QUANTITATIVE ESTIMATES OF MAGNETIC FIELD RECONNECTION PROPERTIES FROM ELECTRIC AND MAGNETIC FIELD MEASUREMENTS

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PURPOSE OF TALK

USE SUBSOLAR DATA FROM THE POLAR SATELLITE AND A NEW MEASUREMENT TECHNIQUE TO DISCUSS STATISTICS OF THE RECONNECTION RATE AND ITS DEPENDENCE ON THE GUIDE MAGNETIC FIELD

Reconnection rate $\equiv E_{TAN}$

Dimensionless reconnection rate $\equiv B_{NORMAL}/B_{REC}$

$= (E_{TAN}/B_{REC}) \times v_{ALFVEN}$

QUESTIONS:

1. **IS THE RECONNECTION RATE FAST ENOUGH TO EXPLAIN MAGNETIC ENERGY CONVERSION EVERYWHERE IN THE UNIVERSE?**
2. **HOW DOES THE RECONNECTION RATE DEPEND ON THE GUIDE MAGNETIC FIELD (THE CLOCK ANGLE)?**

RECONNECTION ON THE ION SCALE USING A NEW MEASUREMENT TECHNIQUE

LET

X = normal to the current sheet
Y = out-of-plane direction
Z = direction of reconnecting component of B
E_X, B_Y, B_Z = the large fields in a reconnecting current sheet
e_Y, e_Z, b_X = the small fields in a reconnecting current sheet

The most important field components for reconnection are:

b_X
because a normal magnetic field is required for the field lines on the two sides to be connected

e_Y and e_Z
because a tangential electric field is required for $(\mathbf{E}X\mathbf{B}/B^2)_X = (e_Y B_Z - e_Z B_Y)/B^2$ to be inward from both sides

PROBLEM

The most important fields (e_Y, e_Z, b_X), being the smallest fields, are contaminated by the largest fields when the normal to the current sheet is inaccurate.

The analysis assumes a normal direction that is constant, whereas the normal oscillates by several degrees due to surface waves on the magnetopause. These produce error signals ~ (Big Field)*sin5^{o} which are comparable to the (Small Field).

CONCLUSION

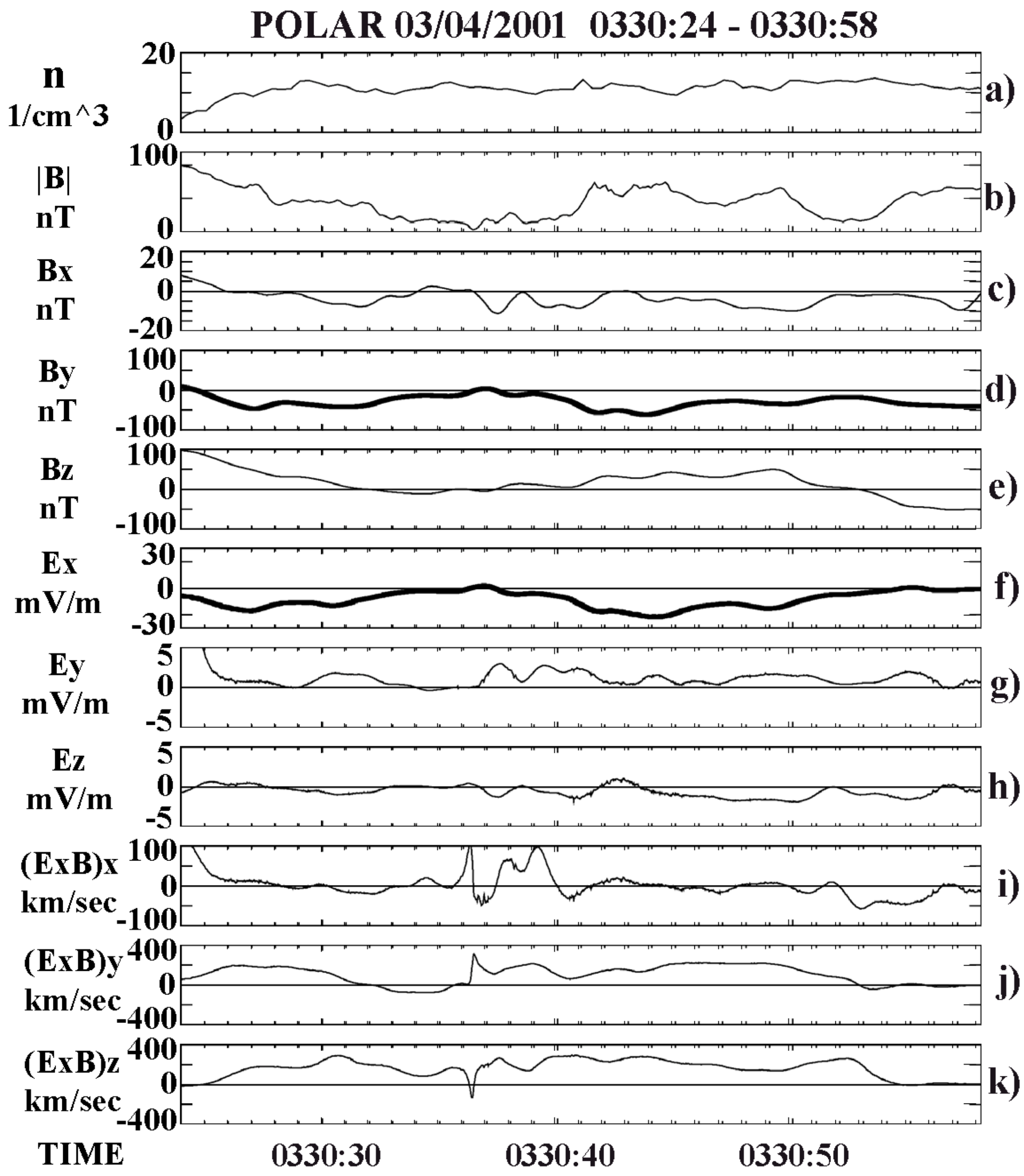
The parameters that determine the occurrence and magnitude of reconnection can be measured well but interpreted poorly.

