Distant Tail Plasma Jetting and B_z Properties at Slow-Mode Shocks: A Model of Reconnection During Northward IMFs

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To be Submitted to *Geophysical Research Letters*

April 22, 1995

Abstract Previous distant geotai studies find a difference i the locations where the plasma flow reverses direction ($x \approx -20\ R_e$) and where the magnetic field B_z reverses ($x \approx -200\ R_e$). These results raise some questions abou he standard Petchek reconnection model and its applicability. n this study, we use 66 slow-mode shock events to study he flow properties both earthward and tailward of he x-type neutral line. The location of he neutral line relative to the spacecraft is determined by: a) use of the measured slow-mode shock orientation, and b) he magnetic B_z polarity. We find that plasmasheet flow speeds downstream of slow shocks are similar, using either of the above two methods. On average, for events tailward of the neutral line, the tailward flow speed is statistically higher than for earthward cases by ~100 - 150 km/s. This is consistent with magnetic reconnection where jetting plasma flows of 50 - 75 km/s are superposed on top of a more-or-less continuous high speed tai ward convection flow of ~ 600 km/s. By examining the elationship between hese slow shock events in the distant tail and upstream IMF orientations, we also find that a significant amount (40%) of slow shock events occur during northward IMFs. Thus, we propose a distant ai model of reconnect on during northward IMF periods. Using this model and the standard substorm reconnection model (southward MF cases), we believe we can explain all observations n this paper.

Define IMF

INTRODUCTION

In the classical reconnection picture of e chek [1964], the plasma flow (jetting) earthward of the neutral line is toward he earth and the flow tailward of the neutral line is tailward. The magnetic field B_z ear hward of the neutral ine should be nort iward (positive B_z) and B_z tailward of the neutral ine should be southward (negative B_z). Iowever, the plasma and field observations do not yield such a simple picture [Zwickl et al., 984; Tsurutani et al., 1984; Slavin et al., 985; Heikkila, 988; Yamamoto et a ., 1994; Nishida et al., 1994]. Through statistical analysis of plasma data from ISEE-3, Zwick et a [984 found that within ~ -120 R_e. plasmasheet flows are eart iward, while beyond ~ - 20 R_e the flows are predominantly tai ward. The average flow speed also becomes progressively larger with increasing distances. On he other hand, statistical studies of ISE -3 magnetic field ıave shown ıat equally B_z north/south polarities are not reached until $x \approx -200\ R_e$ Siscoe et al., 1984; Tsurutani et al., 1984; Slavin et al., 1985]. To explain this nconsistency in the locations between he B_z and V_x reversals, Slavin et al. [1985] have proposed a parabola- ike curved neutral line model which starts from $x = \sim -140\ R_e$.

In recent GEOTAIL studies, Yamamoto et al. [1994] find that the typical B_z direction in the plasmasheet is northward even at distances beyond -1 50 R_e. Although the average B_z becomes small, it does not reach a negative value in the meridian (aberrated Y = O) plane. 'l'Hey conclude that their results are inconsistent wit h a curved neutral line as proposed by Slavin et al [1985j. Furthermore, the observations strew a large flaring angle Of magnetic field lines in the ecliptic plane. The authors have suggested that the field lines in the tail should connect at least partially with those in the magnetosheath across the magnetopause [Yamamoto et al.1994]. A viscous model [Heikkila, 1988], and IMF penetration models [Nishida et al., 1994; 1 yons et al., 1994] have also been used to explain the recent GEOTAIL observations.

In a recent study, Ho et al. [1994 and 1 995] identified 66 slow-mode shocks in the distant geomagnetic tail using ISEE-3 magnetic field and plasma data. Ho et al. [1994] shred an example Of a plasma flow reversal and a B_z reversal associated with a pair Of slow-mode shocks at - -220 R_e. These signatures are strong evidence Of distant magnetic reconnection. The event occurred during northward IMFs without concurrent substorms (AE < 100 nT).

