Theory and Simulations of Magnetic Reconnection at the Dayside Magnetopause

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Magnetic Reconnection in Plasmas
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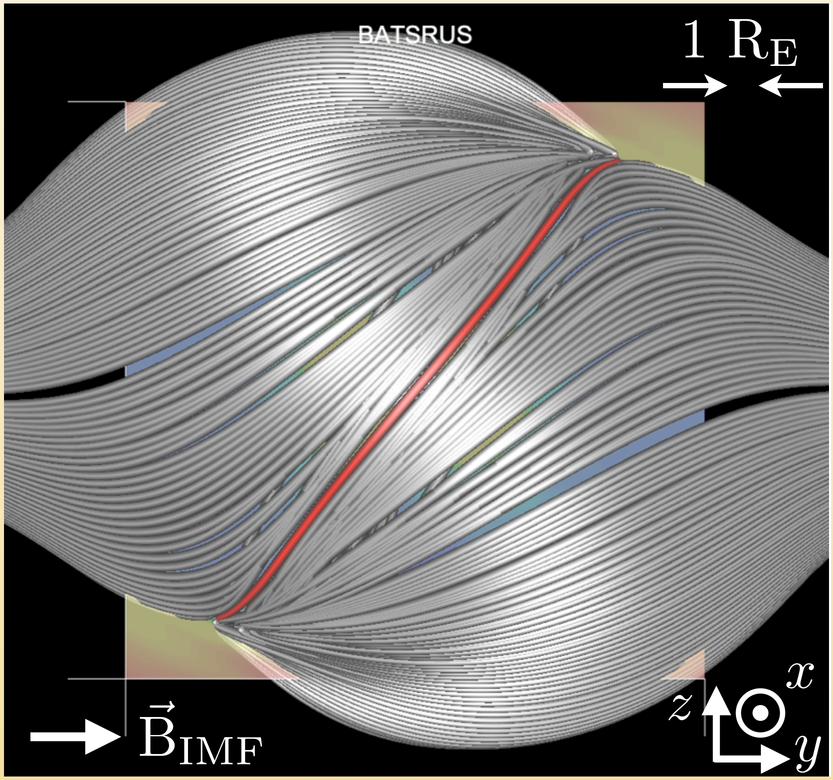
Dayside Reconnection

- Advances in the last decade are vastly changing our understanding of dayside reconnection
  - Both observational and numerical/theoretical

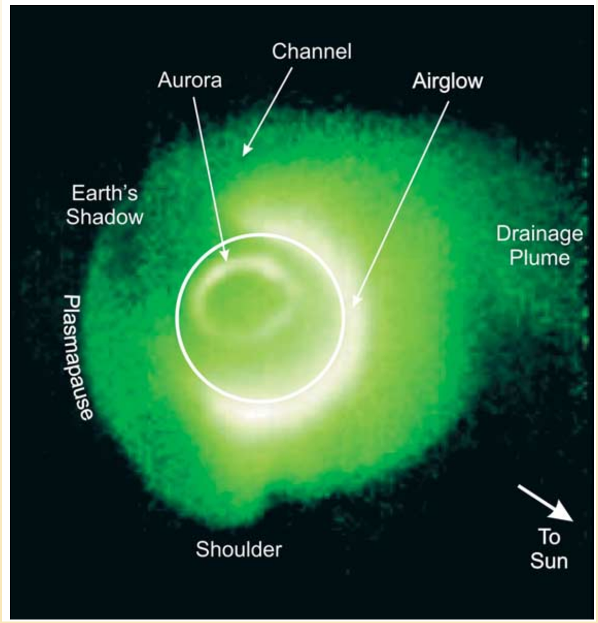


- This talk:
  - *Quantifying* local properties of dayside reconnection for arbitrary solar wind conditions
    - Global MHD simulations
  - Impact of magnetosheath flow (due to solar wind) on dayside reconnection ("asymmetric reconnection with a flow shear")
    - Theory and two-fluid/PIC simulations
- Many results here are applicable to other settings

Some results are surprising!

Quantifying Dayside Reconnection

- The canon of solar wind-magnetospheric coupling
  - The amount and rate of flux reconnected at dayside is controlled (solely) by input from the solar wind
    - Up until saturation of polar cap
  - Long time goal - describe coupling efficiency completely in terms of solar wind parameters (see Newell et al., 2007 for a review)
  - Borovsky and Denton, 2006 showed geomagnetic indices are altered when there is a plasmaspheric plume (pictured) at the dayside reconnection site
    - Solar wind is not only controller of geomagnetic indices!



