A Detailed Examination of a X-line Region in the Distant Tail: ISEE-3 Observations of Jet Flow and B_Z Reversals and a Pair of Slow Shocks

C. M. Ho, B. T. Tsurutani and E. J. Smith
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

W. C. Feldman
Los Alarms National Laboratory, Los Alamos, NM 87545

Abstract: Wc report an observation of I'c!schck-type magnetic reconnection at a distant neutral line (X= -230 R_e, July 8, 1983) with a full set of signatures of the magnetic merging process. These features include a reversal of plasma flows from earthward to tailward, a pair of slow shocks and the magnetic field X-type line. These two slow shocks arc shown to satisfy the shock criteria used by Feldman et al. [1987]. The spacecraft first crosses slow shock to enter the earthward flowing plasm ashcet with velocity of about 440 km/s. The embedded magnetic field has a positive B_z component. The spacecraft next enters a region of tailward plasma flow with speed -670 km/s and an embedded negative B_z, indicating entry into the plasmasheet tailward of the X-line. These observed velocities arc comparable to calculated velocities based on Rankine-Hugoniot conservation relationships. The spacecraft subsequently returns into the south tail lobe by crossing another slow shock. Coplanarity analyses show that the two slow shocks have orientations consistent with that predicted by the Petschek reconnection model. We note that this event occurs during northward interplanetary magnetic fields. "i'bus, a magnetic stress built-up in the distant tail may be responsible for this reconnection process.

Introduction

Magnetic reconnection in the earth's magnetic tail has been long suspected as being the source of energy for substorms and storms. Petschek's model has well described a magnetic merging process occurring at a X-type neutral line in the magnetic tail [Petschek, 1964; Sonnerup, 1979]. '1'here arc four slow mode shocks which bound a magnetic field directional reversal layer an d are connected together at the neutral line as shown in Figure l. Through this reconnection process, magnetic energy is converted into the plasma thermal and kinetic energies. "i'bus, jet-like hot plasma flows arc ejected from both sides of the merging region (scc Figure 1). Existence of slow shocks in the near-carlh tail and the distant tail (X < -200 R_e) have been confirmed by previous ISEE observations [Feldman et al., 1984, 19S7; Smith et al., 1984]. Tailward jetting in the distant tail (X< - 1 20 R_e) has also been detected [Zwickl et al., 19 S-1]. However, a full signature of the .X- line topology, slow shocks and jetting plasma flows has never been seen before in a single event.

Through a careful examination of ISEE-3 data **during** the distant tail passes, **wc** have found an event that clearly shows magnetic merging taking place. As we will illustrate, both earthward and tailward plasma flows on both sides of a neutral line arc found. We also determine that there is a pair of slow shocks bounding the plasmasheet. We believe this is the best documented case of magnetic merging in the geomagnetic tail found to date.

Instrumentation

The data for this study was taken during the second ISEE-3 distant tail pros. The magnetic field measurements were obtained by the Jet Propulsion laboratory magnetometer [Frandsen et al., 1978]. "This instrument measured 6 vectors per second. However, wc have used 30 second averages of the field data for this study to match that of the plasma data time average. The plasma observations presented here were obtained by the Los Alamos electron analyzer [Bame et al., 1978]. Two-dimensional electron clataarc intcgratccl ovcr*67.5° polar-angle intervals centered on the spacecraft spin plane, which is nearly coincident with the ecliptic. Although a complete spectrum was measured in 3 s, consecutive measurements were only taken every 12 s. We have constructed 30 s averages of the plasma data to improve statistical accuracy. The electron data wc usc in this study include the electron density N_e, temperature T_e and the two-dimensional plasma flow velocity V (V_x, V_y). The ion measurement part of the' instrument was not functional during tbc ISEE-3 distant tail passes.

