ON ANALYSES OF SATELLITE ION SCALE RECONNECTION DATA

by F.S. Mozer(1) and C.M. Cully(2)
1. Physics Department and Space Sciences Laboratory
University of California, Berkeley
Berkeley, CA. 94720
2. Laboratory for Atmospheric and Space Physics
University of Colorado
Boulder, CO. 80303

ABSTRACT

Analyses of satellite-measured fields and flows through reconnecting current sheets have assumed that the relative velocity of the satellite and the current sheet is in the direction of the current sheet normal. During analyses, this relative normal velocity has been removed by translation of the satellite data. The assumption that the relative motion is along the normal may be invalid such that, in the satellite reference frame, the reconnection structure moves in the plane of the current sheet during the crossing. In this case, the fields and flows are not measured in the reconnection rest frame although they must be known in this frame for quantitative analyses of the reconnection data. Consequences of this slippage of the reconnection rest frame in the plane of the current sheet are investigated to show that errors may be large and that rotation (minimum variance, maximum variance, or Faraday Residue) or translation (to the normal incidence frame, the deHoffman-Teller frame, etc.) can exacerbate them. It is often the case that little can be done to guarantee a meaningful event analysis because of the insufficiency of the data collected in single satellite crossings of a reconnecting current sheet.

OVERVIEW

To assess the microphysics and determine the reconnection rate at a reconnecting current sheet, several vector components must be analyzed, including the magnetic field component normal to the current sheet, the electric field component tangential to the current sheet, the plasma flow into the current sheet from each side and the plasma outflow jet speed. To obtain these quantities, it is necessary to know the direction normal to the current sheet, which is typically computed by a minimum variance analysis of the magnetic field, a maximum variance analysis of the electric field, or a combined analysis of the two fields by the method of Faraday Residues (Sonnerup and Scheible, 1998 and references therein). Because the electric field and the plasma flow are frame dependent, it is necessary to transform the data from the satellite frame to the reconnection frame before or while performing these analyses. To do this, it is assumed that the relative velocity between the satellite and the rest frame of the reconnection geometry is in the normal direction and transformation of the data along this direction is accomplished as part of the above analysis.

Errors in these analyses arising from statistical fluctuations, lack of one-dimensionality, and lack of stationarity have been discussed (Sonnerup and Scheible, 1998 and references therein). However, significant uncertainties arise from an additional source which is associated with the assumption that the relative motion between the satellite and the reconnecting structure is strictly perpendicular to the plane of the current sheet. When there is relative motion in the plane of the current sheet, the fields and flows are not measured in the reconnection rest frame (the frame in which the X-line and the separatricies are at rest) although they must be known in this frame for quantitative analyses of the reconnection data. In this paper, for the first time, consequences of this slippage of the reconnection rest frame in the plane of the current sheet are investigated. It is easier to describe this problem than to deal with it because sufficient data to understand the orientation and motion of the reconnection rest frame are not generally obtained during a satellite pass through a current sheet and, absent this data, little can be done to prepare the data for quantitative analyses.

DISCUSSION OF THE PROBLEM

Consider data obtained at the magnetopause of Fig. 1, and assume that this data has been translated from the measurement frame to the magnetopause frame along the X-axis, which is the magnetopause normal. There is a tangential electric field, E_Y, so reconnection is occurring. The inflow speed of plasma and magnetic field lines is

$$(\mathbf{E}x\mathbf{B}/B^2)_X = E_Y B_Z/B^2 \qquad (1)$$

which is negative, as it should be, at the location of the electric field vector in the upper left portion of Fig. 1, because B_Z is negative. Now suppose that the data is transformed into a frame moving at speed V_0 in the +Z direction. In this new frame

$$E_Y' = E_Y + (\mathbf{V_0}x\mathbf{B})_Y = E_Y + V_0 B_X \quad . \qquad (2)$$

The second term of equation (2) is negative because B_X is negative in the upper left portion of Fig. 1, so the tangential electric field is smaller in the transformed prime frame. Also

$$(\mathbf{E}'x\mathbf{B}/B^2)_X = E_Y B_Z/B^2 + V_0 B_X B_Z/B^2 \qquad (3)$$

so the plasma and magnetic field inflow speed of equation (3) is reduced relative to that in the unprimed frame because the second term of equation (3) is opposite in sign to the first term. Furthermore, the plasma outflow speed in the Z-direction in the prime frame is decreased by the amount V_0. Thus, all estimates from data in the transformed frame indicate a diminished reconnection rate. Or, if V_0 is large enough, the tangential electric field and all estimates of the reconnection rate may be made equal to zero (this is the deHoffman-Teller frame) or they may even be made negative such that, in the transformed frame, particle energy is converted to magnetic field energy at this location. How is it that all indications of reconnection with its associated conversion of electromagnetic energy to particle energy can be diminished, turned off, or even reversed simply by viewing the situation in a different frame?

The resolution of this apparent paradox can be found by considering measurements made in the lower left portion of Fig. 1 in the prime frame. At this location, the signs of all quantities in equations (1) through (3) are unchanged except for B_X, whose sign is now positive instead of negative. Thus, the measured tangential electric field, the inflow speed and the outflow jet speed that would be measured in this frame are all increased at this location below the X-line, which compensates for the decreases above the X-line. Viewing the problem in the moving frame makes the reconnection geometry asymmetric such that reconnection occurs mostly below the X-line of Fig. 1. Thus, deducing global properties of reconnection from a local measurement requires that the measurement be in the rest frame of the current structure. Whether this requirement is met in a given satellite measurement is not generally known.

The above discussion was given in terms of electric and magnetic fields but it is equally valid in terms of plasma flow and magnetic field measurements. In fact, considering the above discussion in terms of plasma flow instead of electric fields, leads to a second apparent paradox. How is it that adding a velocity in the Z direction can change the inflow velocity in the X direction? From addition of velocities, it seems that this cannot happen, even though it does. What is wrong here?

Fig. 2 discusses the above situation in terms of vector addition of velocities. In part (a) of this figure, the velocity, $-V_0$, that is added to all particles in the prime frame, is broken into components parallel and perpendicular to **B** to show that there is a component of V_0 perpendicular to **B**. This perpendicular component is broken into its parts in the X and Z directions in part (b) of this figure. In part (c), the parallel component is also broken into its components in the X and Z directions. It is seen that, although $V_{0\perp X}$ is non-zero, it is equal and opposite to $V_{0\parallel X}$ such that V_0 does not have a component in the X direction but it does a have a component that is perpendicular to **B** in the X direction. From the geometry of Fig. 2,

$$V_{0\perp X} = V_0 B_X B_Z / B^2 \qquad (4)$$

which is exactly the amount by which $(\mathbf{E}'\mathrm{x}\mathbf{B}/B^2)_X$ differs from $(\mathbf{E}\mathrm{x}\mathbf{B}/B^2)_X$ according to equations (1) and (3). Thus, as expected, it is immaterial whether one considers reconnection from the point of view of electric fields or flows because they are equivalent in the ideal MHD regime, provided that the perpendicular component of the flow is considered. It is also noted that the expression for the transformation of the electric field to a moving frame has been obtained in Fig. 2 from purely geometric considerations. The summary of these discussions is that it is incorrect to analyze the data in a frame that is different from the rest frame of the X-line.