IN THIS TALK

1. A Polar satellite magnetopause crossing is analyzed to show that reconnection was occurring but that the reconnection rate was uncertain due to oscillations of the normal direction.

2. A new method is described for minimizing this uncertainty by using correlations between **only** the three large field components to obtain the three small components.

3. Of >100 sub-solar magnetopause crossings, about 40% had correlations that suggest a constant reconnection rate. Detailed statistics are presented for 14 of these crossings.



Data low pass filtered at 0.5 Hz, in Joint Variance Frame, tied to magnetopause

9.28 $R_{E,}$ 1320 MLT, 8.9^{0} MLAT

Density (panel a)), B_Z (panel e)) show passage from sphere to sheath through magnetopause.

Two current layers, each 1-2 c/ωpI thick

Big fields more than an order of magnitude larger than small fields

$<b_X>$ <0 (panel c)) NECESSARY CONDITION FOR RECONNECTION Magnitude uncertain due to oscillations

$<e_Y>$ > 0 (panels g)) NECESSARY AND SUFFICIENT FOR RECONNECTION. Magnitude uncertain due to fluctuations (of the normal?)

$(\mathbf{E}X\mathbf{B}/B^2)_X$ inward from both sides (panel i))

<bX> < 0 requires outflow in +Z direction. It is (panel k)). Outflow speed of 350 km/sec compares with
v_{ALFVEN} = 330 km/sec (sheath)
= 1120 km/sec (sphere)

E_X CORRELATES WITH B_Y (panels d) and f)

Although major changes in B, By is not quadrupolar

Statistics of 100 events. One quadrupolar

20% bipolar B, i.e., Btotal constant

Rest varied

REASON THAT E_X CORRELATES WITH B_Y AND/OR B_Z

$E_X b_X + e_Y B_Y + e_Z B_Z = e_{||} B_{total}$

If $b_X = e_Y = e_Z = e_{||} = 0$ because there is no reconnection, then E_X, B_Y, and B_Z have no necessary relationship to each other.

