A SIMPLIFIED DISCUSSION OF RECONNECTION AND ITS MYTHS

By Forrest Mozer

WHY A SIMPLIFIED DISCUSSION OF RECONNECTION?

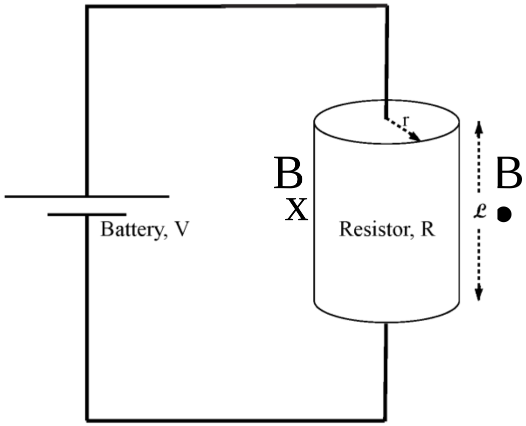
For many people, magnetic field reconnection is too complicated to understand in the detail that we present it to them.

For these people, magnetic field reconnection is a black box that is invoked whenever needed to solve whatever problem.

This situation is a little like that in cloud physics. Many people understand the fundamental principles behind cloud formation but very few people really care about understanding all possible cloud shapes, structures at different altitudes, etc.

The solution for magnetic field reconnection is that a first-order-principles view is needed to explain the fundamental physics without delving into anomalous resistivity, waves, component reconnection, magnetic field annihilation, frozen-in condition, flux ropes, 2-d simulations, etc.

START THE WITH A SIMPLE ELECTRICAL CIRCUIT



LEVEL 0 DESCRIPTION

$V = RI$

$\text{POWER} = VI$

LEVEL 1 DESCRIPTION

$\text{POWER} = \int \mathbf{j} \bullet \mathbf{E}\, d\mathrm{vol} = (I/\pi r^2)(V/\mathcal{L})(\pi r^2 \mathcal{L})$

$= VI$

LEVEL 2 DESCRIPTION

$B = \mu_o I/2\pi r$

$E = V/\mathcal{L}$

POYNTING FLUX = $\mathbf{E} \times \mathbf{B}/\mu_o$ at the surface of the resistor is everywhere inward.

.

$\text{POWER} = (\mathbf{E} \times \mathbf{B}/\mu_o) \times \text{surface area}$

$= (V/\mathcal{L})(\mu_o I/2\pi r)(2\pi r \mathcal{L}/\mu_o)$

$= VI$

LEVEL 3 DESCRIPTION

Magnetic field lines move at velocity = $\mathbf{E}\mathrm{x}\mathbf{B}/B^2$

So the field lines that circle the resistor move into the center of the resistor where they annihilate themselves. THIS IS RECONNECTION.

In this reconnection, there is:

energy conversion that heats the resistor

while the magnetic field is constant (until the battery is discharged)

CONCLUSION

You cannot determine the electromagnetic energy conversion from the change of the magnetic field configuration.

MYTH 1:

UP TO HALF THE ELECTROMAGNETIC ENERGY CONVERTED IN A SOLAR FLARE GOES INTO ENERGETIC ELECTRONS.

MAKING THE PROBLEM LOOK MORE LIKE RECONNECTION

LOOK AT THE RESISTOR END-ON

Ex**B** is radially inward and B-lines and Poynting flux move into the resistor

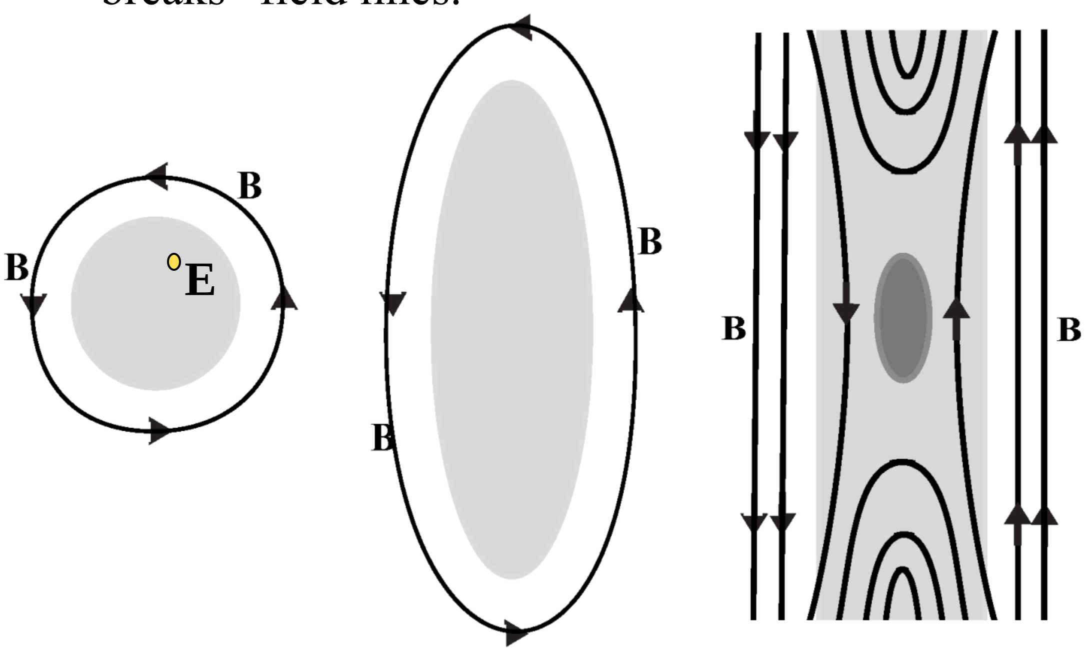
STRETCH THE RESISTOR UNTIL IT LOOKS OVAL IN CROSS-SECTION.

STRETCH IT MORE SO IT HAS A RECTANGULAR CROSS-SECTION

IN THE CENTER MAKE THE RESISTIVITY HIGHER

There is less current in the center so the B lines are further apart. Because E/B is larger near the center, the field lines near the center move faster and are therefore curved

Reconnection occurs in the absence of waves, parallel electric fields, or anything that “breaks” field lines.

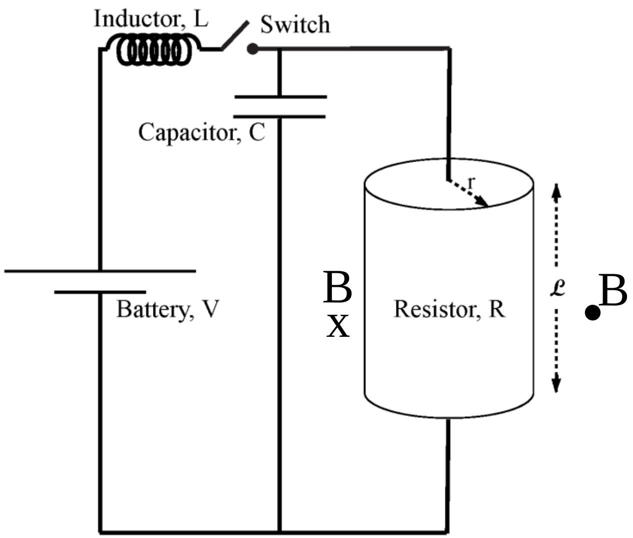


MYTH 2

A mysterious process is needed at the X-line for reconnection to occur. There is nothings at all mysterious about this X-line.

THERE IS NOTHING EXPLOSIVE ABOUT THIS RECONNECTION

Fix this by adding an inductor, a capacitor, and a switch.



When the switch is closed, energies $0.5LI^2$ and $0.5CV^2$ are added to the system, and the magnetic field around the resistor is the same as if no inductor or capacitor is present. When the switch is open, there is an explosive release of energies $0.5LI^2$ and $0.5CV^2$ in addition to the energy in the magnetic field.

THE AMOUNT OF ENERGY RELEASED IS MORE THAN THAT IN THE MAGNETIC FIELD ALONE. THIS IS ANOTHER REASON TO DOUBT THAT AS MUCH AS 50% OF THE ENERGY RELEASED IN A FLARE APPEARS AS ENERGETIC ELECTRONS.

IS THERE A CHANGE OF TOPOLOGY IN THIS EXAMPLE?

IS A CHANGE OF TOPOLOGY A REQUIREMENT FOR RECONNECTION?

LEVEL 4 DESCRIPTION

Use field line motion to compute the power conversion in the resistor.

Consider the magnetic field energy, $B^2/2\mu_o$, in a cylindrical shell surrounding the resistor and having a thickness equal to the distance that the field lines move at speed E/B in time dt.

$$dW/dt = (B^2/2\mu_o * 2\pi r \mathcal{L} * E/B * dt)/dt = EB * 2\pi r \mathcal{L}/2\mu_o = V/\mathcal{L} * \mu_o I/2\pi r * 2\pi r \mathcal{L}/2\mu_o = VI/2$$

WHY DO WE GET AN ANSWER THAT IS A FACTOR OF 2 SMALLER THAN THE CORRECT ANSWER?

THE REASON IS THAT THIS CALCULATION IS TOTAL NONSENSE

THE CONCEPT OF FIELD LINE MOTION WAS DEVELOPED SOLELY FOR THE PURPOSE OF UNDERSTANDING THE TIME EVOLUTION OF A MAGNETIC FIELD, AND IT CAN BE INCORRECT TO EXTEND THIS NOTION TO ANYTHING ELSE.

TO SEE THIS, CONSIDER POYNTING'S THEOREM

$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B},$$

$$u = \frac{1}{2}\left(\epsilon_0 \mathbf{E}^2 + \frac{\mathbf{B}^2}{\mu_0}\right)$$

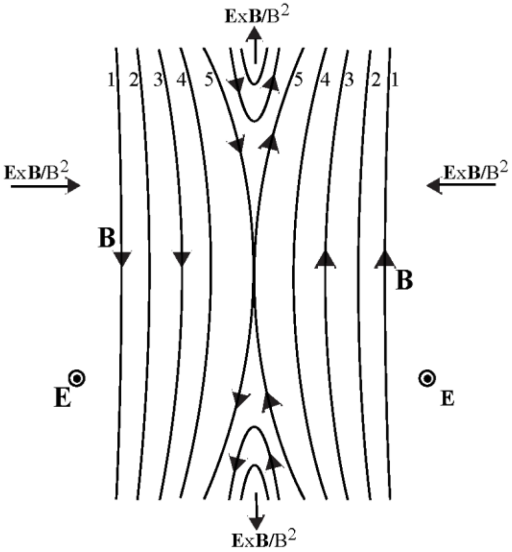
POYNTINGS THEOREM: $-\nabla \bullet \mathbf{S} = \partial u/\partial t + \mathbf{j} \bullet \mathbf{E}$

POWER DISSIPATION = $-\int \mathbf{S} \bullet d\text{surf} = \int \mathbf{j} \bullet \mathbf{E}\, d\text{vol} + \int \partial u/\partial t\, d\text{vol}$

u is constant so the second term on the right is zero, and the power dissipation is given by the first term, not by integrating moving magnetic field energy.

MYTH 3 coming up

USE OF FIELD LINE MOTION TO DEDUCE THE MAGNETIC FIELD GEOMETRY AT A RECONNECTION SITE.



