GEOPHYSICAL RESEARCH LETTERS, VOL. 12, NO. 10, PAGES 631-634, OCTOBER 1985

OBSERVATIONS OF FIELD-ALIGNED CURRENTS AT THE PLASMA SHEET BOUNDARY: AN ISEE-1 AND 2 SURVEY

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Abstract. Using ISEE-1 and 2 magnetometer data we have performed a survey of field-aligned currents at the boundary of the plasmasheet between 10 and 22 Earth radii down the magnetotail. Most cases are observed as the plasma sheet expands across the spacecraft. We find that the currents are most often observed flowing earthward throughout this region of the tail; however, a fraction of the cases correspond to tailward flowing currents and these tend to be found dawnward of midnight. Toward dusk no tailward currents are found. The currents at the plasma sheet boundary should map to the high latitude boundary of the auroral zone, and consequently one might expect them to have a Region 1 polarity; just the opposite is observed. Typical sheet current densities for these cases are roughly 5 mA/m.

Introduction

The boundary between the plasma sheet and the magnetotail lobes has long been recognized as a site of important plasma dynamics. Aubry et al. [1972] noted the dependence of boundary phenomena on quiet and disturbed conditions. Fairfield [1973] investigated the field-aligned currents at the plasma sheet boundary. More recently, researchers have reported high speed earthward and tailward plasma flows [Eastman et al., 1984], large amplitude electric fields [Cattell et al., 1982] and plasma waves [Parks et al., 1979, 1984], in addition to the field-aligned currents. Some have suggested that the plasma sheet boundary layer is the primary location for magnetotail dynamics; in the reconnection picture, this region maps to the vicinity of the tail neutral line. It also presumably maps to the high latitude boundary of the auroral zone, near where the large scale Region 1 current system flows [Iijima and Potemra, 1973]. Fairfield [1973] has presented some plasma sheet boundary data that are consistent with this system, but no survey of the high-altitude data has been performed. Such a survey of boundary layer field-aligned currents may shed light on how the magnetotail communicates its changes in configuration to the high-latitude ionosphere.

To study the overall characteristics of field-aligned currents at the boundary of the plasma sheet, our survey includes magnetometer data from ISEE-1 and 2 between 10 and 20 Earth radii down the magnetotail. At these intermediate distances we have attempted to sample the boundary layer currents as extensively in nighttime local times as possible, taking cases from -15 to +10 Earth radii in Ygsm. We include data from both the northern and southern lobes, so that asymmetries between north and south can be seen. We have confined our study to only the "outermost" field-aligned currents in the plasma sheet boundary, i.e., the currents observed closest to the lobe side of the boundary layer. Thus we are observing the currents which should map to the highest latitudes in the auroral ionosphere.

Paper number 5L6622
0094-8276/85/005L-6622$03.00

Selection of Cases

The primary data used in this study are the ISEE-1 and 2 magnetic field data. We have found that the plasma sheet boundary crossings are usually very conspicuous in the field data, consisting of a transition from quiet, steady lobe fields to turbulent, noisy fields in the plasma sheet boundary. This transition is usually accompanied by a diamagnetic drop in the field strength, indicating the $\beta \sim 1$ conditions in the plasma sheet boundary layer. While most boundary crossings can be identified this way in the field data, some may require concurrent plasma data in addition to be certain. A subset of our data, the cases from 1978, have been verified as crossings into the plasma sheet boundary layer on the basis of medium energy particle data (D. Mitchell, private communication, 1985).

Examples of boundary layer crossings are shown in Figure 1. The field data are in Geocentric Solar Magnetospheric coordinates. The Y component is thus roughly parallel to the magnetic equator and hence to the plasma sheet surface. The Z component is nominally normal to the plasma sheet surface, and the X component is roughly aligned with the background field. The ISEE-1 spacecraft passes from the northern lobe into the plasma sheet boundary at roughly 0222. At this time there is a dip in the field strength and a sudden excursion in +By, marking the passage of the spacecraft into the plasma sheet boundary layer. Once inside this region considerable field fluctuation is seen, mostly transverse to the background field. These variations can be attributed to sheets of field-aligned currents flowing within the plasma sheet. The spacecraft re-emerges from the plasma sheet boundary at about 0255, only to re-enter it again near 0315.

To place these events in context, we should note that ground magnetometer data show that substorms occurred near 0200 and 0310 [M. Lester, private communication, 1984]. It is likely that associated plasma sheet expansion and thinning were responsible for carrying the boundary across the spacecraft. The spacecraft was located dawnward of midnight, at (-13.1, -6.3, 3.2) Re in GSM coordinates.