If there is reconnection, b_X, e_Y, and/or $e_Z \neq 0$ and

$E_X = -(e_Y/b_X)B_Y - (e_Z/b_X)B_Z + (e_{||}/b_X)B_{total}$

$= -aB_Y - bB_Z + cB_{total}$

where $a = (e_Y/b_X)$, $b = (e_Z/b_X)$ and $c = (e_{||}/b_X)$

IF

a, b, and c are constant and E_X correlates with B_Y and/or B_Z

THEN

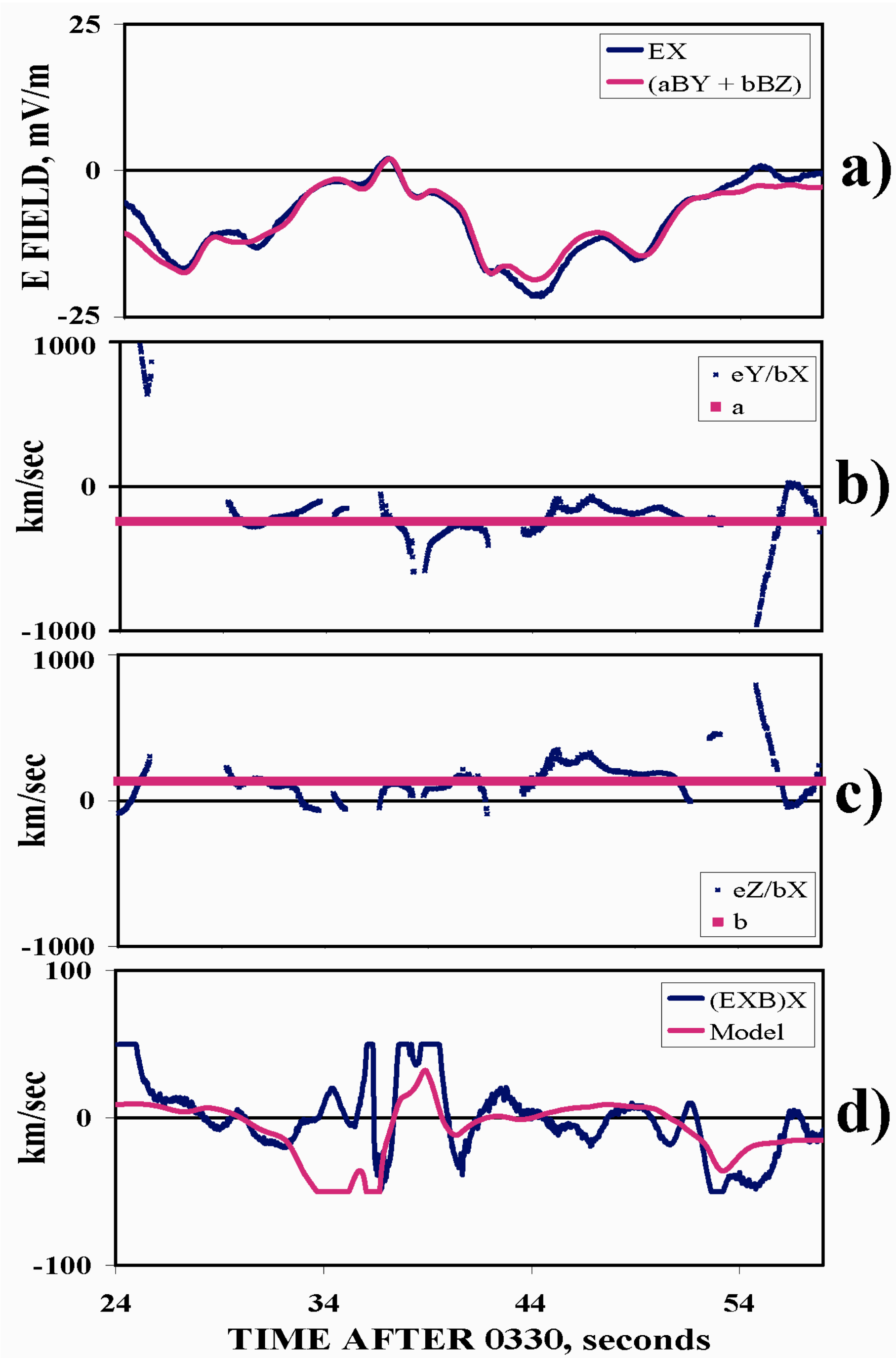
The small fields that determine reconnection may be obtained from the large and easily measured fields, by least-squares fits.

LEAST SQUARES FIT TO MARCH 4, 2001 DATA

R^2	$a = e_Y/b_X$	$b = e_Z/b_X$	$c = e_{\parallel}/b_X$
0.990	-0.33	0.16	0.07
0.977	-0.24	0.13	$\equiv 0$

COMMENTS

1. $e_{\parallel}$ is an order of magnitude smaller than e_Y, two orders smaller than E_X, and statistically not different from 0.
2. R^2 =0.977 means that 97.7% of the variation of E_X is accounted for by $(aB_Y + bB_Z)$



Remarkable correlation between measured E_X and model

Agreement of a with e_Y/b_X and b with e_Z/b_X speaks for the quality of all the measurements.

Inflow from both sides

OBTAINING BEST VALUES FOR e_Y, e_Z, b_X AND $(\mathbf{E}X\mathbf{B}/B^2)_X$

Have five measurements $<e_Y>$, $<e_Z>$, $<b_X>$, a, and b,
of three quantities, $\mathbf{e_Y}$, $\mathbf{e_Z}$, and $\mathbf{b_X}$,

where $<e_Y>$, $<e_Z>$, and $<b_X>$ are the average values of the measured small fields
and the bold lower case fields are the best estimates of the small fields.