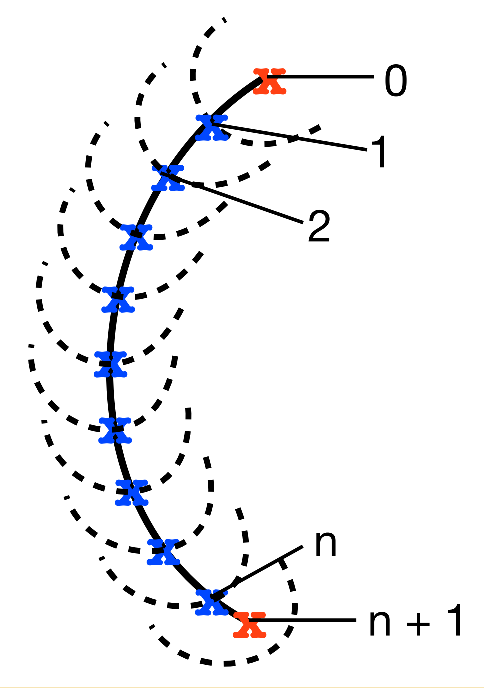
Sandel et al., 2003

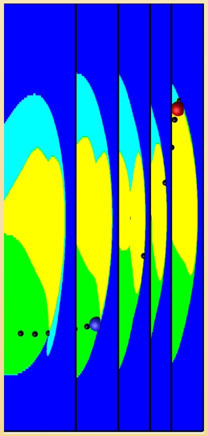
- Up until relatively recently, it has been hard to even find where dayside reconnection happens in global simulations!
  - Except for simplest cases (southward IMF with no dipole tilt)
    - How can dayside reconnection be quantified if it can't even be located?!?
      - Very important for understanding solar wind-magnetospheric coupling
        - » Similar problem for solar corona

Finding Dayside Reconnection

- Solar context
  - Intersection of separator surfaces (Longcope and Cowley, Phys. Plasmas, 1996)
  - Progressive Interpolation Method (PIM) (Close et al., Solar Phys., 2004)
  - Simulated annealing (Beveridge, Solar Phys., 2006)

- Magnetospheric context
  - Map of field topology in a given plane (Dorelli and Bhattacharjee, JGR, 2009)
  - Sample topology, find where it changes along where separator (X-line) should be (Laitinen et al., Ann. Geophys., 2006; JGR, 2007)
  - Simple, robust method to find X-line (separators) (Komar et al., JGR, 2013)
    - Locate magnetic nulls (X) (Haynes and Parnell, Phys. Plasmas, 2010)
    - Center hemisphere at null, find topology of field lines on surface
    - Find point where topologies meet (X), center new hemisphere there
    - Repeat until other null is encountered
      - Works independent of IMF conditions, works to desired accuracy
  - Recent improvements (Glocer et al., JGR, submitted)
    - Extension of above to be more efficient and allow for bifurcating X-lines (FTEs)
    - Find intersection of separator surfaces
    - Find separator location in collection of planes; more efficient than above mechanism





We used Komar et al., JGR (2013) approach to find separators in many global MHD simulations

The Reconnection Plane

- It is usually assumed that the plane of reconnection is normal to separator (X-line)
  - Previously investigated by Parnell et al., JGR (2010)

- How we find reconnection plane
  - Minimum variance analysis is usually not the best tool
  - For every point along the separator, define reconnection plane
    - Out-of-plane (z') - 2nd order finite difference of adjacent points on separator

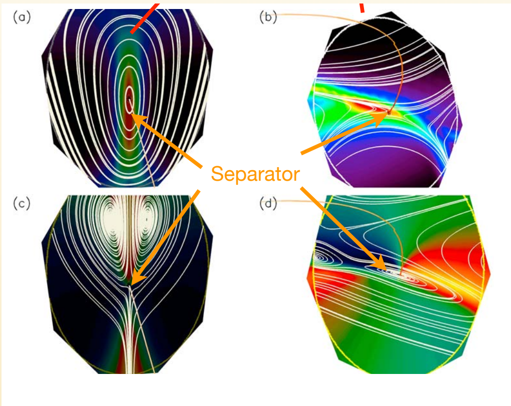
$$\hat{\mathbf{z}}'_k = \frac{\mathbf{r}_{k-1} - \mathbf{r}_{k+1}}{|\mathbf{r}_{k-1} - \mathbf{r}_{k+1}|}$$