In this paper, we will assume the Petchek neutral line mode] to examine its applicability towards tail observations during both substor In intervals and quid times. We will construct a model for reconnection during northward IMFs. We will study the properties of the. magnetic field B_z component and plasma flows for all 66 slow-mode shock events. Two methods (slow-mode shock orientations and downstream 1 B_z) will be used to identify the location Of the spacecraft relative to the neutral line for each event. The plasma flow speeds on either side of the neutral line will be examined statistically. We will also examine the IMF orientation dependence of slow-mode shock occurrence in the distant tail.] 'Ins]] y, we will propose a new model which incorporates the present and past observations.

DATA AND CRITERIA

In this study all of the slow-mode shock events from the t wo distant tail passes Of 1S1 ISEE-3 arc. used [Ho et al., 1995]. This interval of time is from January to July of 1983, where ISEE-3 was between X = -190 and -240 R_e. The magnetic field measurements were obtained by the Jet Propulsion Laboratory magnetometer [Frandsen et al., 1 978]. The plasma observations presented here were obtained by the Los Alamos electron analyzer [Bame et al., 1 978]. Two-dimensional electron data (no proton data are available) are measured in the spacecraft spin plain, which is nearly coincident with the ecliptic plain. "1'0

identify slow-mode slink' applying coplanarity theorem and Rankine-Hugoniot relations), we use 30 s average.s for both of the magnetic field and plasma data. To measure the plasma flow speed, V_x, and the magnetic field, B_z, in the plasmasheet downstream of slow shock, we use five minute averages of these. data. The electron data include the density, N_e, temperature, T_e, and the two-dimensional plasma flow velocity, V (V_x, V_y). The GSE coordinate system has $\hat{X}$ pointing 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 completes a right-hand system. We use five minute average magnetic field data (in GSM) observed by IMP-8 to identify upstream IMF orientation.

We have used a five-s{cp criteria to identify slow-mode shocks (Ibis is described in more detail in 110 et al. [1994"], and we refer the reader to this article). This criteria is similar to the method used by Feldman et al. [1987] in their study. Slow-mode shock normals are determined using the assumption Of magnetic coplanarity. For each case, we have used both plasma and magnetic field data and the Rankine-Hugoniot relations to ensure that the slow-mode shock conditions are indeed satisfied.

RESULTS

In this study, we assume that all slow-mode shocks result from Petchek's type. reconnection. Based on this picture we have employed two methods to locate the neutral line position relative to the spacecraft. They are the slow-mode shock orientations (method A) and magnetic B_z polarity downstream of the slow shock (method B). For a standard Petchek's picture, both methods should identify the same events. A slow shock with negative B_z in its downstream plasmasheet should have a tailward orientation relative to the neutral line, and vice. versa. For a statistic purpose, we have divided all 66 events into two groups, dc.pending on whether the slow shock (i.e., the spacecraft) is located earthward or tailward of the neutral line. Next, the plasma flow velocity in the plasmasheet downstream Of the slow shock for the events on both sides Of the neutral line are recorded.

Figure 1 gives the plasma flow speed distributions both earthward and tail ward Of the neutral line assuming the A method. Figure 1a shin's the V_x distribution for the 27 events which are earthward Of the neutral line. Plasma flow speeds for the.se events peak in the range Of -500 to -600 km/s. The other 39 events identified to be tailward Of the neutral line are shown in Figure 1b. The speeds for these events peak between -600 and -700 km/s. Excluding two positive V_x values [Ho et al.,!], the mean and median plasma flow speed V_x are -550 km/s and -520 km/s, respectively. For events tail ward of the neutral line,

for Earthward events

the mean and median speeds are -691 km/s and -670 km/s, respectively. Thus, the mean and median V_x values for events tailward of the neutral line are higher than for events earthward of the neutral line by ~-150 km/s. If we include the two earthward flow events, this difference in the flow speeds for two sides of events will become much larger.

Using method B to identify the relative location to the x-line, we divide the 66 slow shock events into earthward and tailward events, This is shown in Figure 2a and b. We find that there are 28 events having positive B_z (northward) near the slow shock. This implies that the spacecraft is earthward of' the neutral line based on the Petchek's model. The other 38 events should be located tailward of neutral line. In Figures 2a and 2b, we also find a velocity shift of -- 1 O() km for plasma flows between tailward and earthward events. Their mean and median value for events tailward and earthward Of the neutral line arc also shown in the plots. The negative B_z events have larger tailward plasma flow speed than positive B_z events. The difference is about -100--150 kin/s.