Observations

Even though tailward plasma flow generally dominates **the entire distant** plasmasheet **in the** distant tail [Zwickl et **al,** 19S4], wc have found occasional cases of earthward flows that are associated with slow mode shocks in the region of $X < -200\ R_e$. One such example is given in Figure 2. During July 8, 1983, the spacecraft **bad a** GSE location X=-235.5, Y=10.8, Z=-8.5 R_e (X points toward the sun, Y is $\hat{\Omega} \times \hat{X}/|\hat{\Omega} \times \hat{X}|$, where $\hat{\Omega}$ is the north ecliptic pole, and Z forms the right-hand system). The spacecraft had a general motion from **the** south tail lobe into the plasmasheet and **thCn** returned back to the south lobe.

in Figure 2, from top to bottom arc the: electron density N_e, electron temperature T_e, plasma bulk velocity **components** V_x, V_y, and total plasma velocity V. ***Next*** arc **the three magnetic** field components, B_x, B_y, B_z **and the** total **magnetic** field strength B. Between **11:10 and** 12:20 UT, ISEE-3 **is** completely inside the south tail lobe. $\bar{N}_e$ is ~ 0.2 cm^{-3}, $\bar{T}_e$ **is** ~ 0.8×10^5 K, **and the** tailward plasma velocity $\bar{V}_x$ is ~ 190 km/s, $\bar{V}_y$ ~ 0. The magnetic field magnitude **is** intense, ~ **1 1.5** nT, and composed primarily of **a** B_x component (~ -11.0 nT on average), indicative of a south lobe field, At 12:20 UT the spacecraft partially enters the plasmasheet. There is an increase in N_e and T_e and there are significant fluctuations in plasma velocity. The magnetic field decreases by ~2 to 4 nT. However, the spacecraft does not completely enter the plasmasheet. Instead, it oscillates between the plasmasheet and the boundary layer. As shown in the plot, at 12:38 UT, ISEE-3 enters the lobe and at 12:47 UT reenters the plasmasheet boundary layer once again. At 12:55 UT the spacecraft first crosses a discontinuity (we will show it to be a slow shock later) to completely enter the plasmasheet. At this time, the magnetic field magnitude suddenly drops from 10 nT to 3 nT and $\bar{N}_e$ increases from 0.10 to 0.22 cm^{-3}. The temperature $\bar{T}_e$ also jumps from 0.7x 10^6 to 2.2x 10^6 K. The velocity $\bar{V}_x$ changes from a tailward direction into an earthward one (~ 400 km/s). The magnetic field B_x component becomes nearly zero. B_z has a significant positive component of 2.5 nT. These signatures are consistent with ISEE-3 entering the plasmasheet on the earthward side of the magnetic merging region. These features only last until 13:17 UT. Then T_e suddenly decreases to 0.7×10^6 K and N_e also decreases slightly. V_x reverses direction from earthward to tailward. Between 13:17 and 13:20 UT there is a 3 minute data gap. At about the same time, the magnetic field B_z component reverses direction from positive to negative, while B_x does not have any obvious change. This can be interpreted as a crossing of an X-type neutral line. ISEE-3 enters the tailward side plasmasheet after 13:22 UT. $\bar{N}_e$ is 0.25 cm^{-3} and $\bar{T}_e$ is 1.5×10^6 K. $\bar{V}_x$ is large with a tailward direction with a speed ~600 to 700 km/s, while the B_z reaches -1.9 nT on average. After 13:53 UT, ISEE-3 crosses another discontinuity (also a possible slow shock) and returns to the south lobe. T_e, N_e, **V**, and B all return to approximately their previous values noted at ~12:00 UT.

Slow Mode shocks

In order to confirm the presence of the two slow mode shocks, we use the magnetic coplanarity theorem and Rankine-Hugoniot relationships to examine the two discontinuities in detail. The same methods as used by Feldman et al. [1984 and 1987] will be applied here. To save space we will not state these procedures and criteria in this paper.