Field lines move from 1 to 2 to 3, etc. to produce the geometry of the magnetic field

MYTH 3

You obtain the correct evolution of the magnetic field in reconnection by moving field lines at $\mathbf{E}\mathrm{x}\mathbf{B}/B^2$

WHY IS THIS A MYTH

Because you get a different geometry by moving magnetic field lines than found by solving Maxwell's equations unless

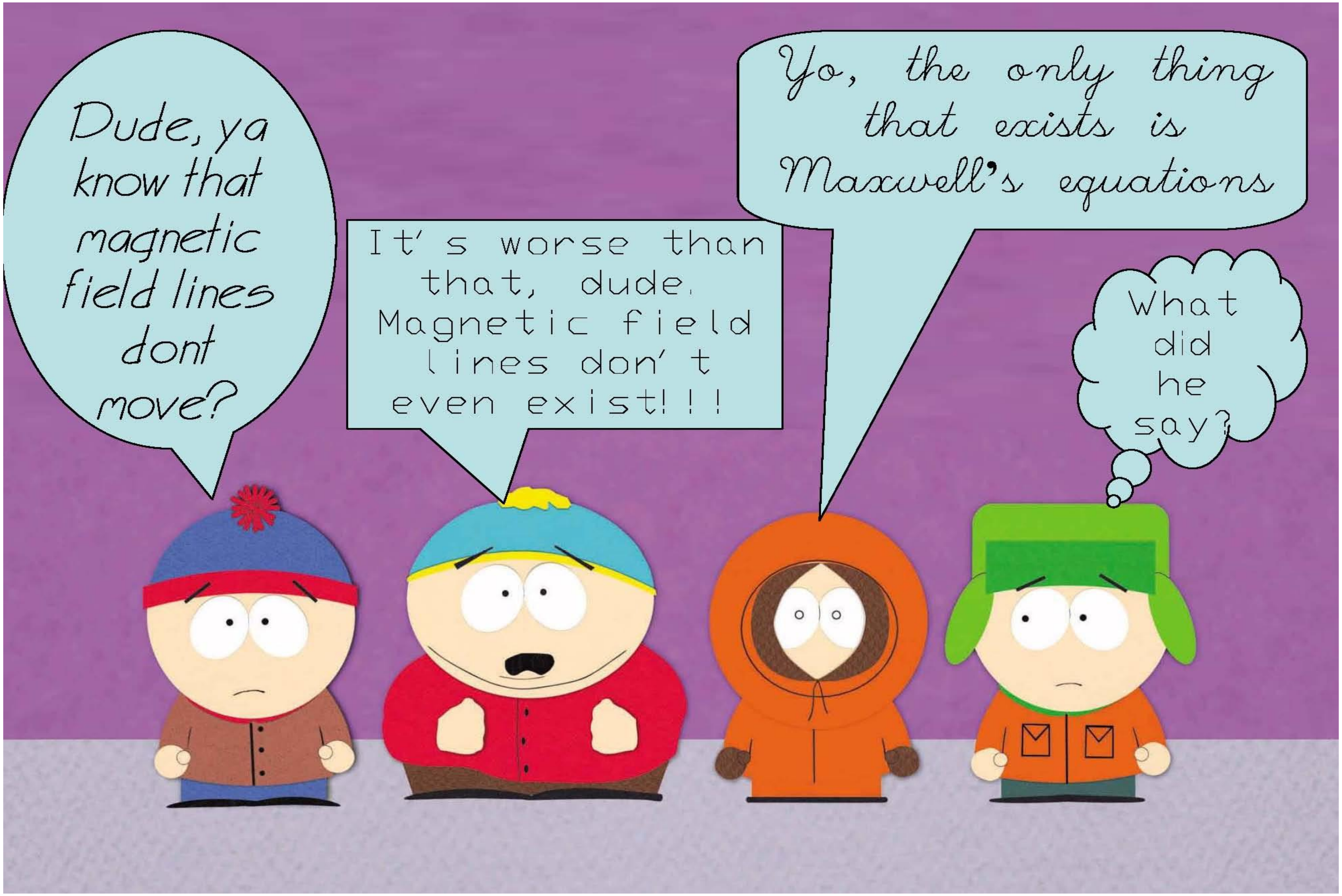
$$\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) = 0$$

Two proofs that follow:

- For moving field lines to produce the same evolution of the magnetic field as does Maxwell's equations, $\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) = 0$.

- In collisionless reconnection, $\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) \neq 0$ at many locations.

THE BOARD OF EXPERTS



FIELD LINE VELOCITY FROM FIRST PRINCIPLES

The task is to show the conditions under which field line motion with velocity $\mathbf{E}\mathbf{x}\mathbf{B}/B^2$ causes the magnetic field MAGNITUDE and DIRECTION to evolve in time in a manner consistent with Maxwell's equations.

MAGNITUDE

Magnetic field lines are not created or destroyed. As the field strength changes, they simply move into or out of the region of interest. Thus, magnetic field lines are conserved and the equation of continuity, for **B** in the Z-direction, is

$$\partial B_Z/\partial t + \nabla\cdot(B\mathbf{v}) = 0 \quad \text{(analogous to the equation of continuity for density)} \qquad (1)$$

Because it is assumed that $\mathbf{v} = \mathbf{E}\mathbf{x}\mathbf{B}/B^2$, the components of $B\mathbf{v}$ are $(B\mathbf{v})_X = E_Y$ and $(B\mathbf{v})_Y = -E_X$.

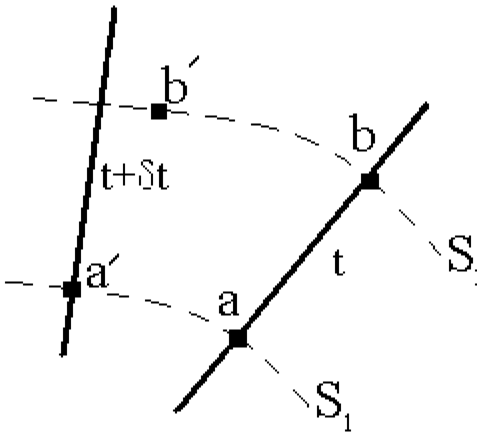
So $$\nabla\cdot(B\mathbf{v}) = \partial E_Y/\partial x - \partial E_X/\partial y$$

which is the Z-component of $\nabla\mathbf{x}\mathbf{E}$. Thus, the conservation equation is Faraday's law. <u>Without approximation and in the presence or absence of plasma</u>, the magnitude of the magnetic field is that expected from Maxwell's equations if magnetic field lines move with the $\mathbf{E}\mathbf{x}\mathbf{B}/B^2$ velocity.

It is noted that any velocity $\mathbf{v}'$ satisfying $\nabla\cdot(B\mathbf{v}') = 0$ may be added to $\mathbf{E}\mathbf{x}\mathbf{B}/B^2$ without modifying equation (1). Thus, there are an infinite number of magnetic field line velocities that preserve the magnitude of the field.

DIRECTION AT t+δt CONSISTENT WITH MAXWELL'S EQUATIONS

Consider two surfaces, S1 and S2, that are perpendicular to the magnetic field at times t and t + δt. At time, t, a magnetic field line intersects the two surfaces at points a and b. Thus, the vector (**b** – **a**) is parallel to **B**(t). At the later time, t + δt, the points a and b have moved at velocities **ExB**/B^2(a) and **ExB**/B^2(b) to points a' and b'. What are the constraints on these motions that cause (**b' - a'**) to be parallel to **B**(a, t+δt), i.e. $(\mathbf{b}' - \mathbf{a}') \times \mathbf{B}(a, t+\delta t) = 0$?



But $(\mathbf{b}' - \mathbf{a}')/\varepsilon = \mathbf{B} + \mathbf{B}\cdot\nabla(\mathbf{ExB}/B^2)\delta t$

and $\mathbf{B}(a, t + \delta t) = \mathbf{B} + (\partial\mathbf{B}/\partial t)\delta t + ((\mathbf{ExB}/B^2)\cdot\nabla)\mathbf{B}\delta t$

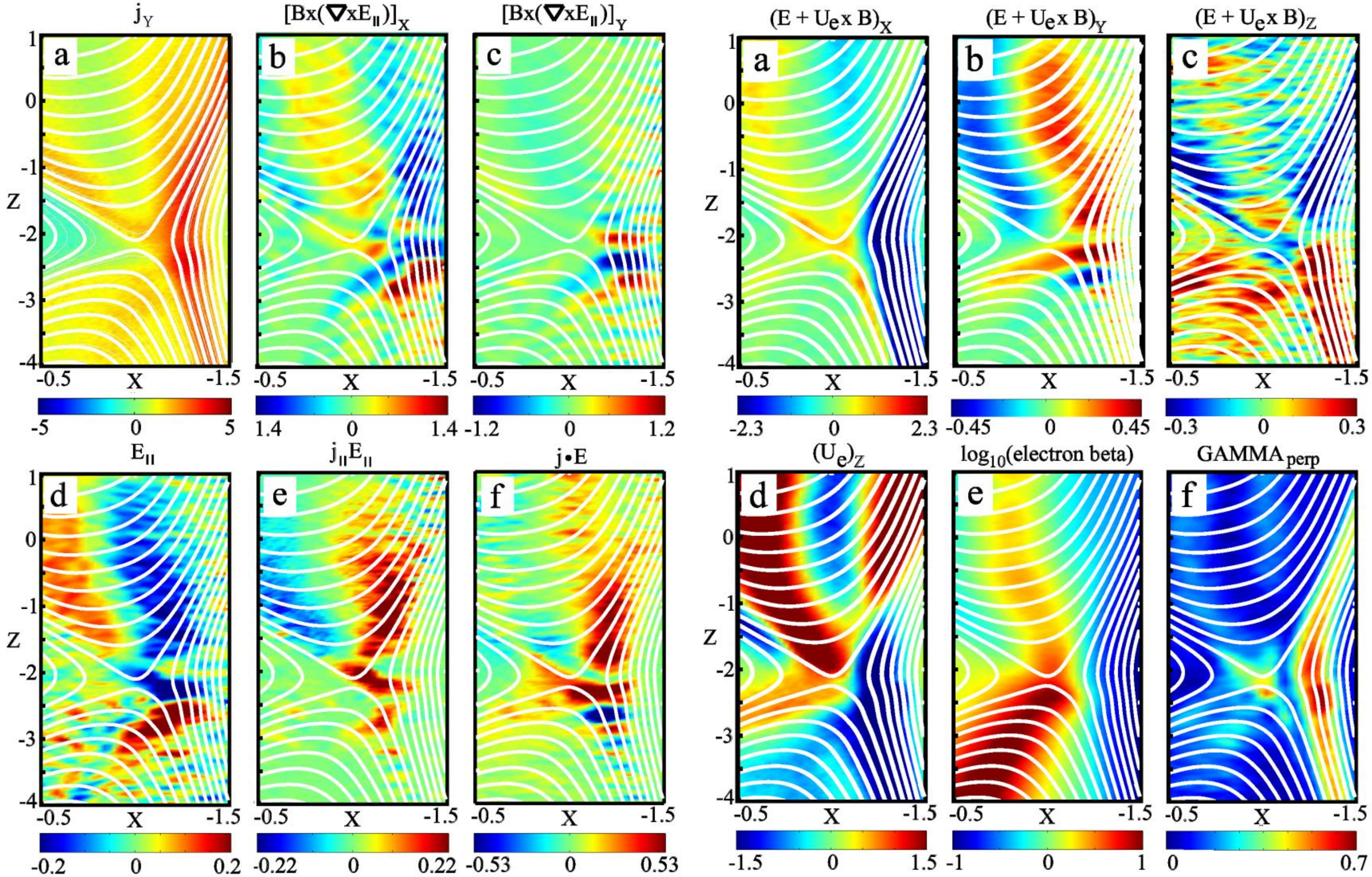
After taking the cross product and simplifying

$$\mathbf{B} \times (\nabla\times\mathbf{E}_{||}) = 0$$

IF $\mathbf{E}_{||} = 0$, **ExB**/B^2 MOTION CAUSES THE FIELD TO EVOLVE IN A MANNER CONSISTENT WITH MAXWELL'S EQUATIONS.

IF $\mathbf{Bx}(\nabla\mathbf{xE}_{||}) \neq 0$, MAXWELL'S EQUATIONS MUST BE SOLVED TO FIND B(t).