The two methods, A and B, agree 68% of the time as to the location of the spacecraft relative to the neutral line. The other 32% of the events which do not agree may have wave. perturbations upstream and downstream of the slow shock causing errors in their orientations. For example, an error in the normal magnetic field of ().3 nT may cause a :42.5° uncertainty in the shock orientation. Also because of the fact that the slow-mode shock normals are often close to 90(' (near the Z direction), a small error in angle may cause a shift from one side of the neutral line to the other. On the other hand, turbulence in the plasmasheet may affect the accuracy of B_z measurements in determining the location of the neutral line. Tail flapping and/or twisting may also al'feet the measurements of B_z to some extent.

Figure 3 shows plasmasheet flow speed V_x vs. the neat-car[]l substorm AE index. In panel 3a, we separate the plasmasheet magnetic field B_z northward polarities (triangles) from southward polarities (solid diamonds). A 30 min lag for the AE index relative to the V_x measure.mcnts is assume.d (other lags have been used with the same general resu] ts). We find that half of events (33 of 66 slow shock evs) ts occur during moderate or high geomagnetic activity intervals (AE > 250 nT). However, the two earthward plasma flow events (+ V_x) occur during northward IMF and magnetic quiet intervals. There is a Weak plasma flow speed dependence on AE, indicated by a linear regression line. The tailward speed increases with increasing, AE index from V_x = -500" km/s at AE = () nT, to V_x = -1003 km/s at AE = 1400" nT. The least-square-fit is with V_x = -0.4 AE -500.

The largest plasmasheet V_x C.veals (> 800 km/s) are almost all (1 1 of I 2 events) associated with negative plasmasheet B_z polarities. Of six events which occur during the largest AE (> 800 nT), five events have negative B_z, and three events are associated with high speed tailward propagating plasmoids. Because we almost always detect slow-mode shocks on the tailward side of the neutral line during the substorm intervals, Ibis suggests that the plasmoid may be Creating a distant neutral line dill'inp its tailward passage. We will discuss this later.

In panel 3b the events are separated by upstream IMF orientations (based on IMP-8 S-rein average observations). Unfortunately, 30 events have no IMF data available, so that the data base is small. For the remaining 36 cases, 2? events arc. associated with southward IMFs (solid diamonds), and 14 have northward IMFs (triangles). For the 14 northward IMF cases, on average, AE is - 137 nT and plasmasheet flow speed V_x is --429 km/s. For the southward IMF cases, the average AE is 344 nT, and V_x is -636 km/s. The results of panel 3b show that there ~~are~~ is a significant number of distant tail slow-mode shocks that arc associated with northward IMF orientations (40%) and arc not associated with near-car[b substorms (low AE). This feature has been noted previously (Feldman et al., 1985; }10 et al., 19941, but there has been no model to explain these observations. We will discuss a model in the next section Of thi S paper.

DISCUSSION

Based on our present results, we have obtained a general picture of magnetic reconnection in the distant geomagnetic tail. We find that 43% of the events (28 of 66 events) have northward (positive) B_z in the plasmasheet downstream of slow shocks, while the other 57% of events have southward (negative.) B_z. '1'bus, northward and southward magnetic B_z occurrence is nearl y equal at $x \approx -200\ R_e$ during sloil'-modc shock intervals. The average tail ward flow speed for events earthward of the neutral 1 ine is lower t han for events tailward of the neutral line by 1 00 - 150 km/s. This bidirectional jetting is superposed on top of a -600 km/s tailward steady stream. There is a significant number amount (-40%) of slow shocks which occur during northward IMFs.

We suggest t wo different models to explain the plasmasheet field B_z component and flow velocity observations in the distant tail. One model is associated with southward IMFs and the other with northward IMFs.