We first use the coplanarity relation [e.g., Colburn and Sonett, 1966] to calculate the shock normals. All measured parameters are listed in Table 1. They include the upstream average magnetic field B_u, downstream field B_d, and N_e, T_e, V_x, V_y and **V** for both the upstream and downstream regions, In this shock reference system, "upstream" is the tail lobe, and "downstream" is the plasmasheet. Both the upstream and downstream magnetic fields are rotated into a shock normal coordinate system [Colburn and Sonett, 1966]. Along the shock normals, there are significant B components (B_n = -0.93 ± 0.3 nT and 1.1 ±0.4 nT) across the shocks. The maximum errors in the magnetic field is derived from the standard deviations of the upstream and downstream field values.

In order to compare these observations with the Petschek model, we need to define some angles related to the magnetic field direction. Using Petschek's simplified slow mode shock model shown in Figure 1, we project the magnetic field and the shock normal into the x-z plane. The first angle is θ_{nz} which is the angle between the normal n and the z axis. $\theta_{nz} = \cos^{-1} n_z$. The second angle is ξ which is the angle between the shock normal in the x-z plane and the z axis. Thus $\xi = \tan^{-1} n_x/n_z$. If n_y is equal to 0, then $\theta_{nz} = \xi$. The third angle is η, which is the angle between the shock normal n in the x-z plane and the field B in the x-z plane. If both n_y and B_y are equal to O, then $\eta = \theta_{Bn}$, where η - $\cos^{-1} \bar{B}_{xz} \cdot \bar{n}_{xz} / |\bar{B}_{xz}||\bar{n}_{xz}|$. The fourth angle χ, lies between the magnetic field line in the x-z plane and the x axis. The angle χ is the acute angle of $(\eta - \xi)$. The above angles arc also listed in Table 1.

The first (entry) shock has a normal orientation consistent with the spacecraft crossings from the left-top quadrant to right-bottom quadrant in the schematic of Figure 1. The shock has an angle ξ_1 of 18.5° as shown in the Figure. So the shock surface should have an orientation from the left-bottom to right-top quadrant. Based on the magnetic field orientation, wc note that this shock corresponds to that of the left-bottom side of the Figure, because the shock normal points to the right-bottom direction. The magnetometer detects a positive B_z field after entering the plasmasheet from the south lobe, consistent with this scenario.

The second (exit) slow shock is consistent with the spacecraft going from the right-top to left-bottom quadrant of the Figure, because the shock normal points to the left-bottom direction. We thus identify this shock with a crossing of the type in the right-bottom side of the Figure. The angle ξ_2 between the shock surface and the x axis is 12.7°. "1'here is a slight asymmetry for both entry and the exit shocks, because there is little difference in the ξ angles. This difference is probably within the errors of the measurements.

We next use the Rankine-Hugoniot conservation relations to calculate the plasma flow velocity along the normal direction in the upstream region under the assumption of the conservation of B_n, mass, **tangential** electric field and momentum. All calculated speeds also arc shown in "1'able 1, which include the Alfven speed V_A, the Alfven speed in the shock normal direction V_{An}, the upstream plasma flow velocity along the normal direction (V_{un}) and the sound speed C_s. Here wc have assumed a 30 eV (GEOTAIL) upstream ion temperature [T. Mukai, private communication, 1994] because of the absence of ISEE-3 ion data. For both discontinuity cases, the plasma flow velocity along V_n is greater than C_s and less than V_{An}, as expected for slow mode shocks.

In the simple model of tail magnetic field reconnection proposed by Petschek [1964], slow mode shocks are important interfaces where magnetic energy from the magnetic lobe is converted into plasma kinetic and thermal energies in the plasmasheet. Using the model in Figure 1, the magnetic merging rule may be calculated. Based on the conservation of B_n and the tangential component of the electric field, assuming a steady state and frozen-in fields, Hill [1975] has obtained the downstream plasma speed:

$$V_{xd} = V_{Au} \cos\chi = V_{Au} \sin(\eta - \xi) \qquad (1)$$

Using the Alfven velocities V_{Au} listed in Table 1, we obtain an earthward plasmasheet V_{xd} of 640 km/s for the entry shock case, and tailward flow of 460 km/s for the exit shock case. The velocities are with respect to the shock reference frames.