Adding a velocity in the Z-direction modifies the fields and flows because of the non-zero B_X component. If the magnetic field was in the Z-direction, then $\mathbf{V_0}\mathrm{x}\mathbf{B}$ would be zero, and none of the above effects would occur. Thus, for strictly planar geometries (such as an idealized bow shock) the above discussion does not apply.

To further discuss the problems associated with the analysis of satellite reconnection measurements, imagine that we are looking down on a crossing from afar and we see that the satellite crosses the magnetopause along the trajectory illustrated in Fig. 3. The unfortunate scientist who analyzes this data does not know the spacecraft trajectory and does not know that the true normal component of B is different at positions 1 and 2 because it increases with distances from the X-line, so he performs a minimum variance analysis to make B_X at positions 1 and 2 approximately equal. This approximate equality is a mathematical property of the minimum variance technique, independent of the data that is analyzed. However, the unfortunate scientist who does the minimum variance analysis finds a normal to the magnetopause that is different from that which we viewers from afar know to be the true normal and this is in spite of the fact that his minimum variance analysis may produce good eigenvalues (as discussed below). So he thinks that he has solved one problem (not knowing the normal direction) while actually creating another (rotating to a frame that is not normal to the magnetopause).

We viewers from afar know that the trajectory of Fig. 3 was at an angle to the magnetopause normal because the rest frame moved in the Z-direction relative to the satellite during the crossing. Thus, we viewers from afar know that the unfortunate scientist's estimates of the reconnection rate, etc. will be wrong because his data is not in the rest frame of the magnetopause. To overcome this problem, why shouldn't the unfortunate scientist transform to the magnetopause rest frame before analyzing his data? This does not work for two reasons:

1. The unfortunate scientist does not know the sign or magnitude of the required transformation velocity.
2. Even if he knew the transformation velocity it would do him little good because he needs data at points 2 and 3 of Fig. 3 to estimate reconnection parameters and he has data only at points 1 and 2. Said differently, the transformation does not change the magnetic field so the unfortunate scientist is still faced with the problem that he does not have enough data to find the normal direction and to test whether B_X is the same on both sides of the magnetopause.

The conclusion of this analysis is that it is generally incorrect to do a minimum (or maximum) variance analysis of data or to translate it into a frame moving in the plane of the current sheet. One may then ask what the unfortunate scientist can do with his satellite data.

The only thing that he can do is rotate the measurements into the <u>correct</u> frame having the X-component normal to the magnetopause and to then observe whether B_X and E_Y are essentially constant and small as they are in a static two-dimensional model of the current sheet. If they are, the data may be argued to be in the rest frame of the magnetopause and further analyses are warranted. If they are not, there is nothing more that can be done with this magnetopause data, so the unfortunate scientist should move on to the next event.

The only thing wrong with this prescription is that the unfortunate scientist needs to know the correct direction of the magnetopause normal. Two possible ways in which he can check his normal are:

1. Multi-satellite timing analyses give the direction of the normal to the magnetopause motion under certain assumptions (often: planarity and constant velocity). If these assumptions are valid, the timing analysis can be used to infer the normal vector.
2. The normal direction may be inferred from a model. As an example, the GSE X-direction may be assumed to be the magnetopause normal for a sub-solar reconnection event.

It is emphasized that the errors that arise in the analysis of satellite data when the frame geometry and motion are not known can be significant. For example, suppose that the normal magnetic field is 5 nT and the frame speed in the plane of the current sheet is 200 km/sec, which is a typical magnetosheath flow speed and a fraction of the typical Alfven speed at the sub-solar magnetopause. For this case, the observed outflow jet speed will be greater or less than the expected Alfven speed by a significant fraction of the Alfven speed, and the tangential electric field will be wrong by 200 km/sec times 5 nT or 1 mV/m. Because the average tangential electric field was 1.2 mV/m in a data set involving 22 magnetopause crossings, (Mozer and Retinò, 2007) the frame motion uncertainty in this example produces a nearly 100% error in the estimated reconnection rate.

ANALYSES USING SYNTHETIC DATA

The error resulting from the frame translation can be quantified by analyzing synthetic data generated from a reasonable field model. The magnetic field lines in Fig. 4 were traced using the current sheet model

$$B_X = B_{X0}*\tanh(z/L_Z) \quad (5)$$

$$B_Y = B_{Y0} + B_{Y1}*\sinh^2(x/L_X) \quad (6)$$

$$B_Z = B_{Z0}*\tanh(x/L_X) \quad (7)$$

where B_{X0} = -5 nT, B_{Y0} = 10 nT, B_{Y1} = 2.5 nT, B_{Z0} = -30 nT, L_X = 2 and L_Z = 20. The length scale for L_X and L_Z is arbitrary, but is scaled so that one unit is roughly one ion skin depth, or 100 km. For the following analysis, additional Gaussian noise is also included with RMS amplitude of 0.01 nT. Note the different scales on the axes in Fig. 4.

The fields measured while flying through such a current sheet depend on the trajectory. Two sets of five trajectories each are analyzed. The upper set of five trajectories begins at a geophysical distance of about 0.5 R_E from the X-line with the first trajectory being horizontal across the magnetopause and the fifth trajectory crossing to the opposite side of the magnetopause, such that B_X changes sign. The lower set of five trajectories begins at a geophysical distance of about 1 R_E from the X-line. The inclination of the trajectories depends on the ratio of the velocity components in the X and Z directions; values of V_Z/V_X of 0, 3, 6, 9 and 12 are shown for both sets.

Magnetic field components measured on the upper five trajectories are given in Fig. 5a while the fields found along the lower five trajectories are given in Fig. 5b. Magnetic field components in the X,Y,Z frame are given in the left panels of these figures where, as shown in Fig. 4, X is the correct normal direction and Z is the direction of the reconnection magnetic field. The right panels of these figures give the magnetic field components in the minimum variance frame, L, M, N. As is expected for minimum variance analyses, B_N is essentially constant along a single trajectory with values that vary over a factor of about three from trajectory to trajectory, depending on their inclinations. Meanwhile, the true normal magnetic field, B_X, varies considerably along most trajectories. In Fig. 5a, B_X changes sign along the extreme trajectories because they crossed to the opposite side of the X-line, while B_N is still approximately constant.