Southward IMF's: We adopt a near-earth neutral line model (similar to that proposed by Cowley [1984] and Richardson cl al. [1 989]) to explain the events that occur during strong substorms. This is shown in Figure 4a. Before the substorm, a distant neutral line. exists between -150 and -200" R_e. On both sides of the neutral line, the plasmasheet has opposite B_z polarities. After substorm onset, a closed-field plasmoid is formed from near-earth reconnection and is ejected towards the anti-solar direction. 'The distant neutral line which is at the tailward boundary of the plasmoid propagates with it at a speed of ~ -800 km/s. On the tailward side of the neutral line there is a negative B_z and high speed tailward flow, while on the earthward side, flows with a speed<800 km/s and positive B_z arc expected. After the substorm ends, the distant tail will return to the pre-substorm state (distant neutral line state).

Northward IMF's: In order to explain the significant occurrence. of slow shocks with negative B_z in the distant tail during northward IMF's, we propose a convected neutral line model in Figure 4b. Under northward IMF conditions, magnetic reconnection takes place at the dayside cusp region (point 1). This is similar to that of the model of Nishida et al. [1 994]. Inside the tail, the field lines cross both lobes and plasmasheet with their ends connecting to interplanetary space (point 2). Because the convection speed (-600 km/s) in the plasmasheet is larger than in interplanetary space (-400" to -500 kill/S), the field lines within the plasmasheet are convected in the anti-solar direction faster than in interplanetary space. Under certain condition, the field lines inside the plasmasheet eventually kink (point 3). Farther down the tail, a distant neutral 1 inc is formed with a magnetic flux loop tail ward of the neutral line (point 4).

In this northward IMF model, northward (positive) plasmasheet B_z field components and tailward V_x plasm flows dominate the distant tail plasmasheet. "'here are some southward (negative) B_z regions tailward of the neutral line (near point 4, inside the magnetic loop), but this is present for only a small fraction of the plasmasheet. The plasma jetting earthward of the neutral line will typically be overcome by a stronger tailward convection speed (~ 600 km/s). Thus we see a difference in the locations between V_x and B_z reversals and also the difference in the flow speeds between the events tailward and earthward of the neutral line as shown in this paper. Based on this northward IMF model, we expect primarily northward Bz occurrence in the distant tail. Slavin et al. [1985] and Heikkila [1988] have found that during relatively low AE, the plasmasheet fields are mainly northward. This is in agreement with our model. In addition, our mode] for northward IMF predicts a low

efficient rate of solar wind energy transfer to the magnetosphere. The plasma is primarily convected downtail in this model. This result is in agreement with the results of a recent study by Tsurutani and Gonzalez [1995].

Acknowledgments: The research conducted at the Jet Propulsion Laboratory, California Institute of Technology was performed under contract to the National Aeronautics and Space Administration. NRC acknowledgement