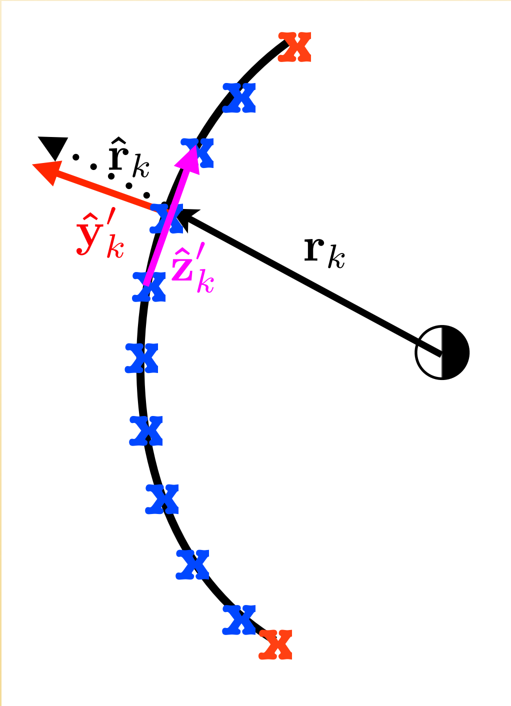
    - Inflow (y') - Projection of radius vector normal to z'

$$\mathbf{y}'_k \propto \mathbf{r}'_k - (\mathbf{r}'_k \cdot \hat{\mathbf{z}}'_k)\hat{\mathbf{z}}'_k$$

    - Outflow (x') - completes triad

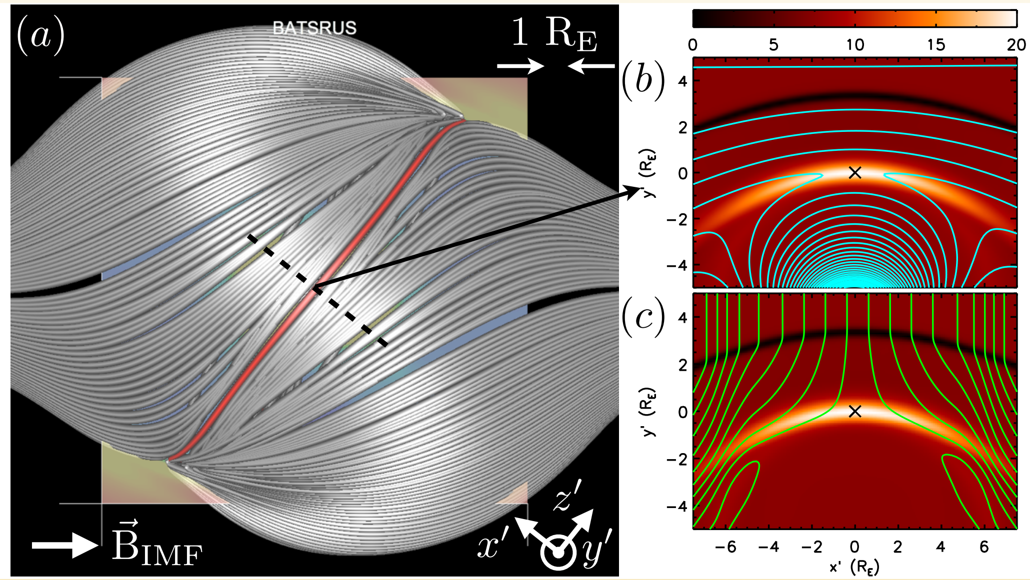
$$\hat{\mathbf{x}}'_k = \hat{\mathbf{y}}'_k \times \hat{\mathbf{z}}'_k$$