We infer the polarity of the field-aligned currents using the knowledge of the boundary's trajectory relative to the spacecraft and the change in the vector field crossing that boundary. For example, the boundary crossing near 0222 is a crossing from lobe into boundary layer; the field

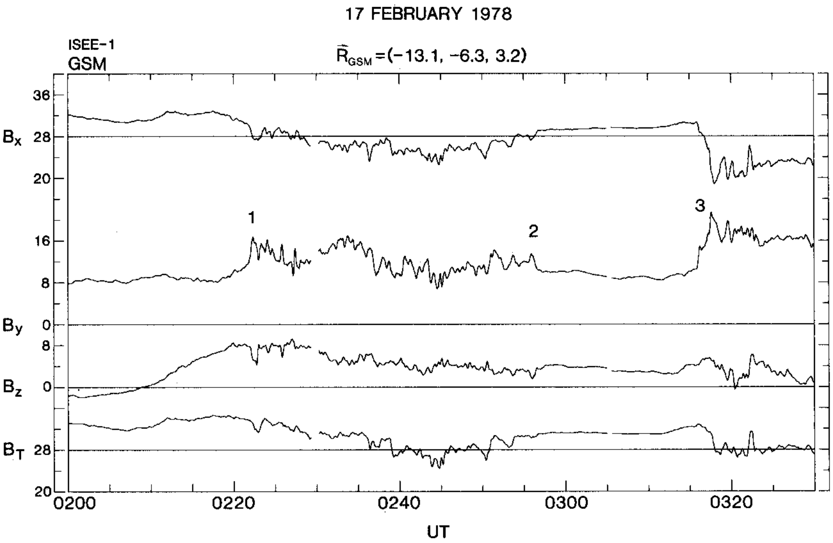

Fig. 1. Entries into and exits from the plasma sheet boundary layer as reflected in the magnetometer data of ISEE-1. The data are in GSM coordinates. Note the entry into the boundary layer at 0222, and the exit at 0257, followed by another entry at 0318. The entries and exits are accompanied by changes in strength, orientation and noise level of the magnetic field. The increase in By seen at the boundary layer entries corresponds to a sheet of field-aligned current flowing earthward.

in the lobe is mainly in the +Bx direction. As the spacecraft passes through the boundary layer current sheet the field rotates, as evidenced by the excursion in By, and decreases slightly in magnitude. It is trivial to show that for a one dimensional current sheet field rotations are due to field-aligned currents, while changes in field magnitude are due to transverse (in this case diamagnetic) currents. The maximum excursion of roughly 8 nT corresponds to a sheet current density of about 6 mA/m.

Ideally, it is possible with two spacecraft to determine the thickness and current density of plasma boundaries. In practice however this is rarely possible in the magnetotail because the ISEE-1 and 2 separation vector usually lies nearly parallel to the plane of the plasma sheet. To obtain velocities and thicknesses of the boundary, significant separations normal to the boundary surface are required. For this reason we decided simply to survey the equivalent sheet current polarities and intensities, which do not rely on the two-spacecraft analysis.

In our survey we sought events which unambiguously indicated entry into or exit from the plasma sheet boundary, and which also bore the signature of field-aligned currents (some boundary crossings do not show a field-aligned current signature; however, most crossings do). We classified each boundary crossing as an entry, an exit or a "mixture". By mixture we mean an entry into the boundary followed immediately by an exit; in this case we cannot be sure that the spacecraft fully penetrated the current sheet. For all cases we have calculated the polarity and magnitude of the sheet current consistent with the observed field changes.

Often the boundary crossing data suggest the presence of considerable current structure, and occasionally the strongest field-aligned current within the boundary layer is not the outermost (highest latitude) one. Study of the detailed field structure at the boundary on a case by case basis may well reveal a much more complex situation. Therefore we caution that the following results obtain for the simplest interpretation of the data.