Minimum variance analyses performed on the data collected along the upper trajectories in Fig. 4 yield a wide range of normal vectors. The direction inferred from the $V_Z = 0$ data is nearly perfectly aligned with the X axis (0.01 degrees error), while the more inclined trajectories disagree substantially: errors of 5.26, 25.5, 41.1 and 34.5 degrees respectively for the upper trajectories. Importantly, the eigenvalues from the minimum variance analyses do not deteriorate significantly for the large-error cases. Even for the most-inclined of the five upper trajectories, the eigenvalues are well-separated (300, 0.50, 0.0013). Thus, the minimum variance analysis offers no intrinsic clue that something is wrong.

For small speeds, V_Z, minimum variance analysis is somewhat more accurate in determining the normal vector for the lower five trajectories in Fig. 4 (fields in Fig. 5b). Errors for these five trajectories are 0.007, 0.43, 3.9 22.1, and 60.0 degrees respectively. Again the eigenvalues are well-separated, even for the trajectories with large errors (470, 1.8, 0.2 in the worst case), and offer little clue that the normal direction is poorly determined.

The magnitude of the error in the minimum variance normal direction depends on the field model. In particular, the error only becomes severe if the parameter B_{Y1} (which parameterizes the departure from a strictly unidirectional current) is comparable to or greater than the parameter B_{X0} (which parameterizes the normal field). In the extreme case, $B_{Y1} = 0$, the minimum variance analysis breaks down for all possible trajectories due to colinearity of the difference vectors (see Sonnerup and Scheible, 1998). Many magnetopause crossings may exhibit a relatively large core field B_{Y1} (e.g. Fig. 9); the minimum variance normal vector for these cases may be relatively accurate. However, the minimum variance normal should not be trusted from crossings with a roughly unidirectional current (e.g. Fig. 7).

The electric field observed along the trajectories of Fig. 4 depends on both the true electric field in the magnetopause rest frame and the induced electric field due to the frame translation. Both of these fields are included in the synthetic data of Fig. 6. A typical normal velocity component, $V_X = 20$ km/s, has been assumed, plus a constant reconnection field E_Y with a value of 1.2 mV/m (Mozer and Retinò, 2007). V_Z has been chosen to give the same trajectories as in Fig. 4: (0, 60, 120, 180, 240 km/s). The solid line in Fig. 6 is the electric field E_M in the computed minimum variance analysis M-direction (tangential), and the dashed line is E_M after correcting for the V_X translation. As expected, the analysis works perfectly for the least inclined trajectory having $V_Z = 0$. After correcting for the normal motion, the "measured" electric field is a constant 1.2 mV/m. In contrast, the more-inclined (larger V_Z) trajectories show systematic errors of several mV/m for both sets of trajectories. These errors arise from both the misalignment of the normal vector and the induced field from V_Z. The result is that the tangential electric field in the minimum variance frame differs from the true field by factors as great as three, depending on the inclination of the trajectory and distance from the X-line.

In summary, there are several salient conclusions from the experiments using synthetic data:

1. In reconnection geometries, the normal vector from the minimum variance analysis may differ substantially from the true normal direction.
    a. The disagreement is most pronounced when the core field is comparable to or smaller than the asymptotic normal field.
    b. In this geometry, the eigenvalues of the minimum variance analysis offer little indication of the error in determining the normal direction.
2. Motion of the X-line in the plane of the current sheet can induce substantial and systematic errors in the observed reconnection field, E_M.
    a. A misaligned normal direction (e.g. from the minimum variance technique) can give rise to an offset in E_M.
    b. The field induced by the X-line motion, V_Z, gives rise to a systematic error in E_M that varies across the sheet.

DATA EXAMPLES

Consider the magnetopause crossing of Fig. 7 by Cluster satellite 3 at a distance of 12.47 R_E, magnetic latitude of 37.3^0, and a magnetic local time of 0830. The fields of panels c) through h) are in the minimum variance frame. Because the density of panel a) decreased from ~3 to less than 1 cm^{-3}, and because the reconnection magnetic field of panel e) changed from ~-10 to +20 nT, the crossing was from the magnetosheath to the magnetosphere. The normal magnetic field of panel c) and the tangential electric field of panel g) are small. Because the average B_X is negative, the crossing was north of the X-line. Because the average E_Y is positive, reconnection was occurring at a rate ~5%, where the reconnection rate is defined as the ratio of the inflow EXB speed to the Alfven speed at the seperatrix. So this appears to be a good example of reconnection on the ion scale. Or is it?

The angle between the assumed normal to the magnetopause found from timing the crossings at the four Cluster spacecraft (using B, E, or density) differs from the minimum variance normal by 30^0. This large difference raises concern with the idea that the minimum variance direction is the normal direction. Fig. 8 displays the normal magnetic field measured on the four Cluster spacecraft for different assumed normal directions. The normal direction of the data in panel a) is the "model" normal, defined as follows. At the local time of the satellite, any direction in the equatorial plane from sunward to dawnward is selected as the boundary normal. Then this selected normal is rotated to the latitude of the spacecraft by assuming that the magnetopause is cylindrically symmetric about the sun-earth line. This rotated vector is the "model" normal.

By performing this procedure for equatorial normal directions of 10 to 80 degrees from the sun-earth line, it has been found that the form of the curves in Fig. 8a remains unchanged and the magnitude of the variation changes by less than 25%. Among all the possible normals consistent with the above recipe, the radial direction from the center of the earth to the spacecraft has been selected for plotting the data of Fig. 8a. If any of these "model" normals are correct then, because B_X changed sign during the crossing for all of these normals, the satellites must have passed from north to south of the X-line.

The normal magnetic field under the assumption that the minimum variance direction is the magnetopause normal is given in panel b) of Fig. 8 and the normal magnetic field assuming that the normal direction is defined by the four spacecraft timing is given in panel c). Because the average magnetic field for the minimum variance normal of panel b) is -0.25 nT, the spacecraft crossed north of the X-line and the reconnection rate was small. Because the average magnetic field for the spacecraft timing normal of panel c) is 1.5 nT, the spacecraft passed south of the X-line and the reconnection rate was 6 times larger.

There is little agreement between the different assumptions on the normal direction, and analyses using the different normal directions yield very different conclusions regarding the reconnection. Hence, little can be deduced from this crossing. This may be because the morning location of the crossing was in a region of shear flow between the magnetosheath and the magnetosphere and the rest frame of the magnetopause may have been carried along with this shear flow.