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Figure Captions

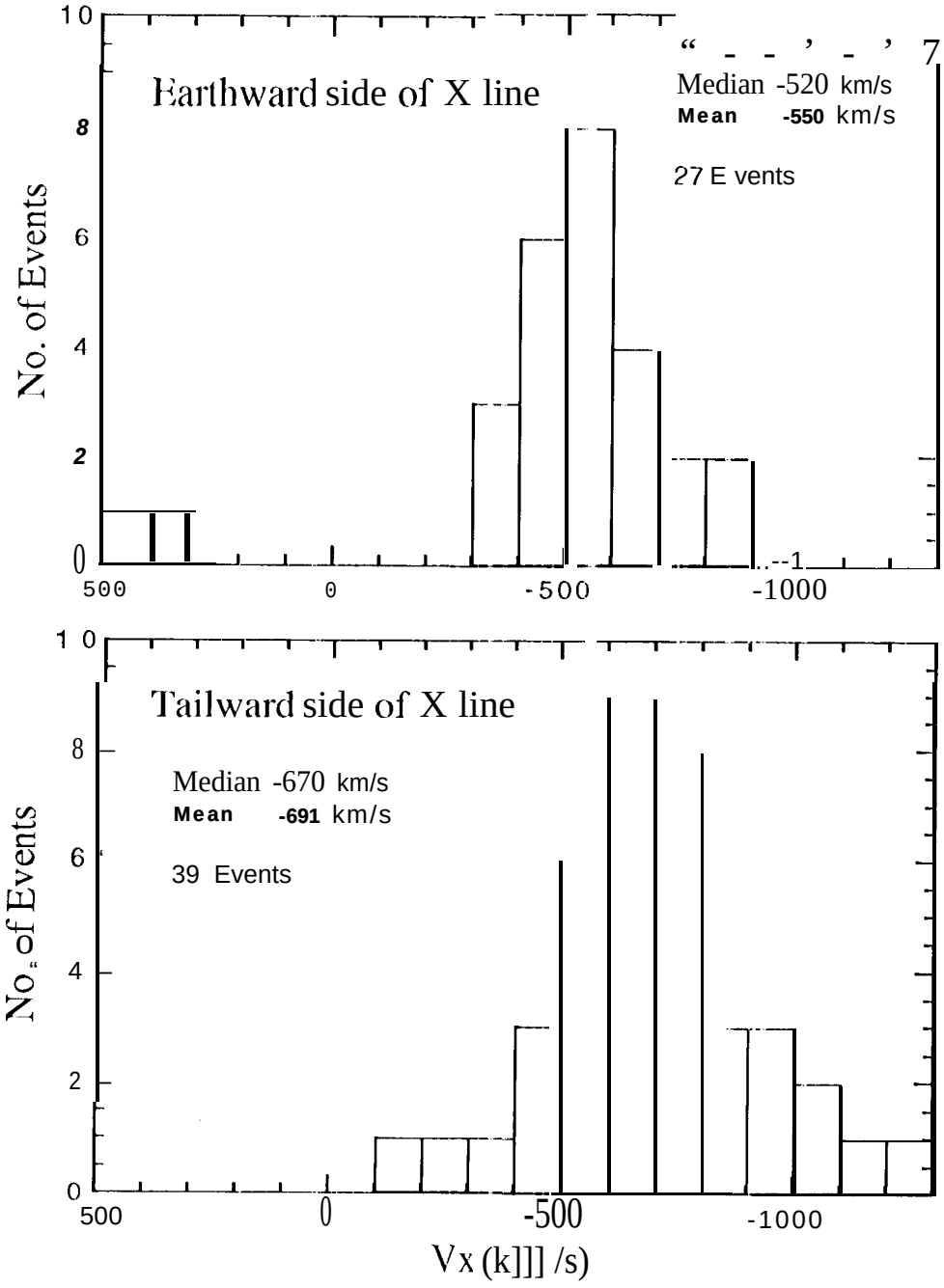
Figure 1. Distributions of plasma flow speeds downstream slow shocks. Based on the slow-mode shock orientation, 66 shock events are divided into two categories: earthward of the neutral line (a) and tailward of the neutral line (b). Earthward events have low plasma flow speed V_x, while tailward events have large tailward speed.

Figure 2. Distributions of plasma flow speeds downstream of slow shocks, but are classified by downstream magnetic B_z. Positive B_z (a) should be earthward of the neutral line, while negative B_z is tail ward of the neutral line. There is a difference of -100 km/sin the tailward plasma flow speed V_x between the two distributions.

Figure 3. Substorm dependence of plasma flow speed V_x in the distant plasmasheet. Data is separated by downstream B_z polarity in the distant plasmasheet (a) and by upstream interplanetary magnetic field orientation (b). The best fitting, equation and correlation coefficient are shown.

Figure 4. Tail ward convected distant neutral line models in a noon-midnight plane. (a) During southward IMF and magnetic substorm times, a tail ward propagating plasmoid released from the near-catlh reconnection will push the distant neutral line downtail at a speed -800 km/s. (b) During northward IMF and magnetic quiet times, a distant neutral line will be convected tailward at a speed of -600 km/s.