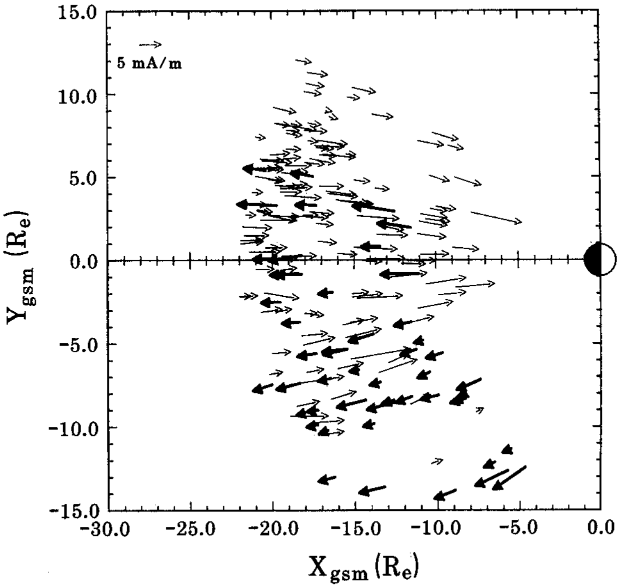

Fig. 2. The magnitude and direction of the field-aligned currents observed at the outermost edge of the plasma sheet, projected into the X-Y GSM plane. Cases from both the southern and northern lobe/plasma sheet boundaries have been included. Bold arrows denote tailward field-aligned currents, lighter arrows earthward currents. Note that the majority of cases are earthward flowing currents.

Results

Figure 2 shows the results of the analysis of 189 plasmasheet boundary crossings between 1978 and 1983. This figure shows the direction of field-aligned currents plotted as a function of position in the X-Y GSM plane. The tails of the vectors correspond to the spacecraft position. The polarity and magnitude of the currents are denoted by the direction and length of the vectors. Since no marked difference was found between the southern and northern lobe distributions, they have been merged in this figure. It is immediately apparent that the majority of the observed cases are earthward flowing currents, and that the only cases of tailward flowing currents tend to be found with increasing frequency toward dawn. One can also see the tendency for current intensities to be greater closer to the Earth, as would be expected qualitatively if the currents map along field lines.

In Figure 3(a) we show a histogram of the number of earthward or tailward polarity cases as a function of position in GSM Y. Once again, it is clear that earthward flowing currents are the most frequently observed overall, making up more than 70% of the total. Equally clear is the tendency for tailward currents to be found toward dawn. Figure 3(b) shows this distribution normalized to the total number of cases in each GSM Y bin, i.e., the fractional occurrence of each polarity. Even though there are fewer cases in the dawn sector, tailward currents tend to dominate those cases.

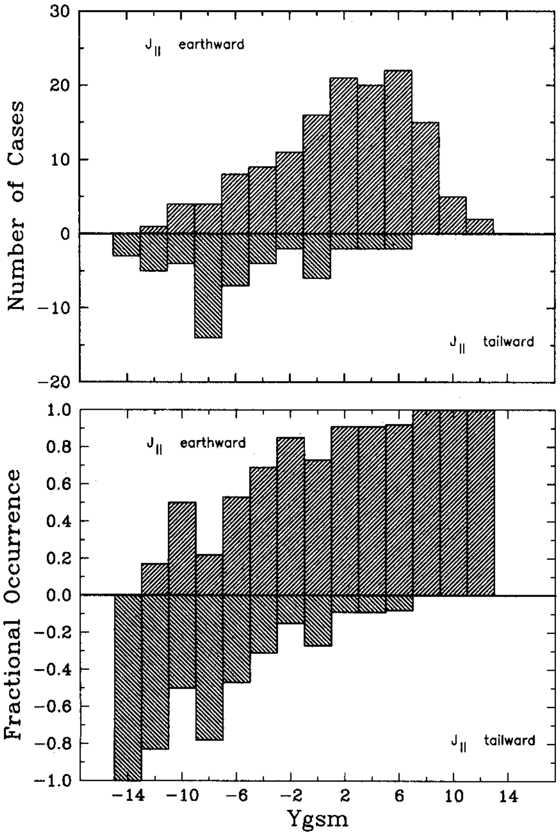

Fig. 3(a). Number of current cases of each polarity vs. GSM Y position. The tailward current cases tend to be found toward dawn, while the earthward current cases are found around midnight and toward dusk. (b) Fractional occurrence of each polarity vs. GSM Y position. The number of cases have been normalized to the total number of cases in the GSM Y bin.