Fig. 9 presents two sets of plots of the field data for a Polar satellite crossing at 9.09 R_E, a magnetic local time of 1140, and a magnetic latitude of 9.4^0. The data in the left panels were computed under the assumption that the normal to the magnetopause was the model normal, defined as the radial direction from the center of the Earth to the point of interest, while those in the right panels were obtained from the minimum variance normal. The angle between the model normal and the minimum variance normal was 4.5^0 (which was essentially the GSE X direction because the crossing was made near the sub-solar point). The two sets of data are almost identical with the density of panels a) and the reconnection magnetic field of panels d) showing that the spacecraft passed from the magnetosphere to the magnetosheath. The average normal magnetic field of panels b) was negative in both cases, which is consistent with a crossing north of the X-line. E_Y of panels f) was positive in both cases and the reconnection rate was 2%. Because both B_X and E_Y had essentially equal values at the magnetospheric and magnetosheath boundaries, the crossing is assumed to have occurred in the reconnection rest frame. Thus, one may conclude that the data of this example are valid for interpretation of the reconnection rate and crossing geometry. It is noted that most crossings at the sub-solar point (Mozer and Retinò, 2007) satisfy criteria like those above because the crossings occurred at the stagnation point of the magnetosheath flow.

CONCLUSIONS

Problems are discussed that arise when the relative motion between the spacecraft and the reconnection frame is not known. In the absence of multi-satellite data or other means of knowing this relative velocity, a procedure for examining the data may be:

1. Do not rotate magnetopause ion scale data into the minimum or maximum variance frames without auxiliary evidence that this is a viable procedure.
2. Do not translate magnetopause ion scale data into any other frame.
3. Assume that the reconnection frame normal is in an independently determined direction such as the model normal or the normal determined from multiple satellite timing.
4. If the normal magnetic field and tangential electric field are essentially constant and small in an assumed and independently justified normal direction, continue with the analysis.
5. If an independently determined normal is not found or if the normal magnetic field and the tangential electric field are not constant and small in any assumed normal direction, stop analyzing this crossing and move on to the next event.

ACKNOWLEDGEMENT

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Sonnerup, B.U.O., and M. Scheible (1998), Minimum and maximum variance analyses, in Analysis Methods For Multi-spacecraft Data, G. Paschmann and P.W. Daly (eds.), ISSI Scientific Report SR-001, ESA Publication Division, The Netherlands

FIGURE CAPTIONS

Fig. 1 Cross-section view of an idealized magnetopause with reconnection parameters indicated in the upper left portion of the figure.

Fig. 2. Velocity components in the prime frame after transformation of magnetopause data to a frame moving in the Z-direction at speed V_0.

Fig. 3. The trajectory of a spacecraft through the magnetopause as is known by an observer looking from afar but as is not known by the unfortunate scientist who has to analyze the data.

Fig. 4. Two sets of five trajectories each across a model magnetopause. The coordinates are units of the ion skin depth. Note the different scales on the axes. The upper set of five trajectories begins at a geophysical distance of about 0.5 R_E from the X-line with the

first trajectory being horizontal across the magnetopause and the fifth trajectory crossing to the opposite side of the magnetopause such that B_X changes sign. The lower set of five trajectories begins at a geophysical distance of about 1 R_E from the X-line.

Fig. 5a. For the five upper trajectories of Fig. 4, magnetic field components in the X,Y,Z and L, M, N, frames where X is the correct normal direction and Z is the direction of the reconnection magnetic field, and L, M, N are the minimum variance coordinates.

Fig 5b. Same as Fig. 5a except for the five lower trajectories in Fig. 4.

Fig. 6. The normal electric field in the minimum variance coordinates for the five upper trajectories of Fig. 4 at left and five lower trajectories at right. The true normal electric field is 1.2 mV/m, as given by the fine dashed lines. For oblique trajectories, the electric field found from the minimum variance technique and corrected for the X-component of the magnetopause motion differs significantly from the true normal electric field.

Fig. 7. Cluster satellite data at a magnetopause crossing as viewed in the minimum variance frame.

Fig. 8. Normal components of the magnetic fields measured on the four Cluster satellites for assumptions that the normal direction is given by a “model” magnetopause in panel a), by the minimum variance direction in panel b), and by the magnetopause velocity determined from four spacecraft timing in panel c).

Fig. 9. Field components measured on a Polar satellite crossing of the sub-solar magnetopause and presented in coordinate systems with the assumed magnetopause normals in the model normal and in the minimum variance directions.