These best values are obtained from the five measurements by minimizing the function

$$f = (\Delta e_Y/\mathbf{e_Y})^2 + (\Delta e_Z/\mathbf{e_Z})^2 + (\Delta b_X/\mathbf{b_X})^2$$

where

$$\Delta e_Y \equiv \mathbf{e_Y} - <e_Y>$$
$$\Delta e_Z \equiv \mathbf{e_Z} - <e_Z>$$
$$\Delta b_X \equiv \mathbf{b_X} - <b_X>$$

Assuming that a and b are error-free and substituting $a = \mathbf{e_Y}/\mathbf{b_X}$ and $b = \mathbf{e_Z}/\mathbf{b_X}$ gives

$$\Delta e_Z = b/a(<e_Y> + \Delta e_Y) - <e_Z>$$
$$\Delta b_X = (<e_Y> + \Delta e_Y)/a - <b_X>$$

and the function, $f(\Delta e_Y)$, to be minimized is

$$f(\Delta e_Y)=[\Delta e_Y/a]^2+[(<e_Y> + \Delta e_Y)/b - <e_Z>/b]^2+[(<e_Y> + \Delta e_Y)/a - <b_X>]^2$$

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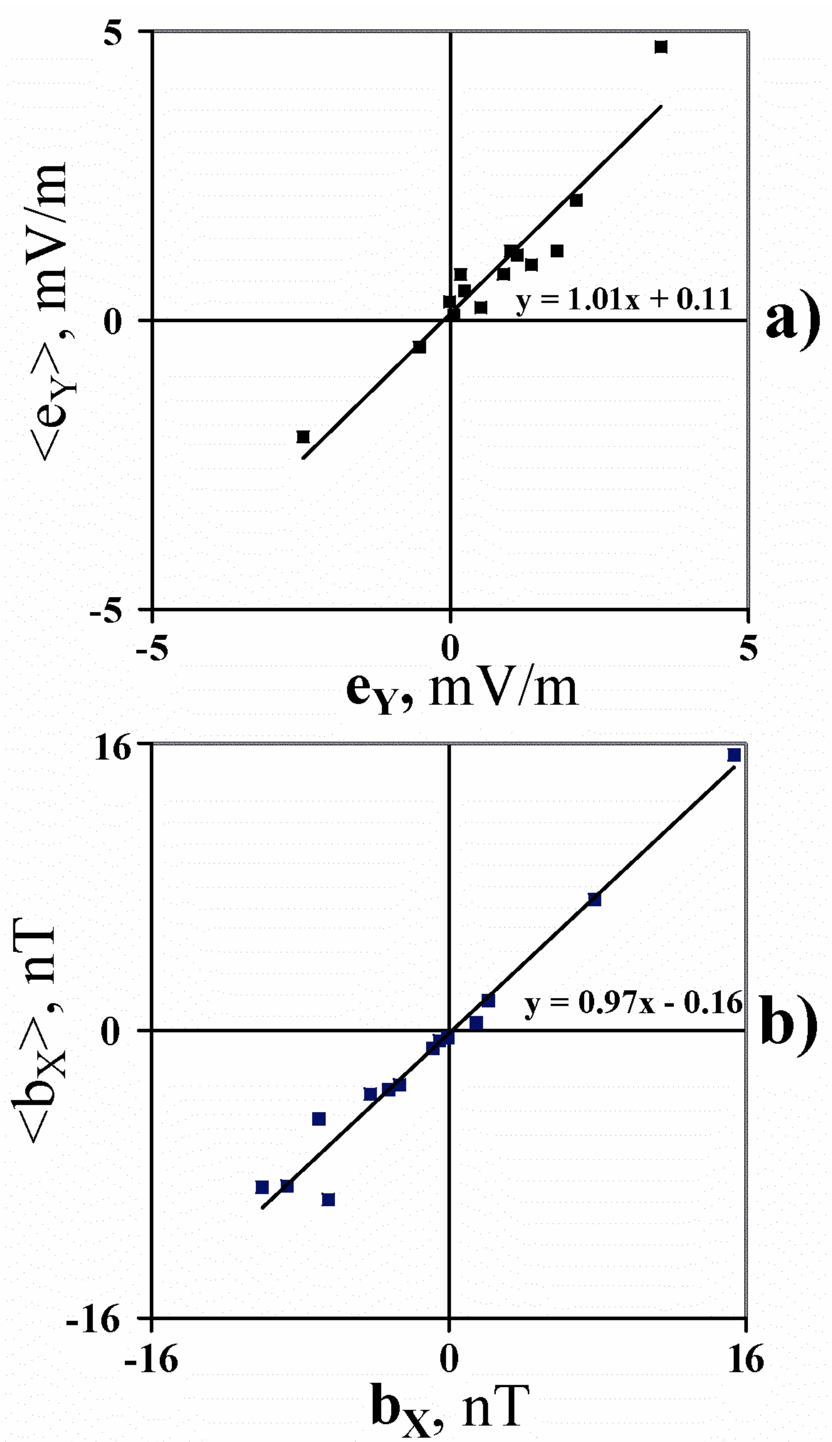
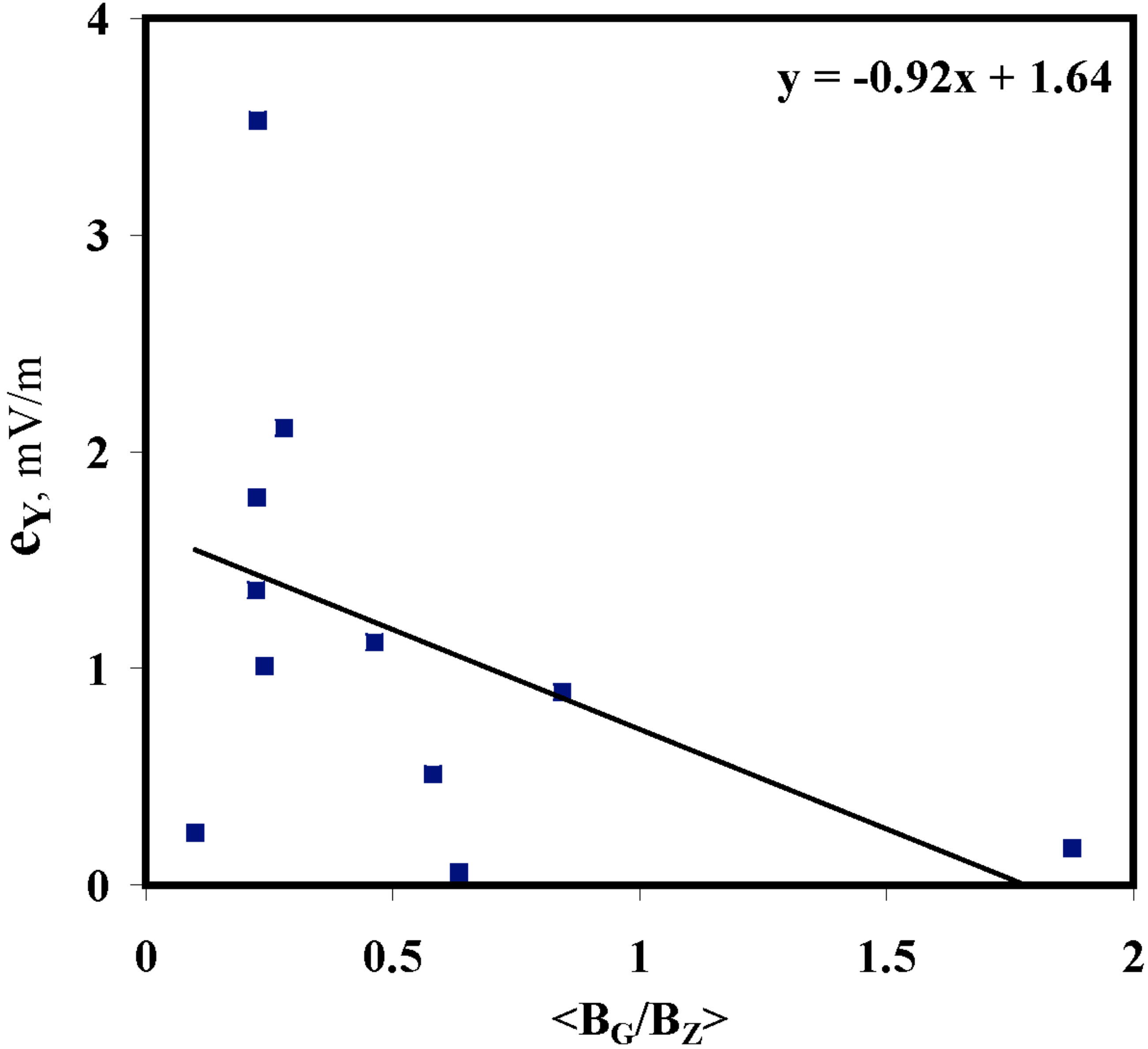


$$\mathbf{e_Y} = \langle e_Y \rangle \pm 0.43 \text{ mV/m}$$

$$\mathbf{b_X} = \langle b_X \rangle \pm 1.1 \text{ nT}$$

And now, for some PHYSICS



RECONNECTION RATE

Reconnection Rate ≡ the number of magnetic field lines entering the magnetopause per second per unit length along the magnetopause.