Assuming conservation of mass flux, we may calculate the shock velocity in the x direction. The results show that for the entry shock, no significant shock motion is found. For the exit shock, we find a tailward shock motion with -180 km/s. Richardson et al. [1992] have also noted the presence of a background tailward plasma flow with a speed of 150 km/s. This should be superposed on to both plasmasheet velocities. Combining these velocities, finally, we obtain an earthward flow -490 km/s for the entry shock, and a tailward flow -790 km/s for the exit shock in the spacecraft frame. These values are comparable to the ob.served (spacecraft) flows of 439 km/s and 668 km/s, respectively.

IMF and Substorm Dependence

We have examined the IMF orientation (IMP-8) data around the time interval of the reconnection event (13:30 UT). There is a positive B_z component with average value -1.6 nT between 11:00 and 16:00 UT. There are no southward components in the 5 minute average during this interval. From 07:00 to 11:00 UT there is a four hour interval with a southward IMF B_z - -2.9 nT. However, because this southward IMF B_z occurred much earlier than the reconnection event, it seems unlikely to be physically related.

We have also examined the AE (aurora-electrojet) index to determine if the reconnection event caused a magnetospheric substorm. Between 11:00 UT and 16:00 UT, there are only two small substorms with the peak AE values (300 nT and 280 nT) at 13:00 and 13:20 UT, respectively. The distant tail reconnection event is time-coincident with the recovery phase of the second substorm. Because this substorm occurred prior to the reconnection event, it cannot be driven by the distant tail reconnection. There is no substorm with intensity > 100 nT for the next two and half hours following the reconnection event.

There has been prior evidence that distant tail magnetic field reconnection occurs during quiet intervals. Tsurutani et al. [1987] show that the large scale field variations with north-south signatures across the plasmasheet occur during all geomagnetic activity levels. Scholer et al. [1986] have shown a reconnection-like event at -140 R_e occurred during quiet geomagnetic conditions. These previous observations support our present findings of a lack substorm dependence and the presence of northward directed interplanetary magnetic fields during the reconnection event.

We should mention that around 12:30 UT there is a reversal of the IMF B_y component. The solar wind velocity was ~440 km/s at this time. Using this velocity, the convection time for the IMF B_y fluctuation to propagate to X=-230 R_e where ISEE-3 is located will take ~60 minutes. This is roughly time coincident with the reconnection" event. '1'bus, it is possible that the IMF B_y reversal may bc related to the reconnection event in the distant tail.

Summary

We report a Pclschck-type magnetic merging event occurring in the distant tail --230 R_e. The observations and calculated results are basically consistent with Petschek's simplified slow shock model. At the reconnection event time, a northward near earth IMF was noted and only minor substorm activity was detected. "I'his event may be simply clue to magnetic stress built-up in the distant tail during quiet time intervals.

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C. M. *110,* B. "1'. Tsurutani and E. J. Smith (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; Tel. 818-354-7894).

W. C. Feldman (Los Alamos National Laboratory, Los Alamos, NM 87545)

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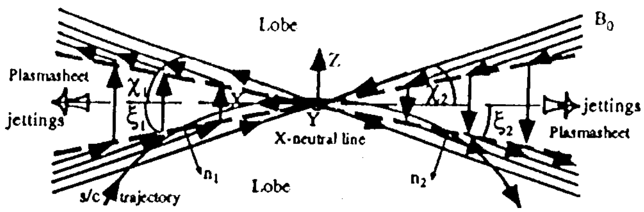
Table 1. Plasma and Magnetic Field Parameters Across Two Shocks