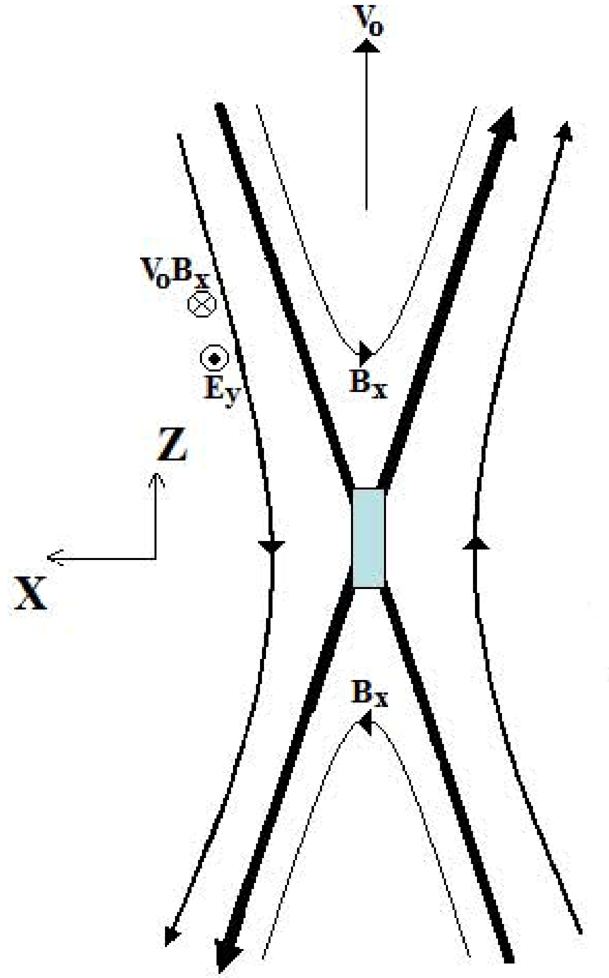


FIGURE 1

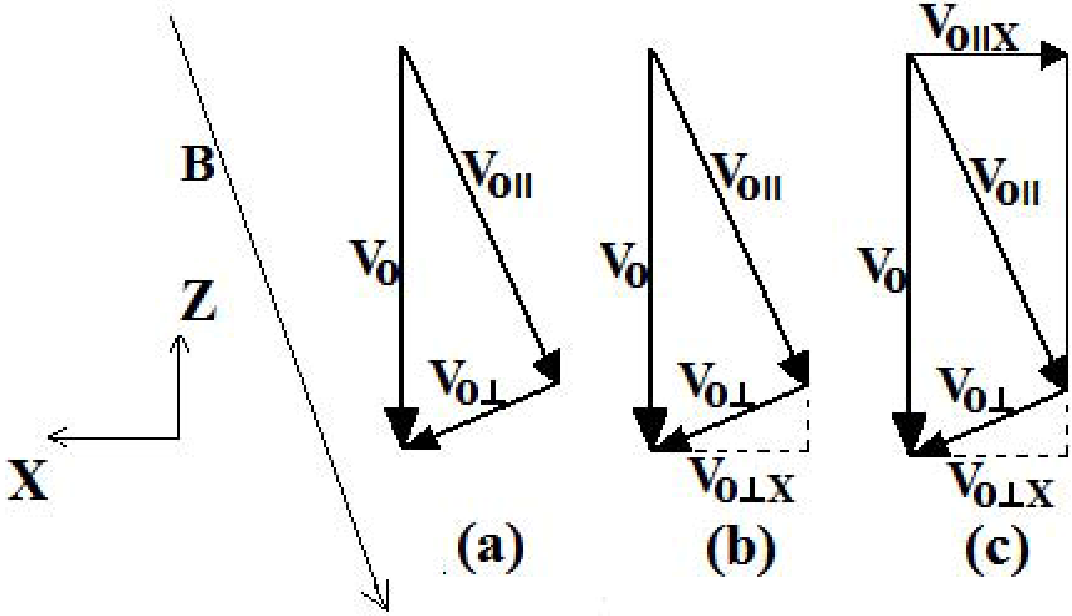


FIGURE 2.