Distributions of Downstream Plasma Flow Velocities
in the Distant Plasmasheet Associated with Slow-mode Shocks



a)

b)

Fig. 1

Distribution of Downstream Tangential Plasma Velocity

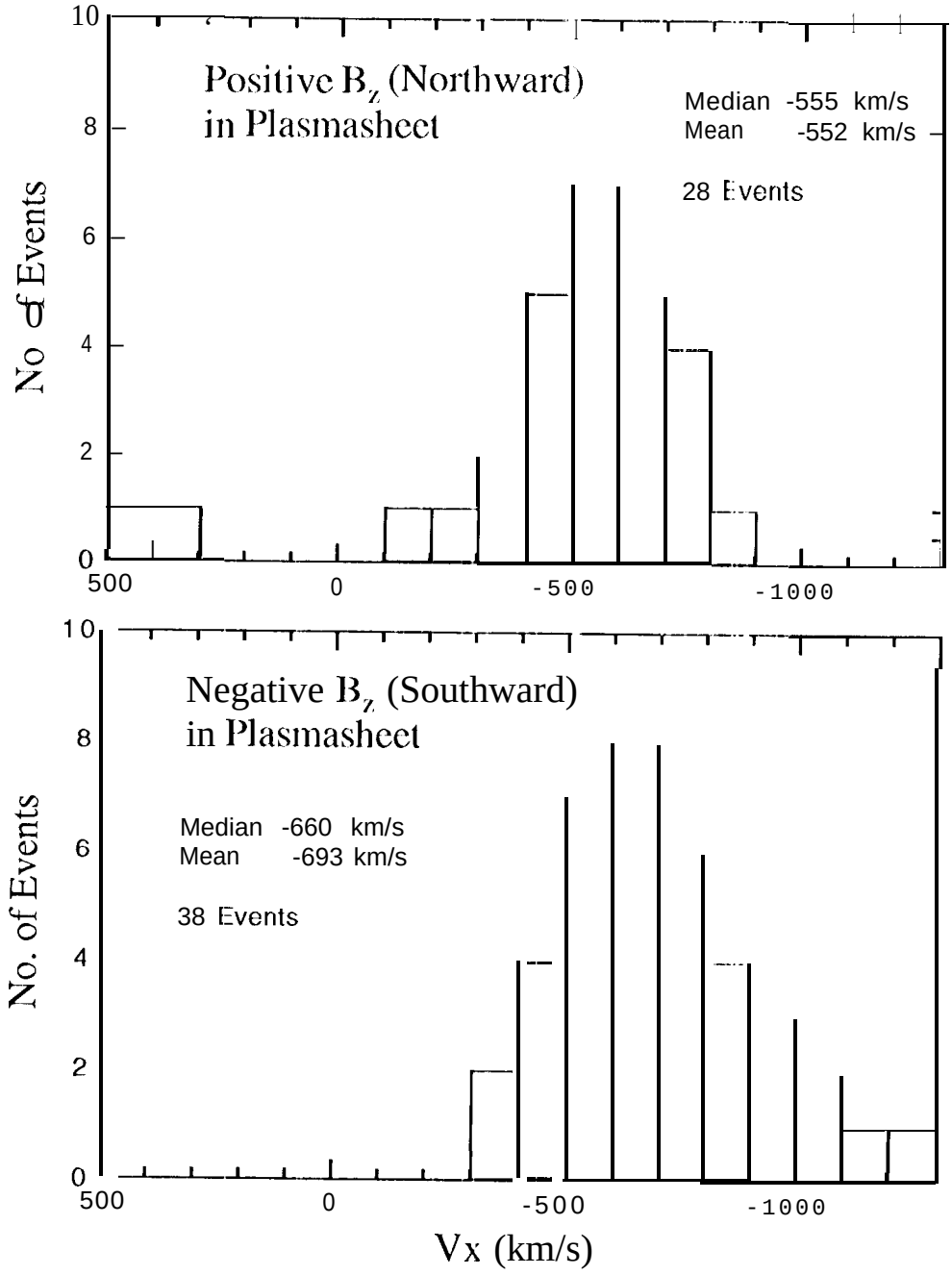