EVIDENCE THAT **B x (∇xE$_{||}$)** ≠ 0 DURING RECONNECTION



MYTH 4

Magic things happen at the X-line like:

It is the locale of electromagnetic energy conversion

Field line “breaking”

Ion and electron acceleration

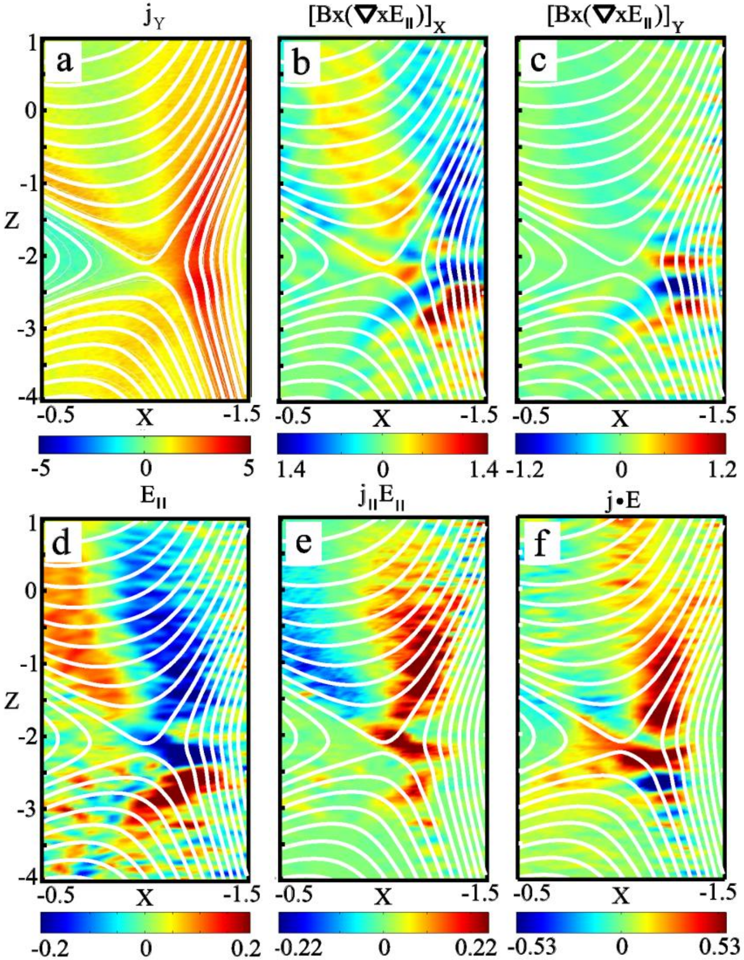
Big fields and waves

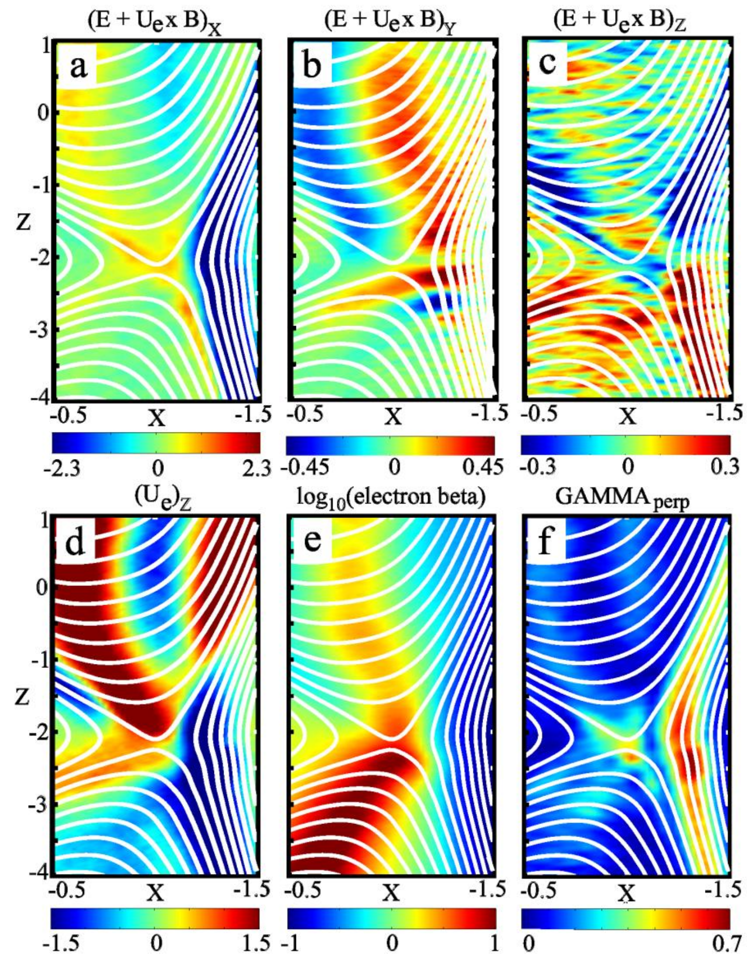
THE LOCALE OF ELECTROMAGNETIC ENERGY CONVERSION

- For reconnection in the resistor, the X-line was a minimum of electromagnetic energy conversion because **j** was minimum there. This is also true in 2D simulations.

- In 2D simulations, the X-line is not the main locale of electromagnetic energy conversion (next slide)

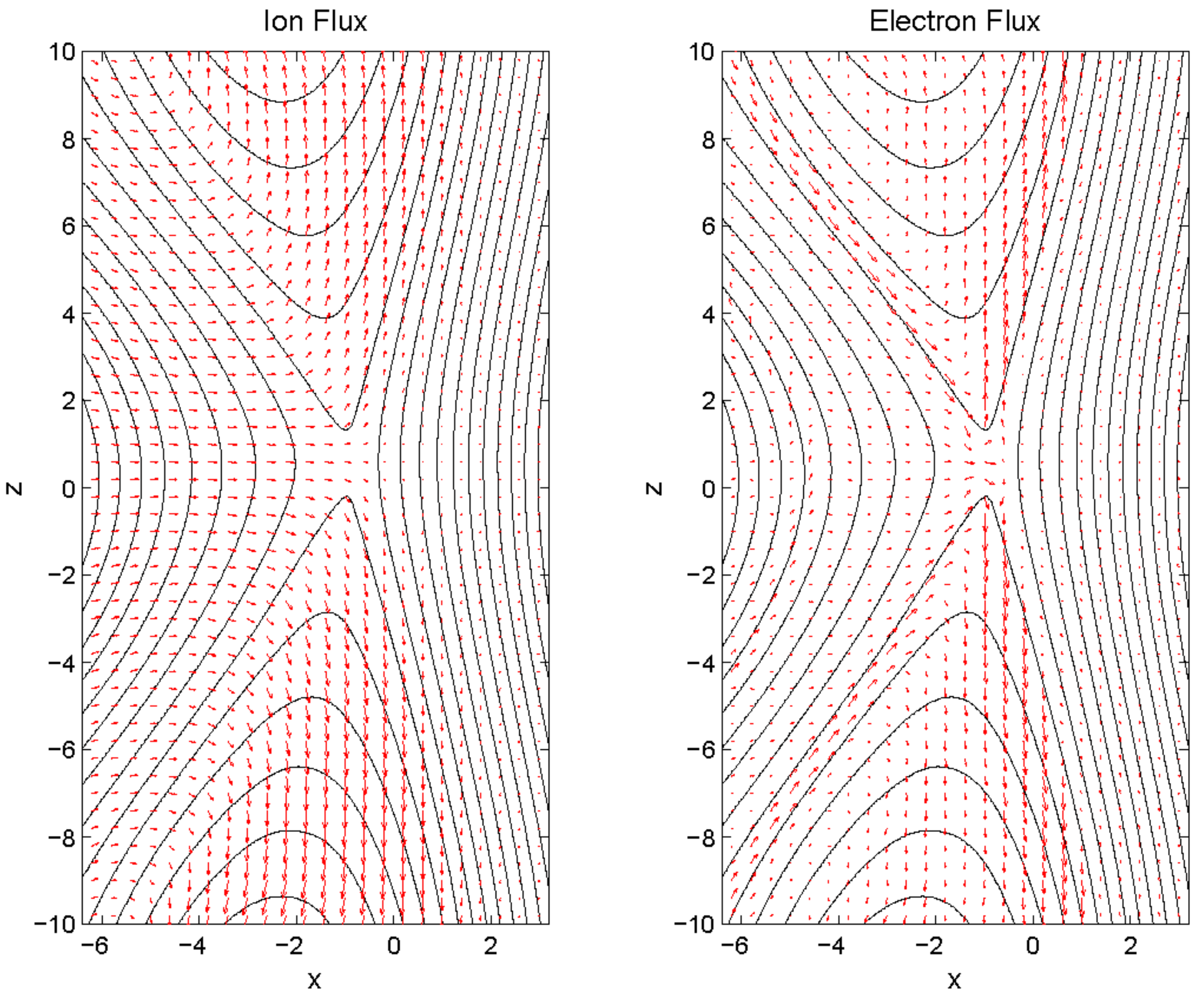
EVIDENCE THAT $\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) \neq 0$ DURING RECONNECTION

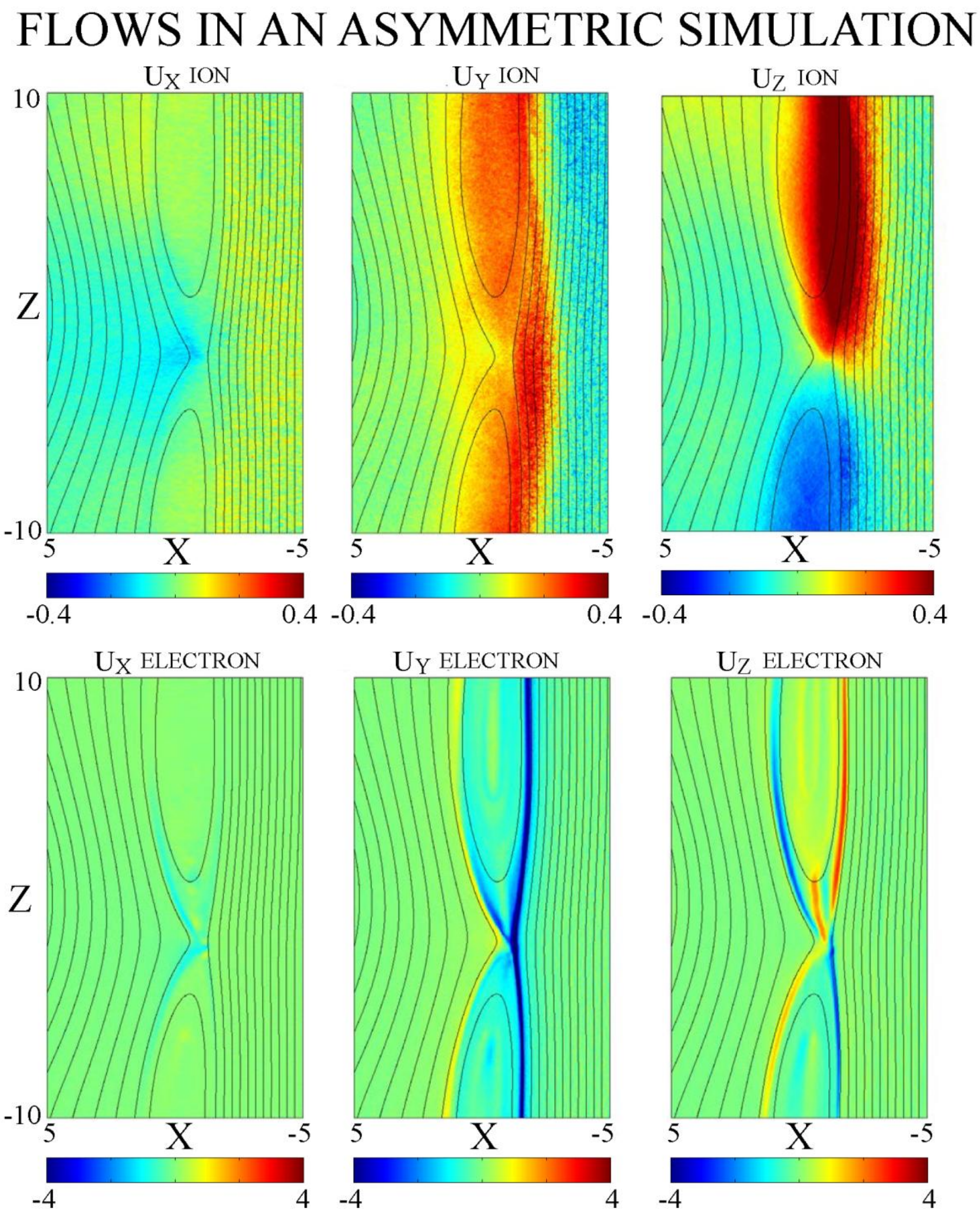




ARE IONS AND ELECTRONS ACCELERATED IN THE SMALL REGION AROUND THE X-LINE?

