasma sheet - theory and observation, in Magnetospheric Substorms, vol. 64 of Geophys. Monogr. Ser., 215, AGU, Washington, D. C., 1991.

Owen, C. J., Slavin, J. A., Richardson, I. G., Murphy, N., and Hynds, R. J.: Average motion, structure and orientation of the distant magnetotail determined from remote sensing of the edge of the plasma sheet boundary layer with E greater than 35 keV ions, J. Geophys. Res., 100, 185–204, 1995.

Raeder, J., Walker, R. J., and Ashour-abdalla, M.: The structure of the distant geomagnetic tail during long periods of IMF, Geophys. Res. Lett., 22, 349, 1995.

Richardson, I. G., Slavin, J. A., Owen, C. J., Cowley, S. W. H., Galvin, A. B., Sanderson, T. R., and Scholer, M.: ISEE 3 observations during the CDAW 8 intervals - Case studies of the distant geomagnetic tail covering a wide range of geomagnetic activity, J. Geophys. Res., 94, 15 189, 1989.

Seon, J., Frank, L. A., Lazurus, A. J., and Lepping, R. P.: Surface waves on the tailward flanks of the Earth's magnetopause, J. Geophys. Res., 100, 11 907, 1995.

Slavin, J. A., Smith, E. J., Sibeck, D. G., Baker, D. N., Zwickl, R. D., and Akasofu, S. I.: An ISEE 3 study of average and substorm conditions in the distant magnetotail, J. Geophys. Res., 90, 10 875, 1985.

Slavin, J. A., Daly, P. W., Smith, E. J., Sanderson, T. R., Wenzel, K. P., Lepping, R. P., and Kroehl, H. W.: Magnetotail configuration of the distant plasma sheet: ISEE 3 observations, in Magnetotail Physics, edited by A. T. Y. Lui, p. 59, Johns Hopkins Univ. Press, Baltimore, Md., 1987.

Zwickl, R. D., Baker, D. N., Bame, S. J., Feldman, W. C., Gosling, J. T., Hones Jr., E. W., McComas, D. J., Tsurutani, B. T., and Slavin, J. A.: Evolution of the earth's distant magnetotail - ISEE 3 electron plasma results, J. Geophys. Res., 89, 1007, 1984.