For $B_G = 0$ and $b_X << B_Z$, $B_{total} = B_Z$ where all fields have their asymptotic values

RR = density of field lines*speed of field lines = $B_Z * e_Y/B_Z$
$= e_Y$

It is useful to have a dimensionless reconnection rate

$$RR \equiv (e_Y/B_Z)/v_{alfven} = (e_Y/B_Z)(\rho^{1/2}/B_Z) \qquad (1)$$

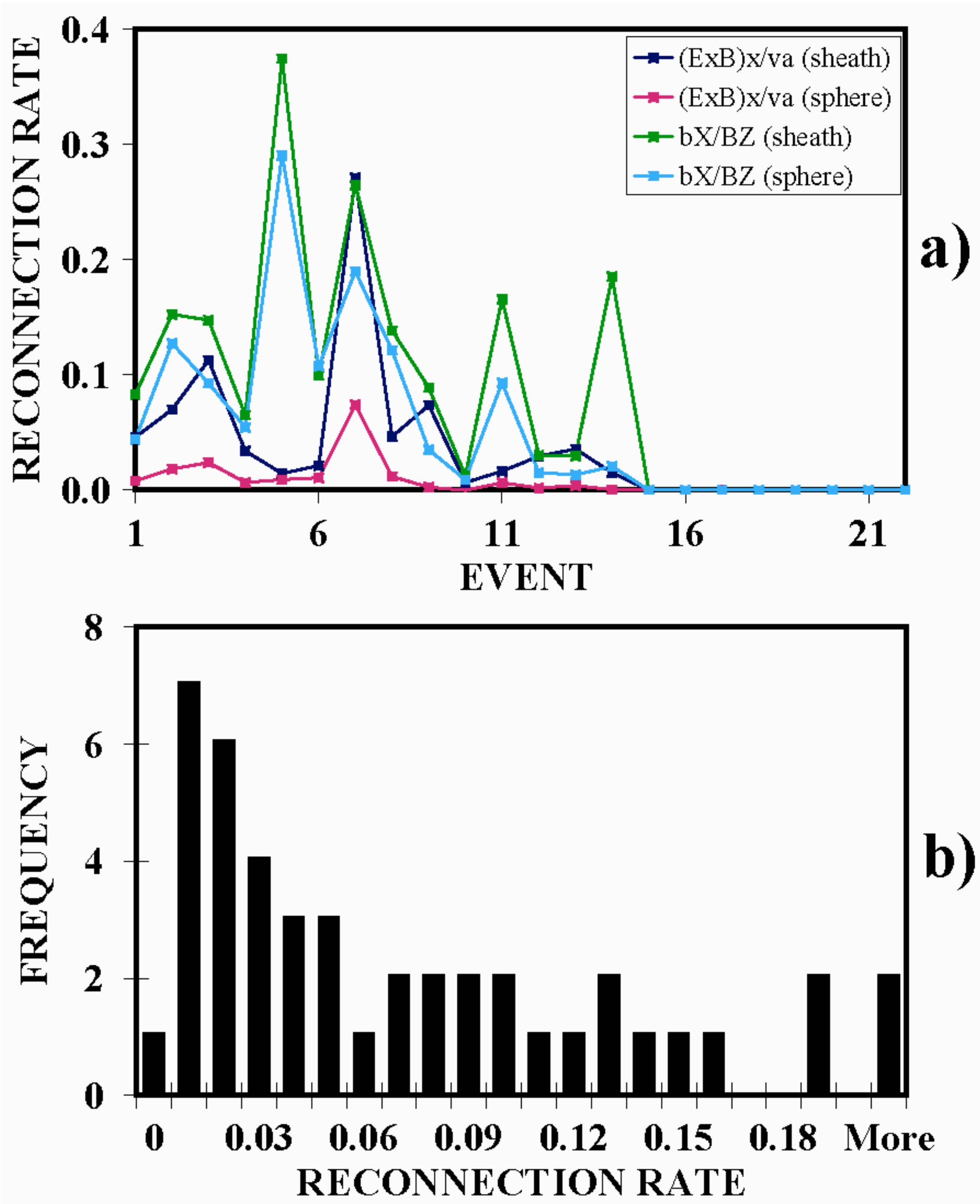
Because $e_Y = (v_{alfven})_n B_Z$ for a rotational discontinuity

Equation (1) becomes

$$RR \equiv b_X/B_Z \qquad (2)$$

Have 2 equations and 2 boundaries = 4 estimates of RR for each event

WHAT TO DO IF $B_G \neq 0$?