Fig. 2

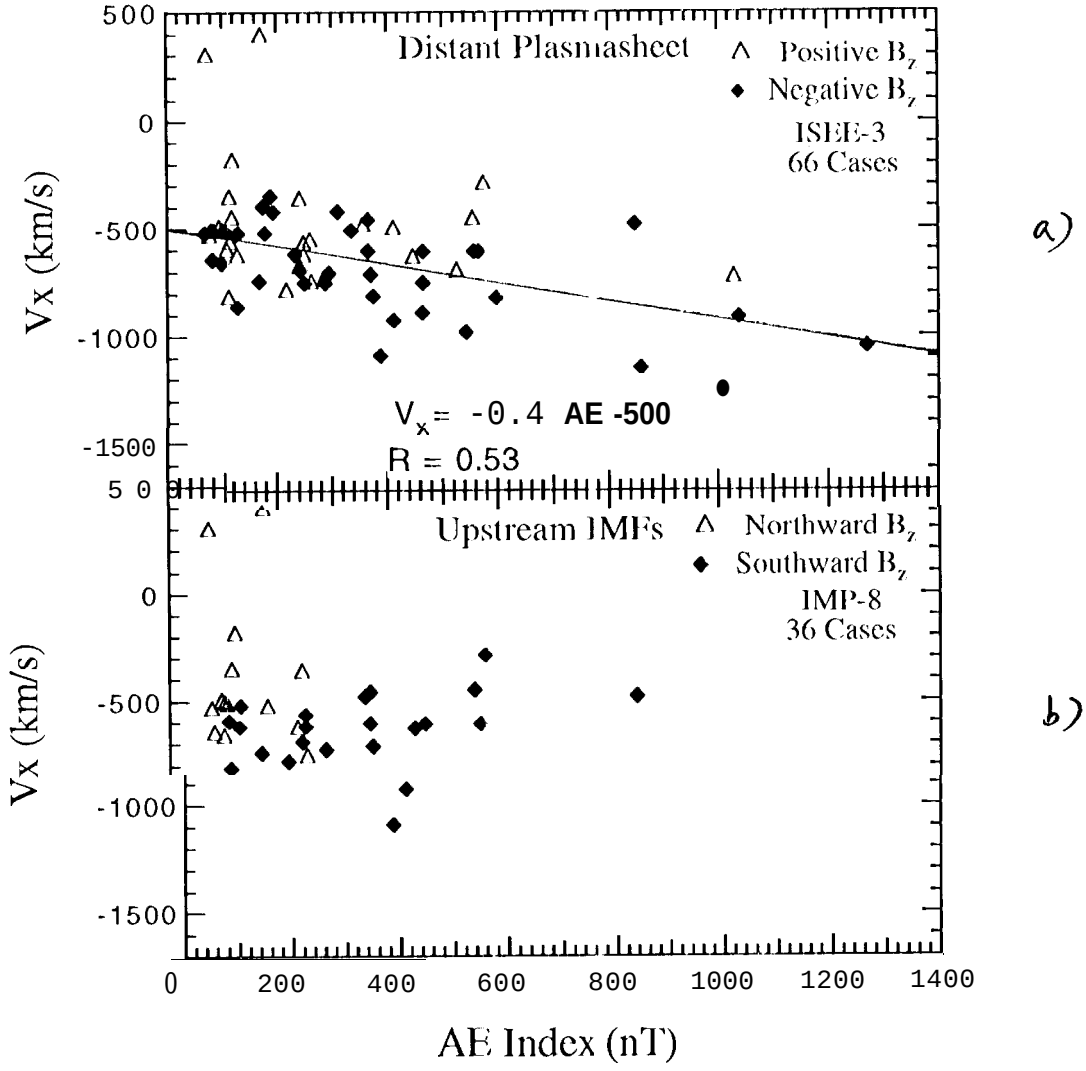

Distant Plasmasheet
Positive B_z
Negative B_z
ISEE-3
66 Cases
V_x = -0.4 AE -500
R = 0.53
Upstream IMFs
Northward B_z
Southward B_z
IMP-8
36 Cases
Vx (km/s)
AE Index (nT)
a)
b)