NO





Ions flow in + Y-direction and electrons flow in –Y-direction to provide the current that is required by non-zero Curl**B**

X-direction ion flow into the reconnection region from both sides over >5 c/ω_{pI} and then vertically out in Z-direction. They are accelerated by E_X.

Electrons flow along magnetic field lines toward the X-line from the magnetosheath and out along magnetic field lines toward the magnetosphere. This is how the electrons move to maintain charge neutrality.

Electrons are accelerated near the X-line to flow out at super Alfvenic speeds before slowing to the Alfven speed and leaving at the same speed as the ions.

ARE THE DC AND AC ELECTRIC FIELDS UNUSUAL AT THE X-LINE?

Examine satellite data at one such crossing to show that they are NOT

Random chance of passing within an electron skin depth of the X-line is ~1/1000

Have examined ~200 crossings and found one that did

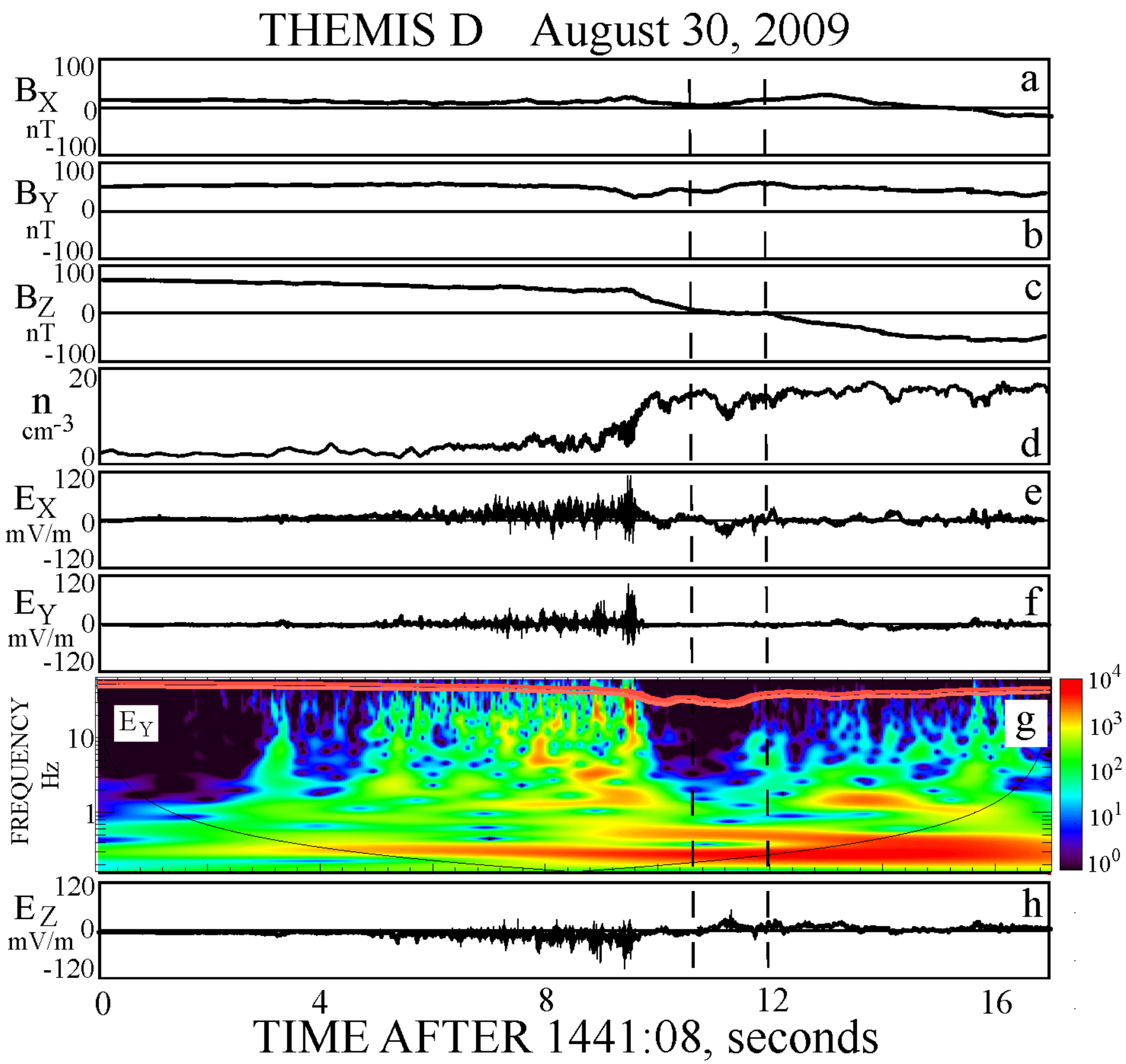
EVIDENCE OF CROSSING AT THE X-LINE

1. $\mathbf{E} \neq \mathbf{U}\mathrm{x}\mathbf{B}$, so other terms in the Generalized Ohm's Law are important.
2. No ion outflow, $U_{IZ} < 0.1V_{alfven}$
3. High resolution electron data has <1 second signatures expected only at the X-line

   <1 second burst of energetic electrons (300-3000 eV) perpendicular to B with . . speeds up to ~3000 km/sec (~6 times V_{alfven})

   20-150 eV electrons moving along field line in one direction (anti-B direction).
4. EM and ES wave turbulence for ~0.2 seconds. No anomalous drag due to these fields and little Poynting flux. But they are signatures of being near the X-line

FOCUS ON THE WAVES AT THE CROSSING



Sub-solar magnetopause crossing (magnetosphere to magnetosheath) at 9.4 R_E, local time 12:38, latitude -10°

Data in minimum variance of B coordinate system.

Electrostatic lower hybrid drift waves at magnetospheric separatrix.

$Beta_e < 0.01$

T_{perp}/T_{par} =1±.15 for e and I

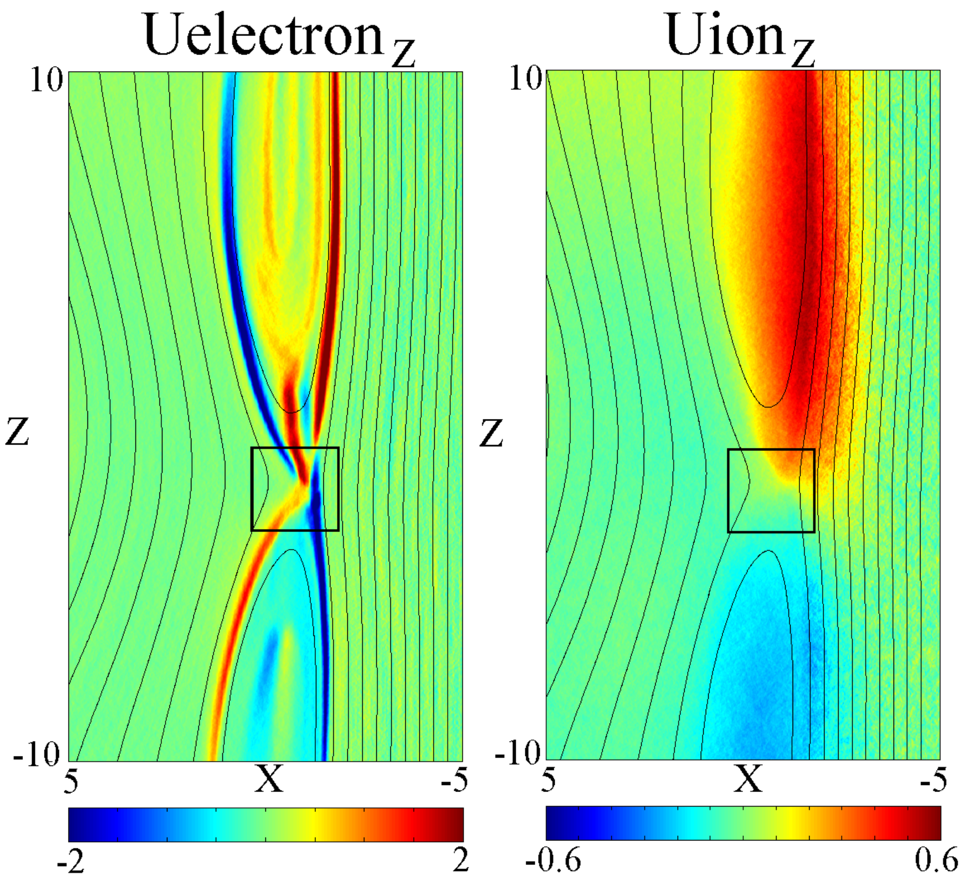
Bguide ~ 0.6

TWO REGIONS OF INTEREST

1. Region of turbulence near magnetospheric separatrix.

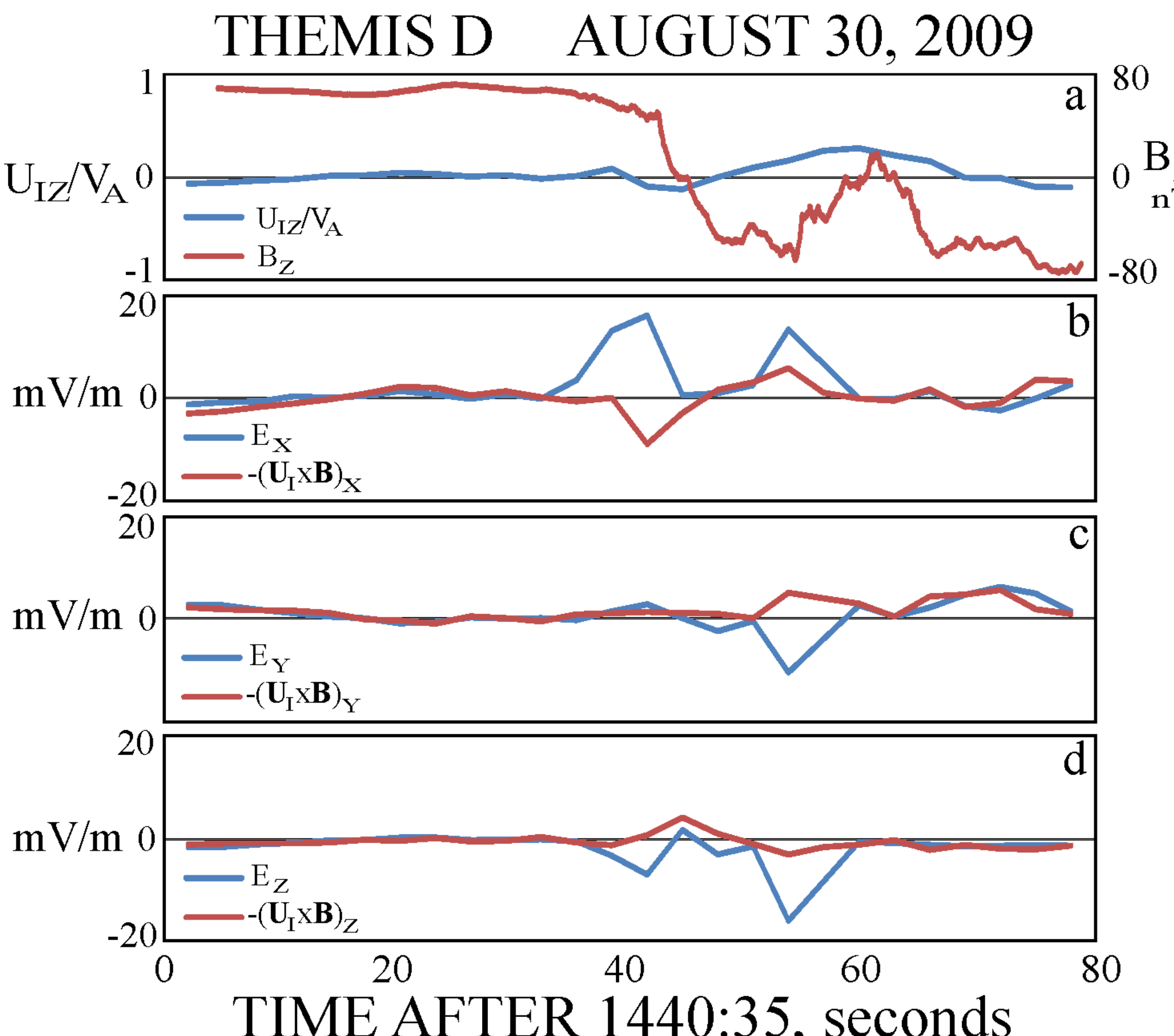
2. Region around the two dashed lines during which $B_Z = 0$ and X-line was crossed. Dearth of wave power in this region.