For 11 events with reconnection and least squares coeffieicnts >0.075

<RECONNECTION RATE> = 0.072

For all 22 events

<RECONNECTION RATE> = 0.046

CONCLUSION: RECONNECTION RATE IS LARGE

AVERAGE VALUES OF PARAMETERS MEASURED IN 14 RECONNECTION EVENTS

R^2 of the correlation	0.901
$\langle b_X \rangle$	-3.21 nT
$\mathbf{b_X}$	-3.13 nT
$\langle e_Y \rangle$	1.25 mV/m
$\mathbf{e_Y}$	1.16 mV/m
$\langle e_Z \rangle$	0.33 mV/m
$\mathbf{e_Z}$	0.33 mV/m

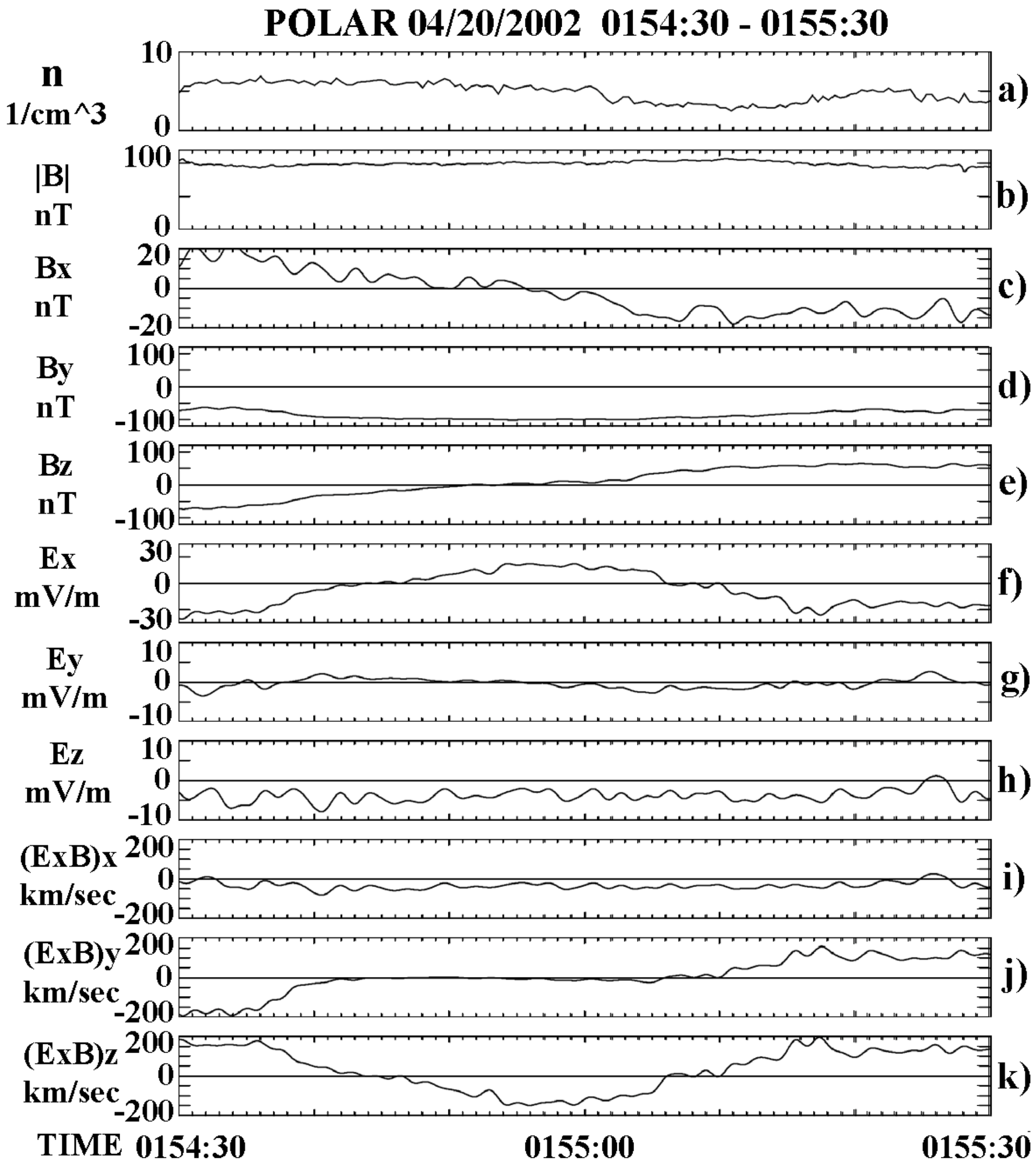
	magnetosheath	magnetosphere
$(\mathbf{E}X\mathbf{B}/B^2)_X$	-23.8 km/sec	14.6 km/sec
$(\mathbf{E}X\mathbf{B}/B^2)_Z/V_{Alfven}$	0.79	0.24
B_Z	-43.5 nT	68.0 nT
$\lvert B_G/B_Z \rvert$	0.72	0.32