July 8, 1993	Entry Shock	Exit Shock
Upstream	12:47:30-12:50:00	13:58:00-14:01:30
Downstream	13:04:00-13:07:00	13:34:00-13:38:30
B_u	-9.4, 1.1, 1.4 nT	-10.6, 0.3, -1.2 nT
B_d	-2.1, -0.3, 0.8 nT	-2.8, -0.9, -1.9 nT
B_n	-0.9±0.3 nT	1.1±0.4 nT
n (n_x, n_y, n_z)	-0.13, 0.56, -0.S2	0.23, -0.19, -0.96
N_{eu}	0,10 cm^{-3}	0.20 cm^{-3}
N_{ed}	0.22 cm^{-3}	0.27 cm^{-3}
T_{eu}	0.7×10^6K	0.6×10^6K
T_{ed}	2.2×10^6K	1.7×10^6K
$V_u(V_x, V_y)$	149 (-147, 22)km/s	140 (-138, 20)km/s
$V_d(V_x, V_y)$	465(439, 152)km/s	680(-672,-99) km/s
θ_{Bnu}	81°± 9°	79°± 8°
θ_{Bnd}	71* 6°	51°± 9°
θ_{nz}	37"* 3°	17°± 2°
ξ	18.5°± 1.6°	12.7°± 1.5°
η	78°* 10°	73°± 9°
V_{Au}	738 km/s	561 km/s
V_{Anu}	140 ±15km/s	118 ± 19km/s
V_{flu}	117 ±12km/s	107 ±15km/s
C_{su}	108 km/s	104 km/s
M_{An}	04,3	0.90
β_e	0.04	0.04

Figure 1. A simplified Petschek's slow mode shock model which is perfectly adapted to this study. The spacecraft enters the central plasmasheet from the bottom south lobe. Then it crosses the neutral line and returns to the south **lobe.**

Figure 2. An event of crossings of the slow shocks, the jet plasma flows and the neutral line in the distant tail on July 8, 1983. From top to bottom are the electron density N_e, electron temperature T_e, plasma bulk velocity x component V_x, its y component V_y, and total plasma velocity V, three magnetic field components, B_x, B_y, B_z and the total magnetic field strength B.


Lobe
Z
B$_0$
Plasmasheet
jettings
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Lobe
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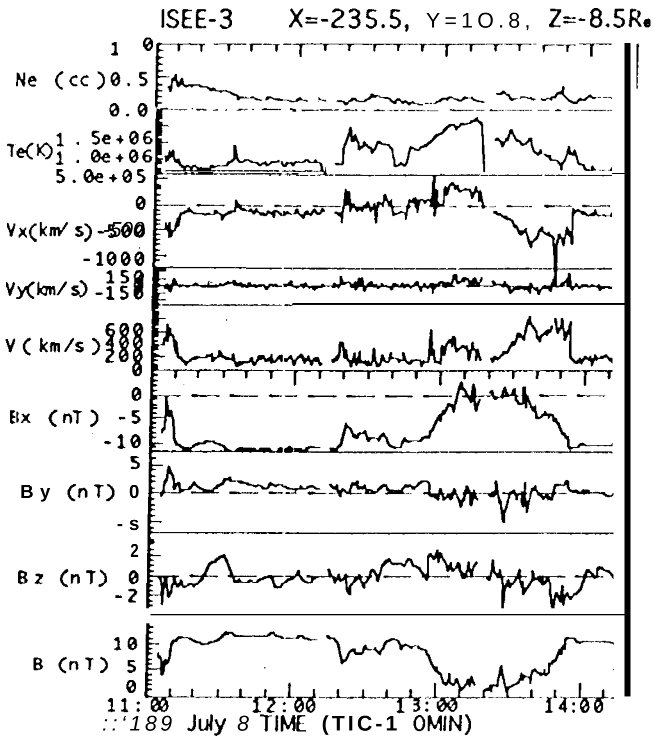
ISEE-3 X=-235.5, Y=10.8, Z=-8.5R
Ne (cc)
1.0
0.5
0.0
Te(K)
1.5e+06
1.0e+06
5.0e+05
Vx(km/s)
0
-500
-1000
Vy(km/s)
150
-150
V(km/s)
600
400
200
0
Bx (nT)
0
-5
-10
By (nT)
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