PLASMA DATA SHOWS THAT THE SPACECRAFT CROSSED THROUGH THE RECONNECTION REGION NEAR THE X-LINE



EXPECTATIONS FROM SIMULATIONS

1. $B_Z = 0$
2. $U_{iZ} << V_{ALFVEN}$
3. $-\mathbf{U}_i x \mathbf{B} \neq \mathbf{E}$
4. Burst of field aligned electrons of 20-150 eV
5. Burst of 0.3-3 keV super-Alfvenic electrons perpendicular to **B**



Region of interest is at 44 seconds in this plot

Ion outflow speed is $<0.1V_A$

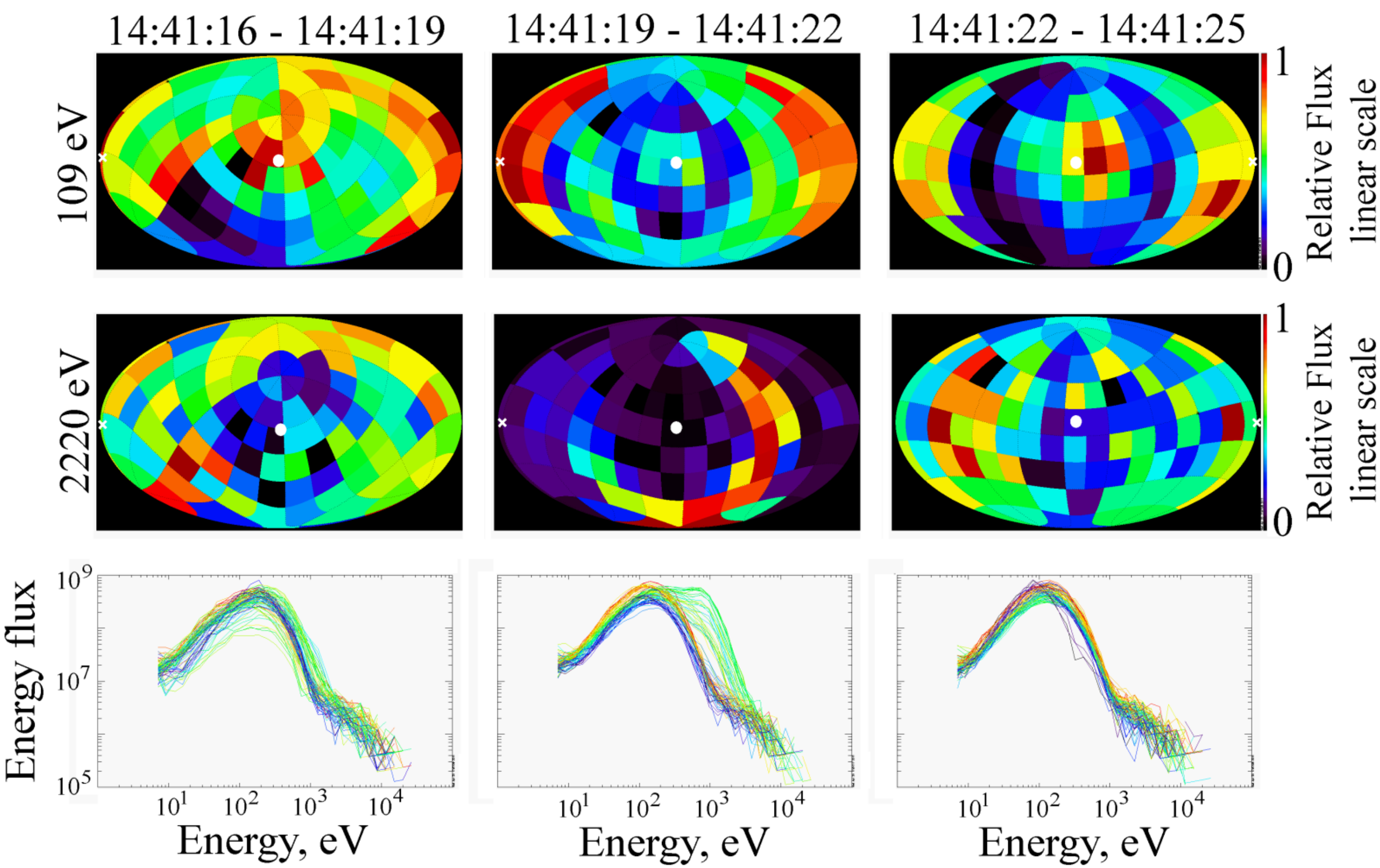
Electric fields at 3 second spin period resolution

$E_X \neq -(\mathbf{U}_i x \mathbf{B})_X$

$E_Y \neq -(\mathbf{U}_i x \mathbf{B})_Y$

$E_Z \neq -(\mathbf{U}_i x \mathbf{B})_Z$

THEMIS D ELECTRONS ON AUGUST 30, 2009



Columns represent 3 successive 3 second spin periods

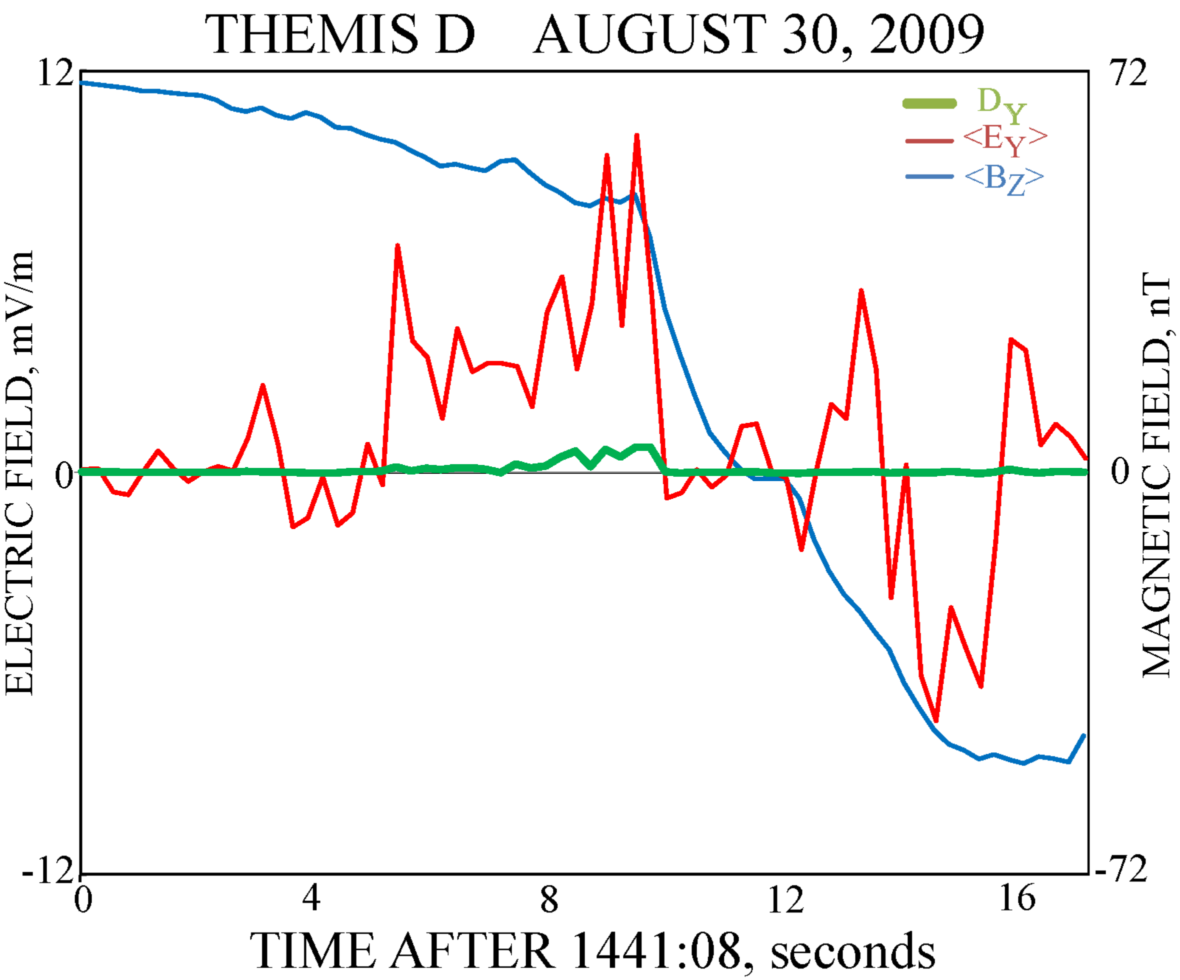
Rows represent 109 eV and 2220 eV electrons