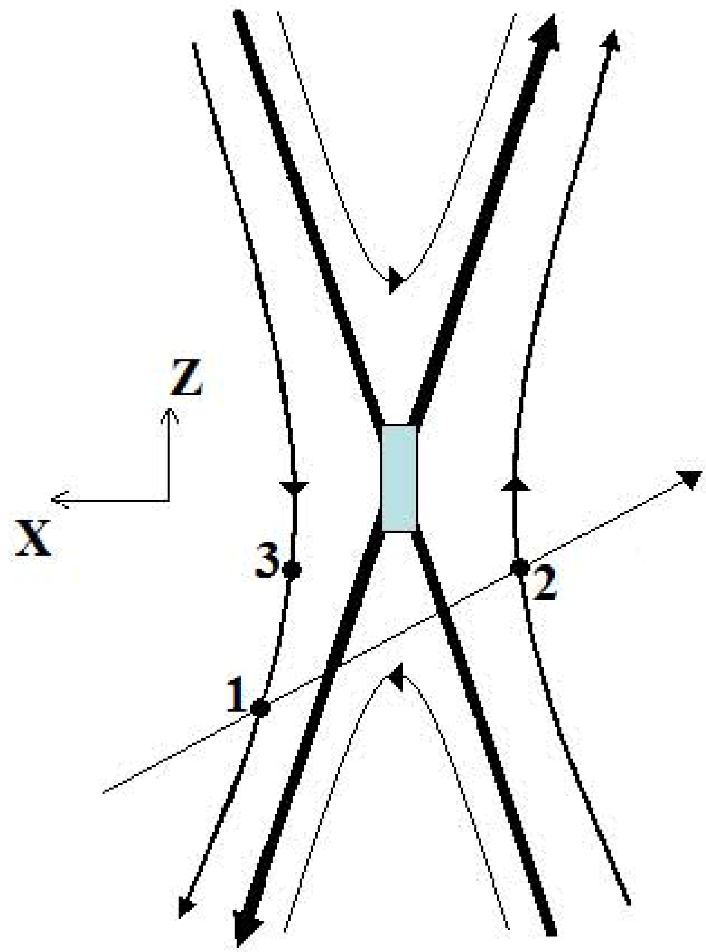


FIGURE 3

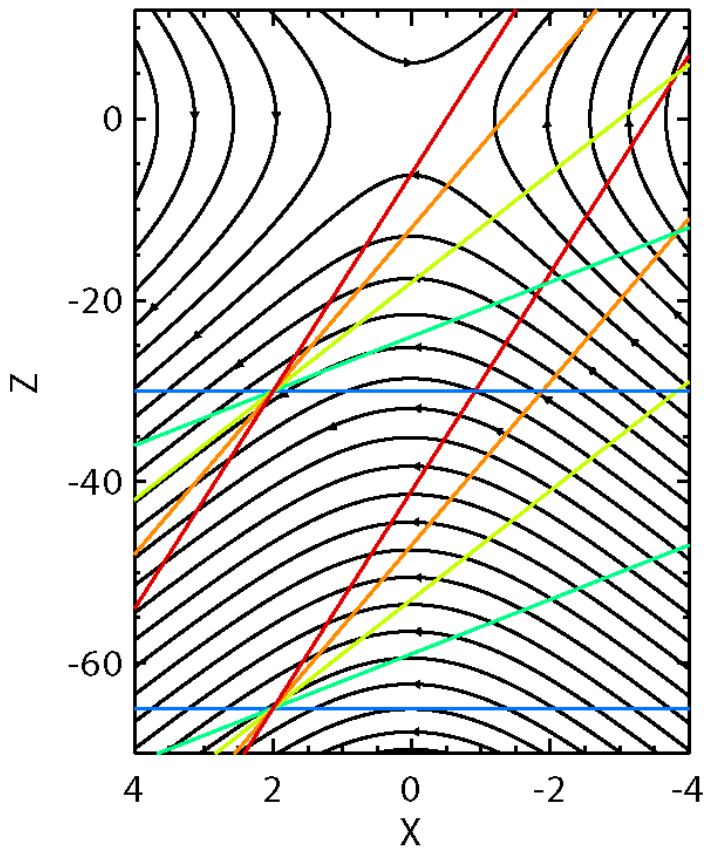
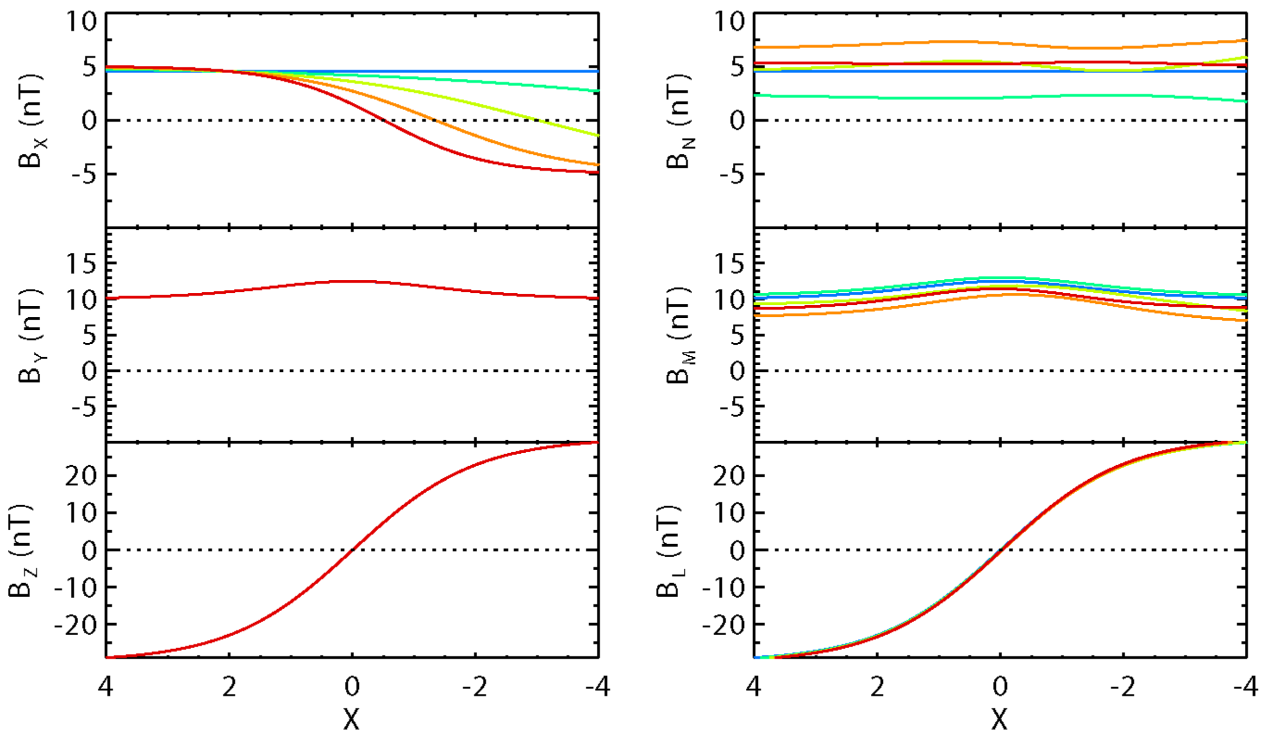
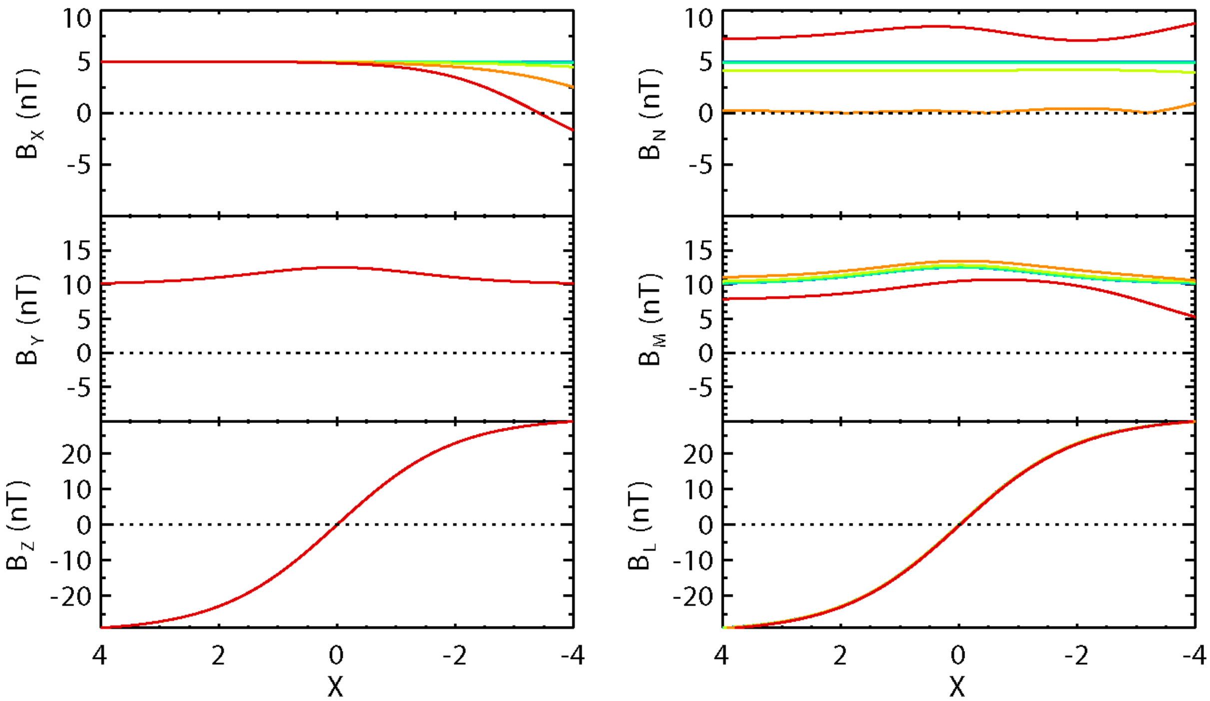


FIGURE 4



10
5
0
-5
B_X (nT)
15
10
5
0
-5
B_Y (nT)
20
10
0
-10
-20
B_Z (nT)
4
2
0
-2
-4
X
B_N (nT)
B_M (nT)
B_L (nT)

FIGURE 5a



10
5
0
-5
B_X (nT)
15
10
5
0
-5
B_Y (nT)
20
10
0
-10
-20
B_Z (nT)
4
2
0
-2
-4
X
10
5
0
-5
B_N (nT)
15
10
5
0
-5
B_M (nT)
20
10
0
-10
-20
B_L (nT)
4
2
0
-2
-4
X