SUMMARY

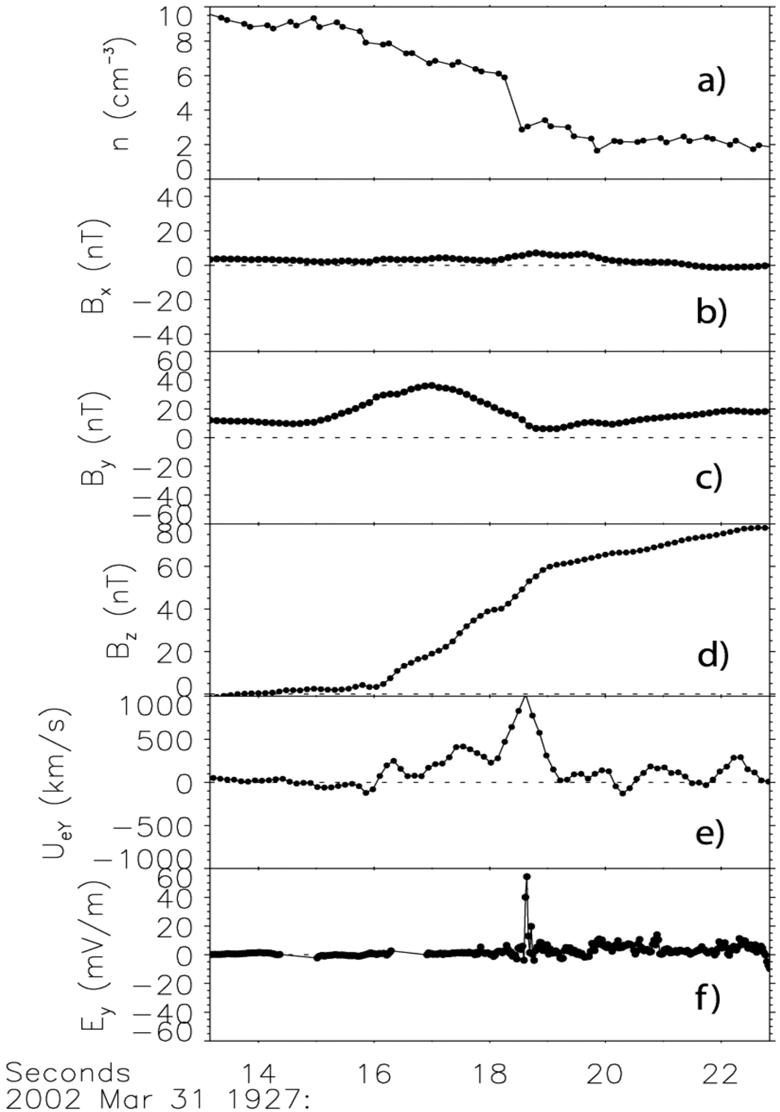
1. Quantitative reconnection estimates depend on values of e_Y, e_Z, and b_X, which are typically an order-of-magnitude smaller than E_X, B_Y, and B_Z.
2. Small variations in the direction normal to the magnetopause produce large errors in estimates of e_Y, e_Z, and b_X.
3. A method is described that produces information about e_Y/b_X and e_Z/b_X from the remarkable correlations between E_X and B_Y and/or B_Z.
4. The well-determined values of e_Y/b_X and e_Z/b_X plus the averages of the measured e_Y, e_Z, and b_X are used to produce best estimates of $\mathbf{e_Y}$, $\mathbf{e_Z}$, and $\mathbf{b_X}$, from which reconnection parameters are determined.
5. Fourteen of 22 sub-solar magnetopause crossings were shown to have active reconnection with:

- <Correlation between normal E and tangential B> = 0.901
- <$\mathbf{e_Y}$> = 1.16 mV/m and <Dimensionless Reconnection Rate> = 6%
- The Reconnection Rate decreases as the guide magnetic field increases
- Quadrupolar out-of-plane magnetic fields are rarely seen in the sub-solar region

AN ADDITIONAL EVENT IN THE IDEAL MHD REGIME



POLAR OBSERVATION OF THE ELECTRON DIFFUSION REGION



Reconnection magnetic field changes in steps

Current filamentary

At largest filament, see 60 mV/m electric field lasting for ~75 msec (width ~c/ω_{pe}).

$E_{\parallel}$ ~ 8 mV/m

$\mathbf{j_{perp}} \cdot \mathbf{E_{perp}}/n$ >100 keV per particle per second

Major density change at this time.

Electron beta <1