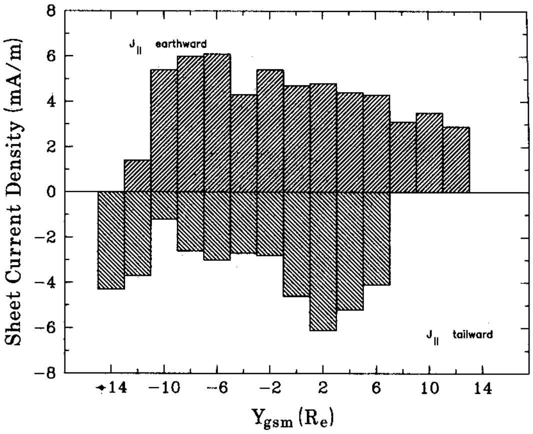

Fig. 4. Mean normalized sheet current densities vs. GSM Y position. The currents have been normalized to a 20 nT field.

Figure 4 displays the mean normalized sheet current densities binned as a function of GSM Y position. By normalized sheet current density we mean the value that would be observed when mapped to some reference field strength, in this case 20 nT. This normalization removes the sheet current variation due to convergence of the field lines. The figure shows that sheet current densities are typically 4 or 5 mA/m. There may be a slight tendency for the tailward currents to be weaker on average than the earthward currents. When mapped to ionospheric altitudes, these current densities are in the neighborhood of 200-300 mA/m, consistent with the inferred values of sheet currents at low altitudes [Sugiura et al., 1983].

Discussion

The most striking result of this survey is that the current polarities appear to oppose the Region 1 sense. This contradicts the results of Fairfield [1973], and runs counter to the idea that the spacecraft is ostensibly observing the highest latitude currents, those which should most readily be identified with the Region 1 system. There are several reasons why we may not necessarily observe the Region 1 sense. First, we are confining our attention to a single high-latitude current sheet which may very well be imbedded in the larger scale Region 1 system. Indeed, the low-altitude, near-midnight data of Sugiura et al. [1983] suggest that there is considerable small scale structure within the large scale systems, and it is often the small scale currents which dominate the local current density. As was seen in Figure 1, there is evidence for many field-aligned current sheets within the plasma sheet boundary layer; we are simply looking at the outermost (or highest latitude) one.

Second, we have assumed that the current sheets are simple tangential discontinuities whose surfaces are defined by the field rotation. If the boundary layer is instead the near-earth extension of a slow shock associated with the neutral line, the sense of field rotation is completely different. For an ideal slow shock, the field variation is contained in a plane normal to the shock surface. On the other hand, the expected slow shock orientations should yield a field excursion primarily in Bz GSM, not By as observed, so this interpretation seems unlikely.

Thirdly, this survey is by no means an exhaustive compilation of boundary field-aligned currents; we have attempted to cover as much local time range as possible, but this survey may not accurately reflect the true distribution of current polarity. Moreover, most of the boundary crossings occurred during a particular phase of magnetospheric activity, namely as the plasmasheet expanded across the spacecraft; the observed currents consequently tend to pertain to that phase.

It is tempting to infer global magnetotail dynamics from these current polarity results. For instance, one might expect the magnetotail lobe fields to respond to IMF By variations; the lobe field would be skewed in the +Y or -Y sense relative to the plasma sheet field. We have not undertaken a complete survey of IMF orientations corresponding to our boundary crossings, but a preliminary sampling shows no dependence of current polarity on IMF By. This must be examined more thoroughly in the future.

Other implications arise: the overall tendency to find earthward flowing currents in the dusk through midnight sector means that the plasma sheet field is sheared relative to the lobe field in the +Y sense in the north and in the -Y sense in the south. An opposite sense of shear is found in the midnight-to-dawn sector. This shear in the field may reflect a shear in the plasma flow of the boundary layer relative to the lobe. For example, localized boundary layer plasma flow toward midnight far downtail of ISEE would propagate a continuous shear Alfven wave earthward, with the boundary layer field having just the perturbation described above. Such plasma flow could be provided by localized reconnection near midnight far downtail.

There are many questions arising from these results: How are the energetic ion beams observed in the boundary layer related to the field-aligned currents there? Are cold ionospheric electrons the charge carriers of earthward currents in the outermost boundary of the plasma sheet? How do these currents map realistically to ionospheric altitudes, and how do they close? Finally, will a more comprehensive survey of the boundary currents continue to support the polarity reported here? Future studies using the full ISEE instrument complement may address some of these questions. Examination of high and low altitude field-aligned current signatures during times when ISEE and DE are in magnetic conjunction may also shed light on the magnetotail-ionosphere connection.

Acknowledgments. We thank Don Fairfield, Harlan Spence and Ray Walker for useful discussions. This work was supported by NASA grant NAS5-28448.

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(Received June 27, 1985;
accepted July 24, 1985.)