FIGURE 5b

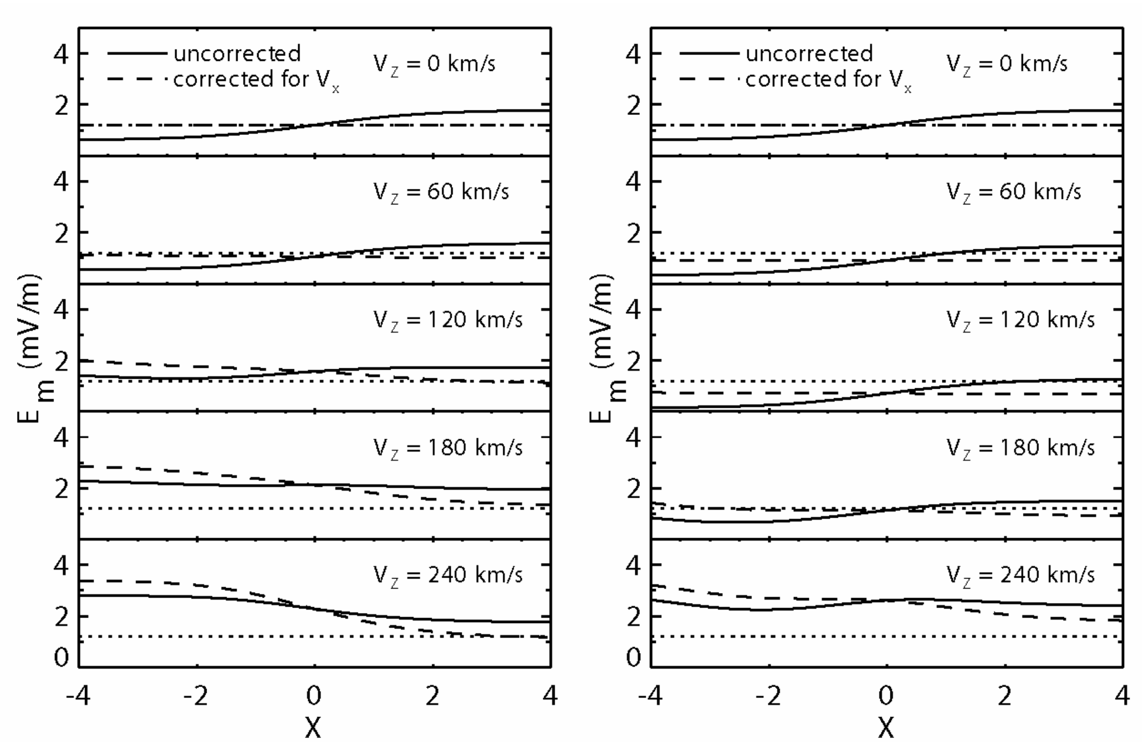

uncorrected
corrected for V_x
V_Z = 0 km/s
V_Z = 60 km/s
V_Z = 120 km/s
V_Z = 180 km/s
V_Z = 240 km/s
E_m (mV/m)
X
uncorrected
corrected for V_x
V_Z = 0 km/s
V_Z = 60 km/s
V_Z = 120 km/s
V_Z = 180 km/s
V_Z = 240 km/s
E_m (mV/m)
X

FIGURE 6

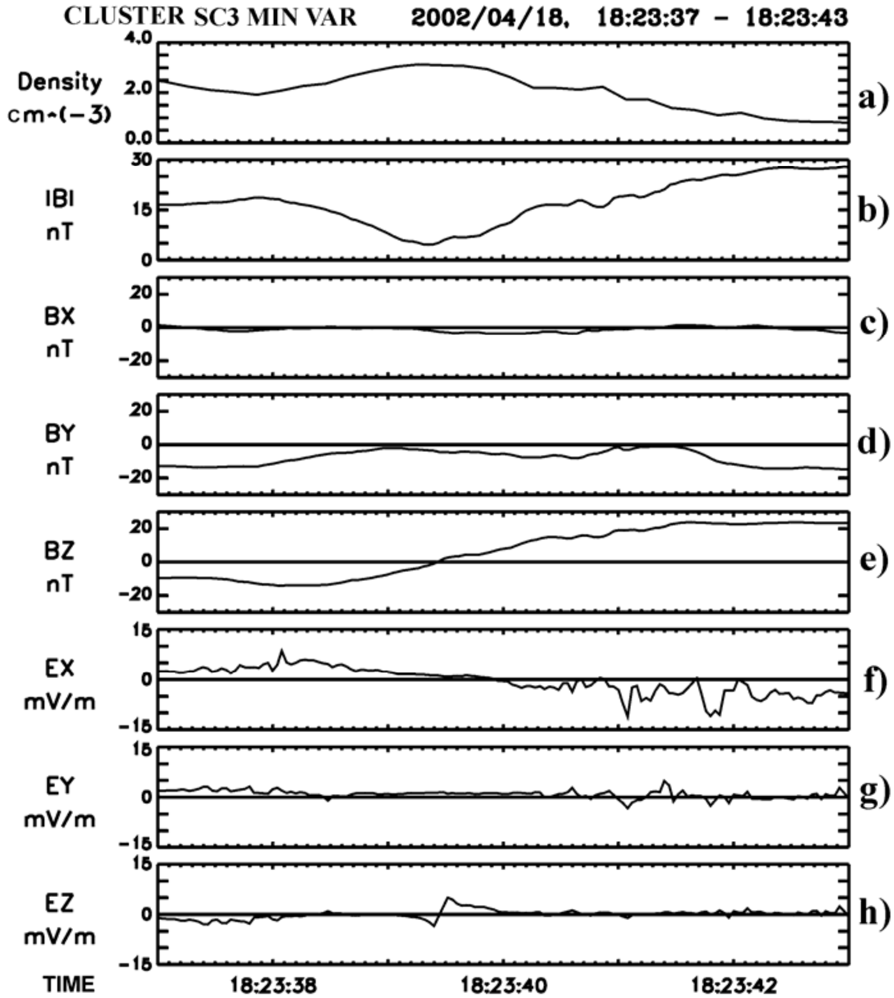

CLUSTER SC3 MIN VAR 2002/04/18, 18:23:37 – 18:23:43
Density cm^(-3)
|B| nT
BX nT
BY nT
BZ nT
EX mV/m
EY mV/m
EZ mV/m
TIME
18:23:38
18:23:40
18:23:42
a)
b)
c)
d)
e)
f)
g)
h)