Fig. 3

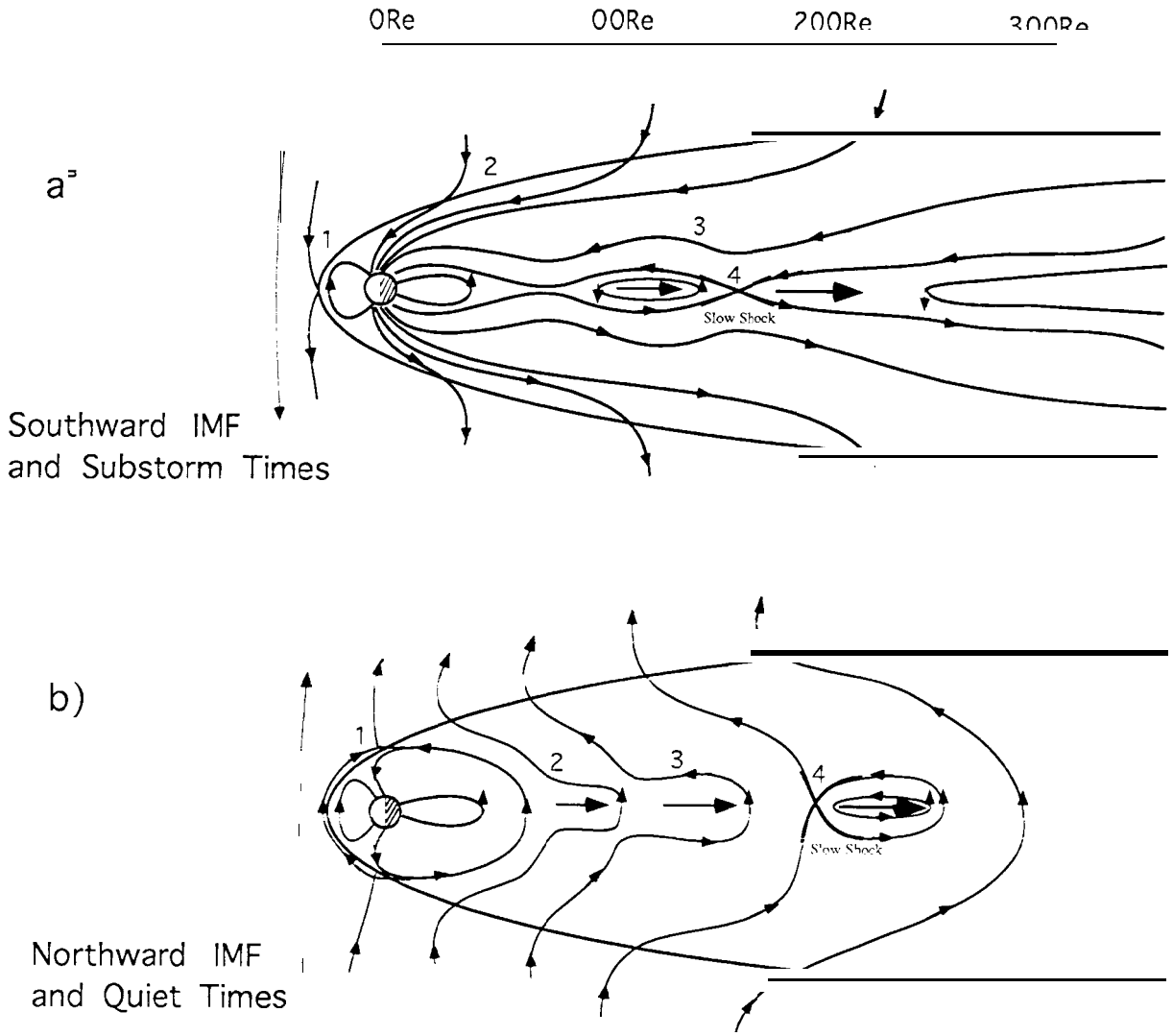

0Re
00Re
200Re
300Re
a)
1
2
3
4
Slow Shock
Southward IMF
and Substorm Times
b)
1
2
3
4
Slow Shock
Northward IMF
and Quiet Times

Fig. 4