B is at the center of each plot and anti-B is around the periphery

Observe ~100 eV field-aligned electrons and

~2 keV perpendicular electrons with velocity ~6 V_A

DRAG AT MAGNETOSPHERIC SEPARATRIX NEAR THE X-LINE



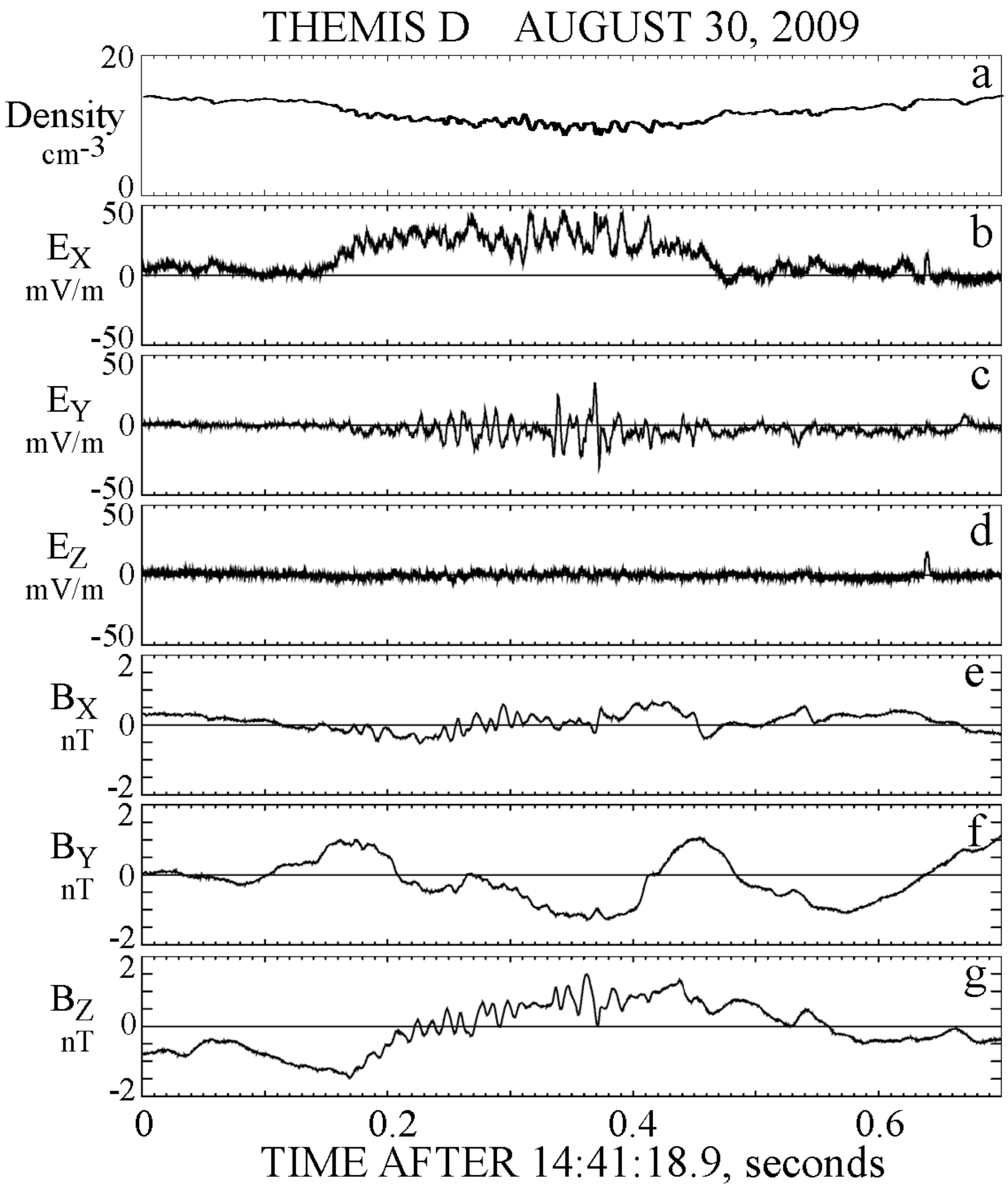
At the magnetospheric separatrix, $D_Y < 0.1E_Y$

At the current layer and especially where $B_Z = 0$,

$D_Y < 0.01E_Y$

ANOMALOUS DRAG DUE TO WAVES IS UNIMPORTANT

0.7 SECONDS OF DATA IN REGION WHERE $B_Z \sim 0$



Data in field-aligned coordinates with Z parallel to the local magnetic field

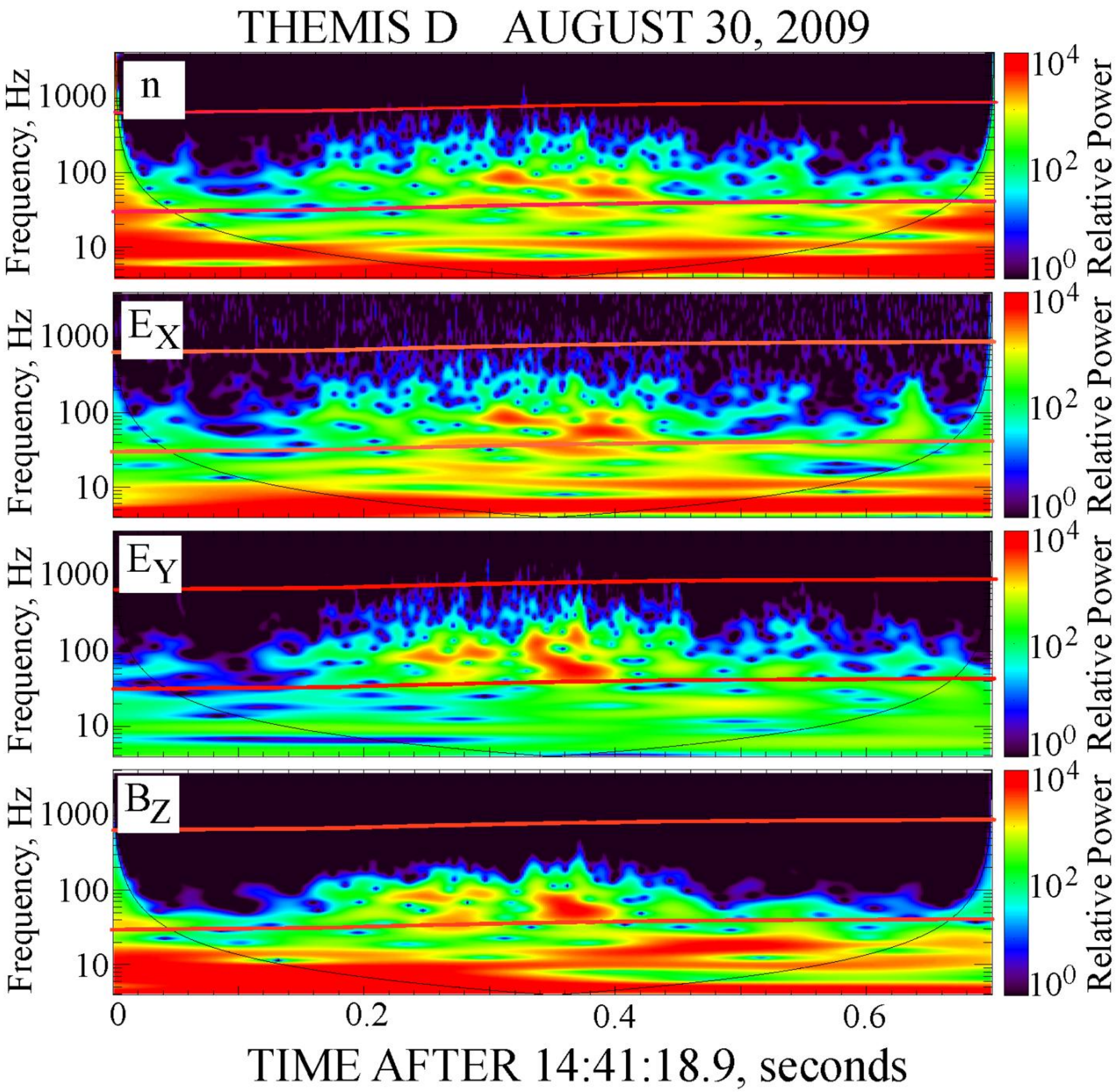
B data comes from search coil magnetometer

Observe ~0.2 seconds of turbulence in density (panel a), electric fields (panels b and c) and magnetic field (panel g)

Biggest B fluctuations are parallel to the background B

Parallel electric field consistent with zero except for 4 msec burst near 0.64 seconds (panel d)

EXAMINATION OF THE WAVE TURBULENCE



Data in field-aligned coordinates

Red lines are ν_{LH} and $\nu_{el}/2$

Note similarity of spectra in n and EX (correlation = -0.94)

Note similarity of spectra in EY and BZ (correlation = 0.72 after phase shift)

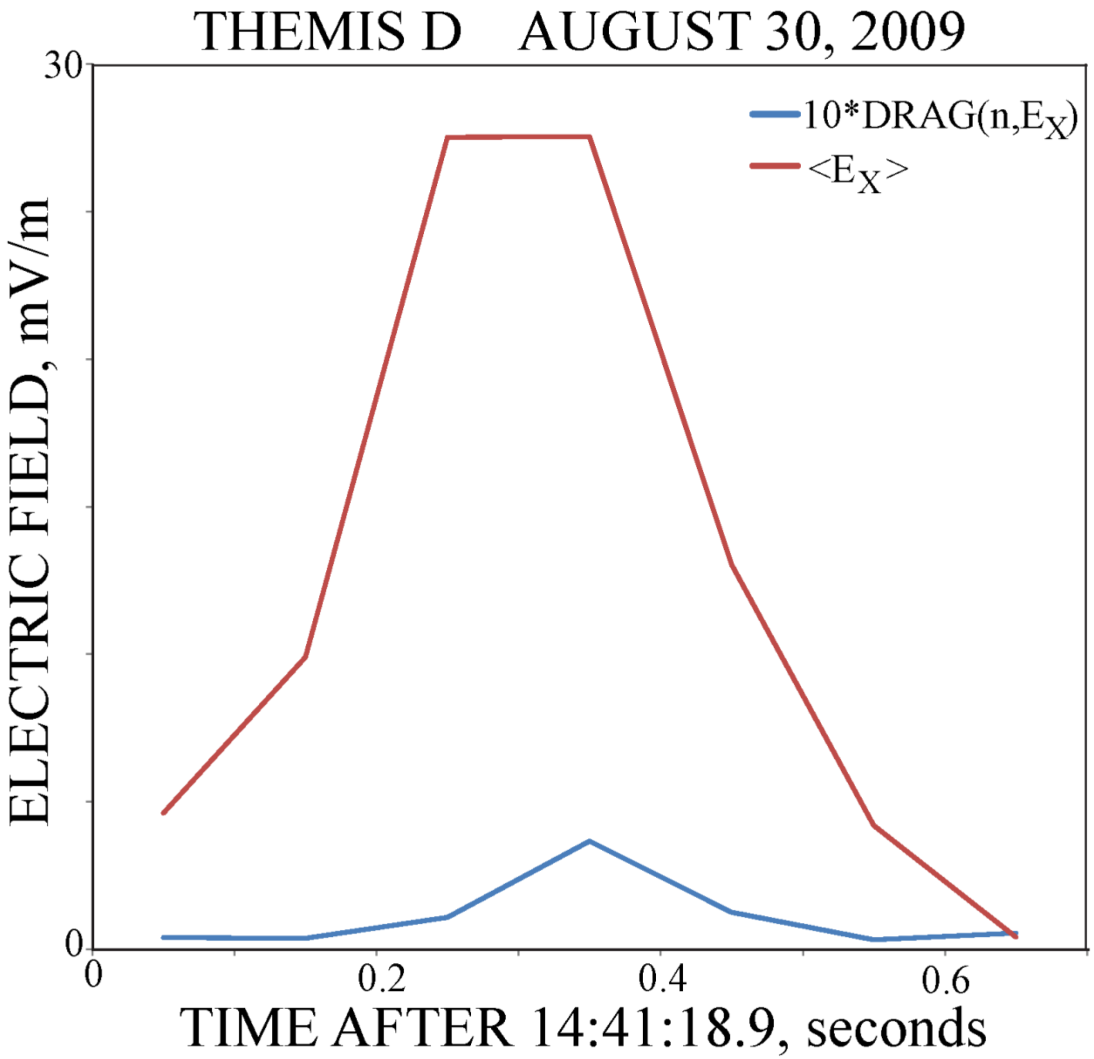
HAVE ELECTROSTATIC AND ELECTROMAGNETIC WAVE COMPONENTS DURING SAME 0.2 SECONDS

If relative speed = 10-50 km/sec 0.1 second wave covers 1-5 km, which is 0.7-3.5 c/ω_{pe}

SIMILAR WAVES ARE SIGNS OF THE X-LINE

Huang et al, Phys. Plasmas, **16**, 042107 (2009)
Daughton, Phys. Plasmas, **10**, 3103, (2003)
Ji et al, Phys. Rev. Lett., **92**, 115001-1, (2004).