FIGURE 7

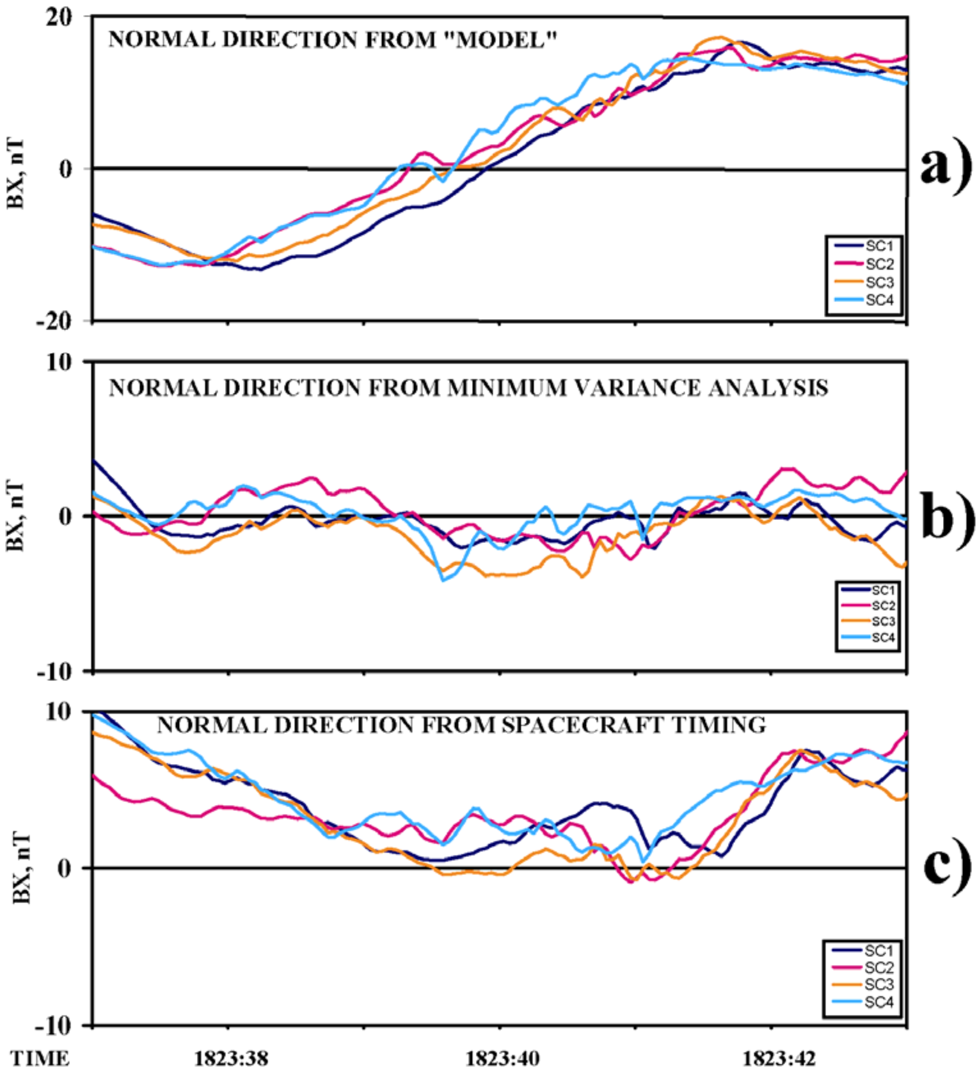

NORMAL DIRECTION FROM "MODEL"
BX, nT
20
0
-20
a)
SC1
SC2
SC3
SC4
NORMAL DIRECTION FROM MINIMUM VARIANCE ANALYSIS
10
0
-10
b)
NORMAL DIRECTION FROM SPACECRAFT TIMING
c)
TIME
1823:38
1823:40
1823:42

FIGURE 8

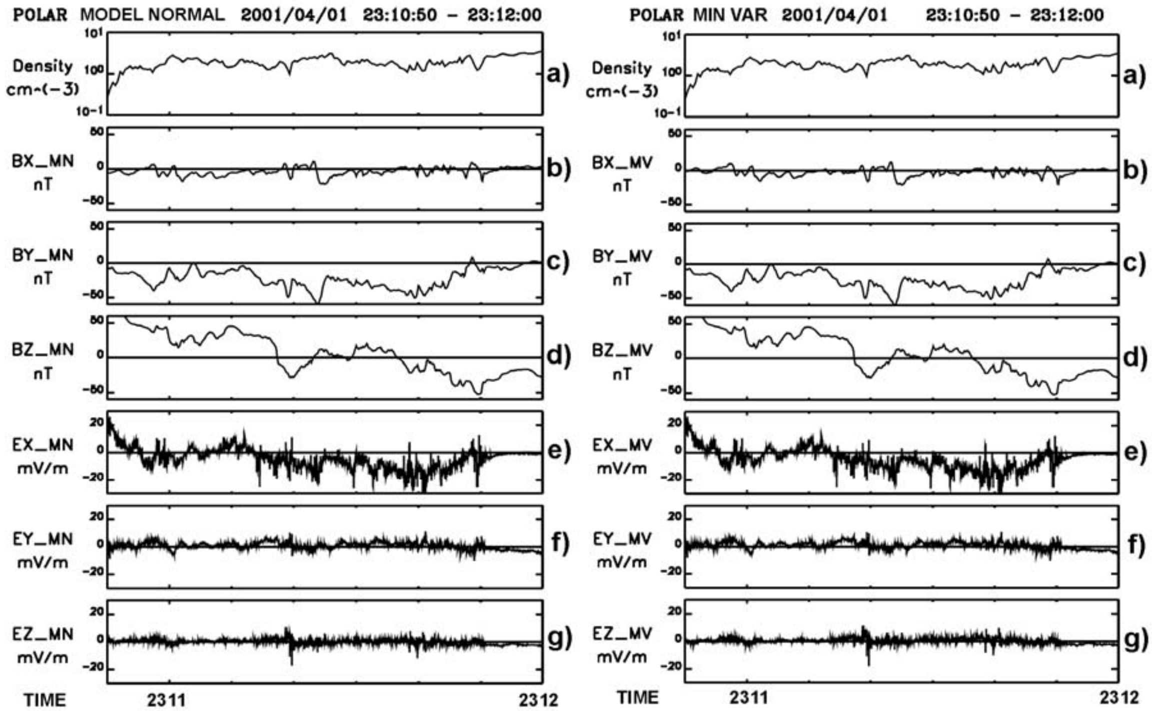

POLAR MODEL NORMAL 2001/04/01 23:10:50 - 23:12:00
Density cm^(-3)
BX_MN nT
BY_MN nT
BZ_MN nT
EX_MN mV/m
EY_MN mV/m
EZ_MN mV/m
TIME
2311
2312
a)
b)
c)
d)
e)
f)
g)
POLAR MIN VAR 2001/04/01 23:10:50 - 23:12:00
Density cm^(-3)
BX_MV nT
BY_MV nT
BZ_MV nT
EX_MV mV/m
EY_MV mV/m
EZ_MV mV/m
TIME
2311
2312
a)
b)
c)
d)
e)
f)
g)

FIGURE 9