ELECTROSTATIC WAVE IN E_X AND DENSITY

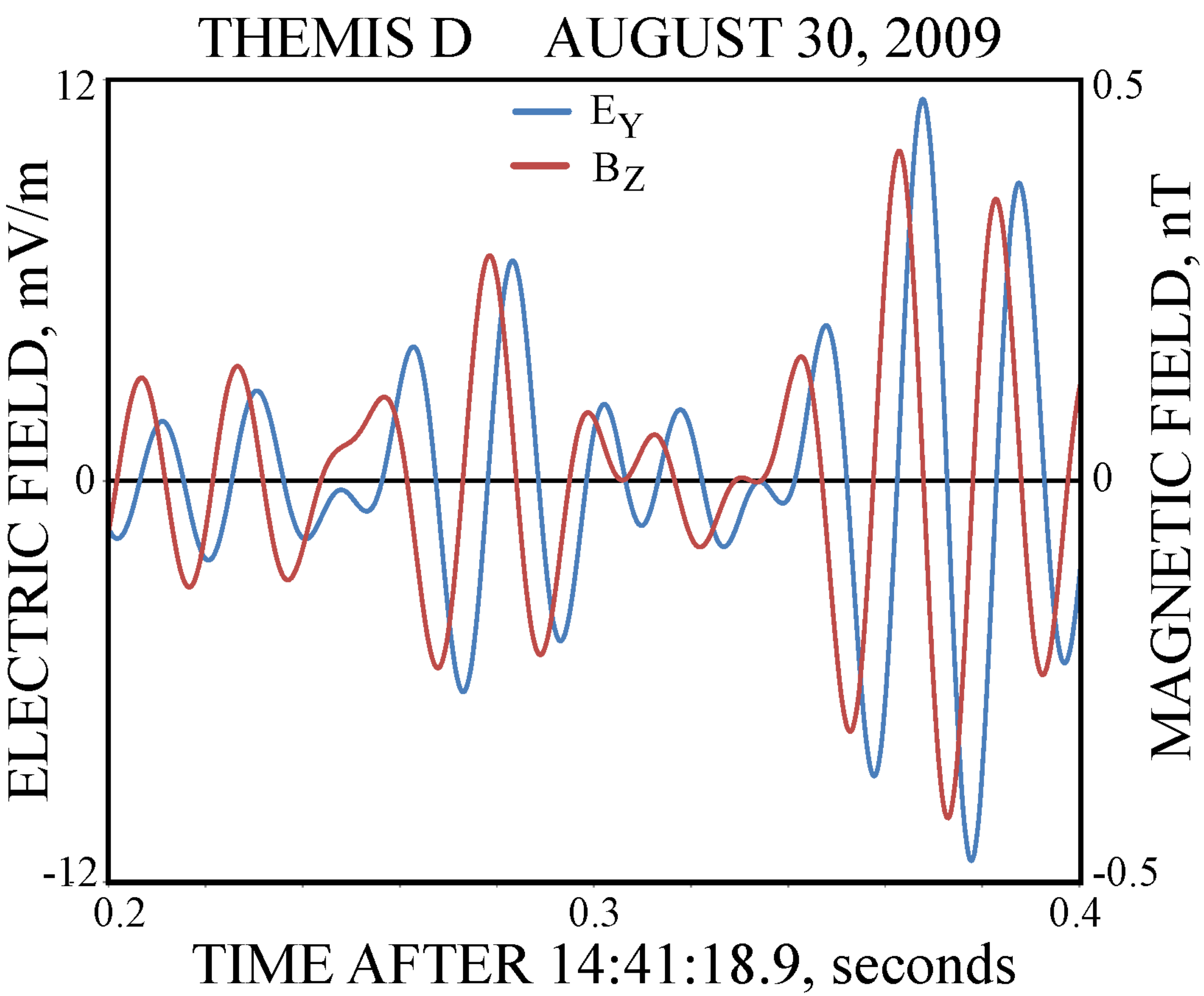


For waves of 10-200 Hz
DRAG < $.01E_X$

CONCLUSION:
Anomalous drag due to the electrostatic wave is not sufficient to support the reconnection electric field, even at the X-line

k in X(min var) direction

ELECTROMAGNETIC WAVE IN E_Y AND B_Z



PROPERTIES

- f_{LH} = 34-40 Hz
- Fields filtered 30-60 Hz
- δB_Z parallel to B_o
- Waves ~90° out of phase
- $\delta E_Y/\delta B_Z$ = 24 mV/m-nT
- **k** in X(min var) direction
- Poynting flux small

  ~0.05 eV/particle

ANOMALOUS DRAG DUE TO ELECTROMAGNETIC WAVES

For electrostatic waves we had

$$\langle E_Y \rangle = -\langle nm(\partial \mathbf{U}_e/\partial t + \mathbf{U}_e \cdot \nabla \mathbf{U}_e)_Y \rangle / e\langle n \rangle - \langle (n\mathbf{U}_e \mathrm{x} \mathbf{B})_Y \rangle / \langle n \rangle - \langle (\nabla \cdot P_e)_Y \rangle / e\langle n \rangle + D_Y$$

D_Y = Anomalous drag due to electrostatic waves $\equiv -\langle \delta n \delta E_Y \rangle / \langle n \rangle$

One may also include the drag due to electromagnetic waves by averaging the second term on the right of the above equation in the same way that the left side was averaged. i.e., by setting $nU_{eZ} = \langle nU_{eZ} \rangle + \delta(nU_{eZ})$, etc. In this way the second term becomes

$$[-\langle nU_{eZ} \rangle \langle B_X \rangle + \langle nU_{eX} \rangle \langle B_Z \rangle - \langle \delta(nU_{eZ}) \delta B_X \rangle + \langle \delta(nU_{eX}) \delta B_Z \rangle] / \langle n \rangle$$

For electromagnetic drag to be important the terms involving the fluctuations must be comparable to the terms involving the averages

Experimentally $\delta(n)/\langle n \rangle < 0.1$ and $\delta B_X/\langle B_X \rangle < 0.1$ so, even with perfect correlations of the fluctuating density and magnetic field, the fluctuation terms must be small compared to the average terms unless $\delta U_{eZ}/\langle U_{eZ} \rangle$ 100, which is unreasonable.

ANOMALOUS DRAG DUE TO THE ELECTROMAGNETIC WAVE IS SMALL

THESE ELECTROSTATIC AND ELECTROMAGNETIC WAVES DO NOT APPEAR TO DO ANYTHING.

THEIR ANOMALOUS DRAG IS INSUFFICIENT TO SUPPORT THE ELECTRIC FIELD

THEIR POYNTING FLUX IS TOO SMALL

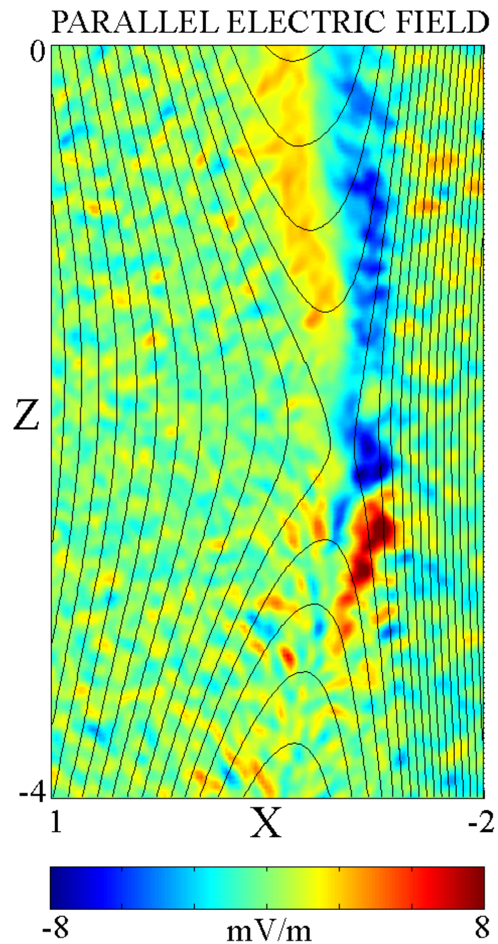
THE PARALLEL ELECTRIC FIELD IS NOT SIGNIFICANT

THE PARALLEL ELECTRIC FIELD

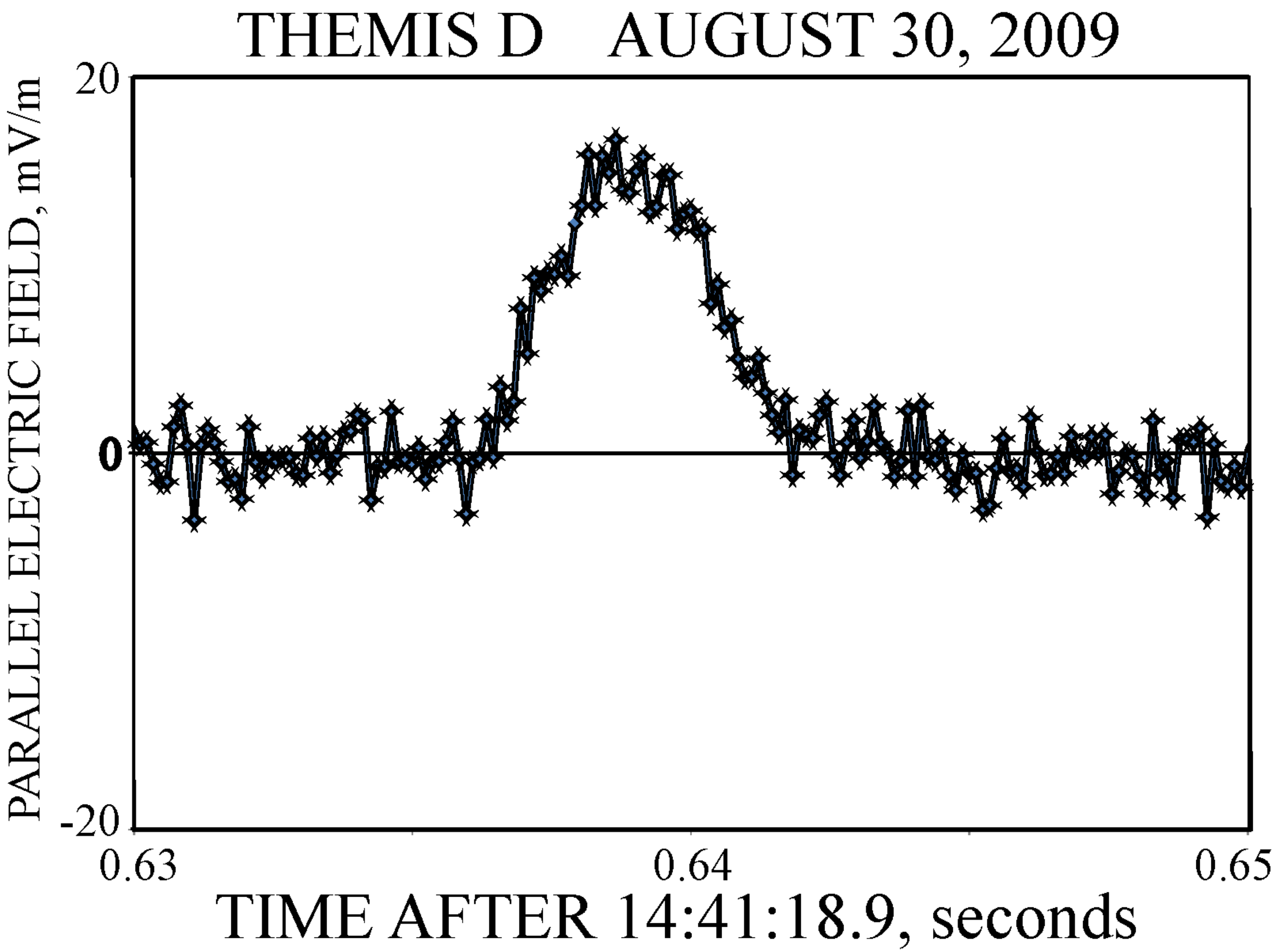
Measured $E_{||}$ has uncertainty of ± 4 mV/m due to uncertainty of shorting factor.

Within uncertainty, measured $E_{||} = 0$, except for pulse 0.15 seconds after the waves.

This is consistent with the parallel electric field seen in simulations. (Can fly through the region and see no $E_{||}$ or short pulses of $E_{||}$)



FOUR MILLISECOND PARALLEL ELECTRIC FIELD PULSE



Pulse lasts 4 milliseconds with amplitude of 15 mV/m.

If speed = 100 km/sec, pulse potential = 6 V

SUMMARY - PROPERTIES OF THESE WAVES

Signatures of the reconnection X-line

Low beta ($\beta_e < 0.1$) and large $B_G \sim 0.6$

ES and EM waves that are coupled?

δB parallel to B_o

ν = LH and above

λ = 9 km ~ 6 electron skin depths

k for both waves is perpendicular to the current sheet

Unimportant electrostatic and electromagnetic drag associated with them

δE and δB are ~90 degrees out of phase so waves carry little Poynting flux

Not the mode observed in MRX because, in MRX

- δB is not parallel to B_o, it is right circular polarized
- Lab waves are below LH frequency
- Lab example had $B_G \sim 0$
- Waves propagate obliquely to B_o
- $\delta B/B_o$ ~5%, (In the magnetosphere $\delta B/B_o$ ~2%)

TIMING OF EVENTS in seconds after 14:41:08

$\mathbf{E} \neq \mathbf{U}\text{x}\mathbf{B}$	5-35
TURBULENCE AT MAGNETOSPHERIC SEPARATRIX	8-9.5
CURRENT LAYER	9.5-14
BZ ~0 REGION	11.1-11.8
ELECTROSTATIC AND ELECTROMAGNETIC WAVES	11.2-11.4
PARALLEL ELECTRIC FIELD PULSE	11.55
FIELD ALIGNED ELECTRONS AND ACCELERATED ELECTRON OUTFLOW	13-14

PROPERTIES OF THE RECONNECTION SITE

1. $E \neq -U \times B$
2. Significant parallel electric field not found (Consistent with simulations)
3. Parallel electric field spike observed. (Often seen in other data and simulations)
4. Electrostatic waves but anomalous drag is ineffective in supporting the quasi-DC electric field.
5. Electromagnetic waves present but with little Poynting flux and drag.
6. No ion outflow
7. Field aligned 20-150 eV electrons are present.
8. Perpendicular beams of ~0.3-3 keV electrons are present with speeds $\sim 6V_A$

THE END

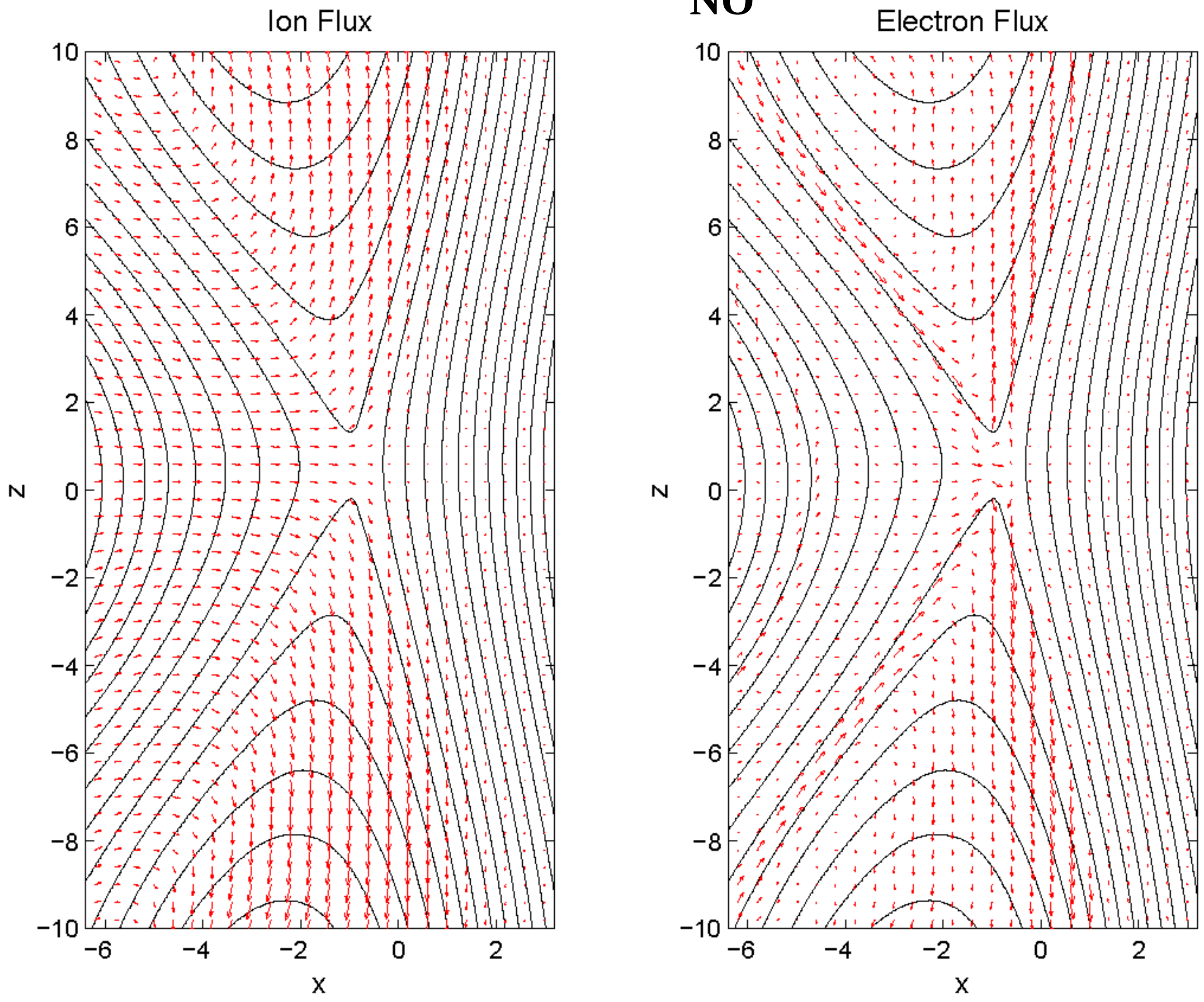
Without a summary?

Yes, without a summary!

WHERE DO THE IONS AND ELECTRONS GET ACCELERATED?

ARE THEY ALL ACCELERATED IN THE SMALL REGION AROUND THE X-LINE (SOMETIMES CALLED THE ELECTRON DIFFUSION REGION)?

NO



Note: These are plots of flux, not velocity

III MAGNETIC FIELD LINE MOTION

TO UNDERSTAND RECONNECTION WE MUST FIRST UNDERSTAND MAGNETIC FIELD LINE MOTION

NOTE - Valid if **$\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) = 0$**, which is true for our resistor problem (BUT NOT FOR RECONNECTION IN GENERAL)

DO MAGNETIC FIELD LINES ACTUALLY MOVE?

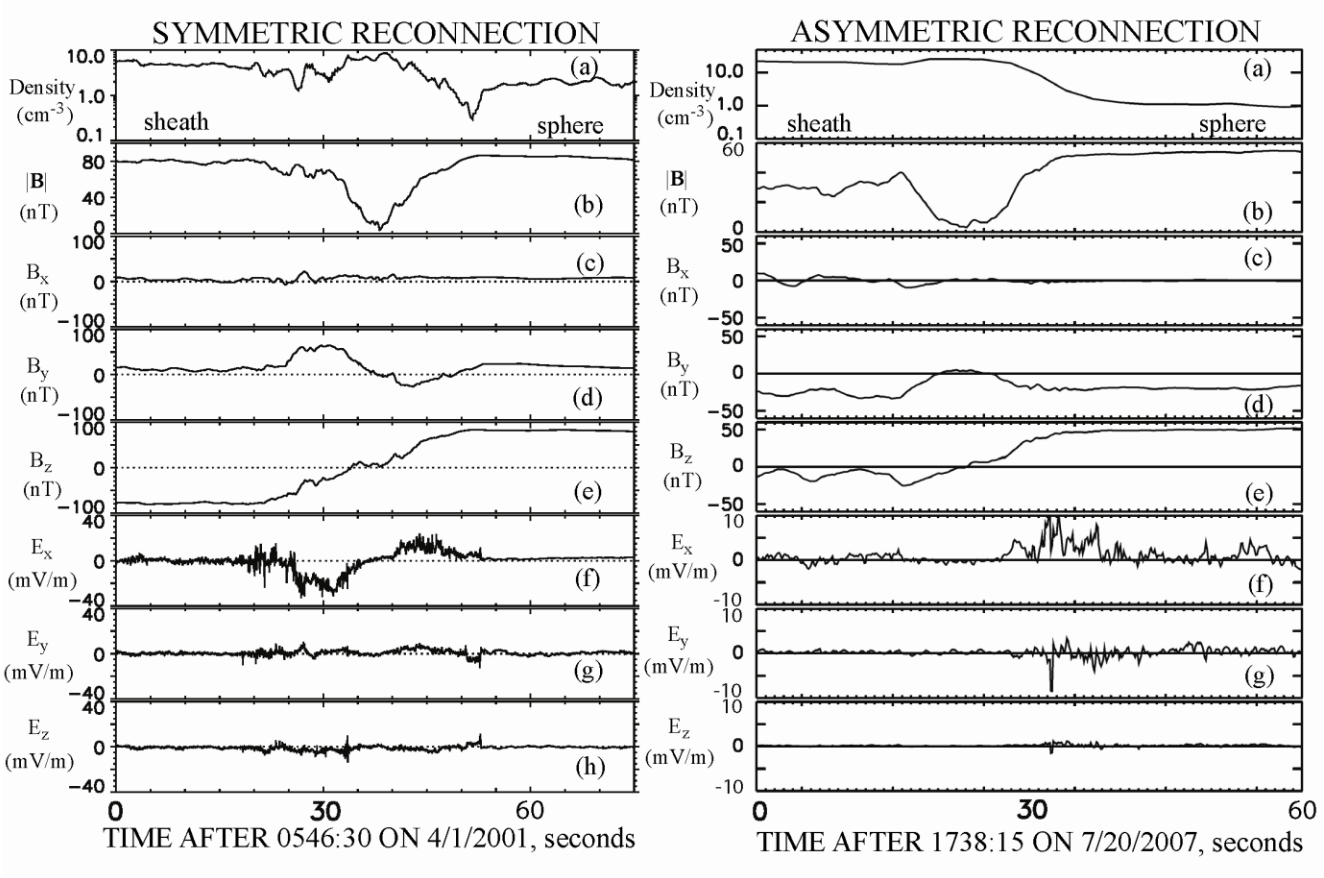
For this to be a well-posed scientific question, one must be able to describe an experiment that can answer this question. There is no such experiment because one magnetic field line looks just like the next one.

SO, WHY TALK ABOUT MOVING MAGNETIC FIELD LINES?

FOR THIS TALK, *the sole purpose of thinking that magnetic field lines move with* $\mathbf{v} = \mathbf{E}x\mathbf{B}/B^2$ *is to provide a means for visualizing the time evolution of the magnetic field without having to solve Maxwell's equations.*

This temporal evolution at $\mathbf{v} = \mathbf{E}x\mathbf{B}/B^2$ *is only acceptable if it agrees with results obtained by solving Maxwell's equations. So it is necessary to consider the requirement that the magnetic field that evolves by moving field lines at* $\mathbf{E}x\mathbf{B}/B^2$ *is identical to that found from solving Maxwell's equations.*

ELECTRIC FIELDS THAT ACCELERATE THE IONS IN SYMMETRIC AND ASYMMETRIC RECONNECTION



Magnetosheath on left, magnetosphere on right.

Symmetric when |BZ| (panels e) and n (panels a) ~same on both sides. Asymmetric otherwise

Quadrupolar BY and bipolar EX for symmetric reconnection. Not for asymmetric.

Symmetric reconnection usually occurs in the magnetotail, asymmetric everywhere else.