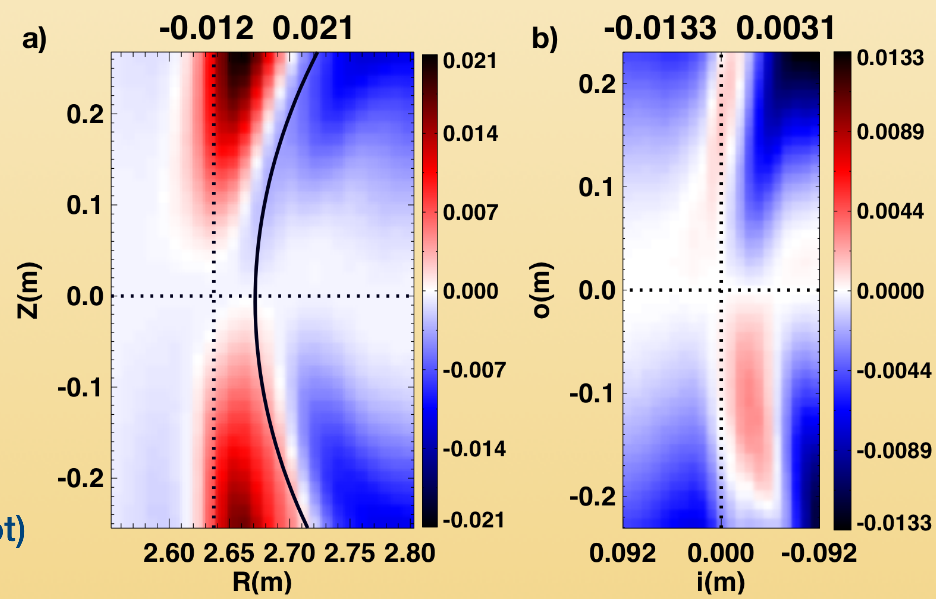


Reconnection Plane in Simulations

- Used BATS-R-US at NASA's CCMC (should work for any code though)
  - 3D resistive MHD, rectangular & irregular grid, highest resolution is 1/8 R_E
  - No dipole tilt with steady solar wind with no B_x (in GSM) for simplicity
  - Typical simulation - B_{IMF} = 20 nT, n_{SW} = 20 cm^{-3}, $v_{SW,x}$ = -400 km/s, T_{SW} = 20 eV (β_{SW} = 0.4)
  - Explicit resistivity $\eta/\mu_0 = 6.0 \times 10^{10}$ m^2/s

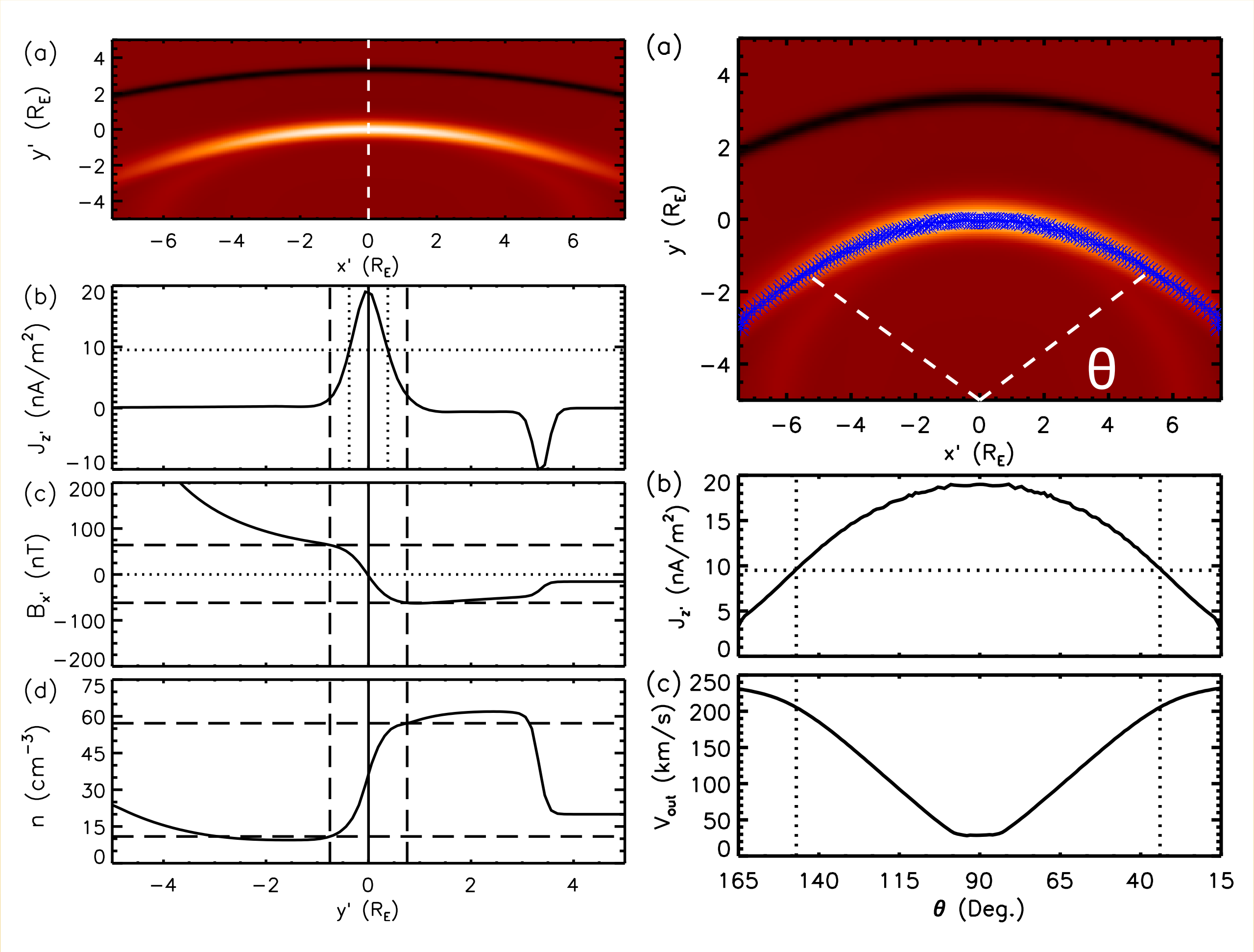


- Sample result (top plot): $\theta_{IMF} = 90^o$
  - Reconnection plane through subsolar point
  - Top right plot shows field lines in plane
  - Bottom right plot shows flow lines in plane
    - Qualitatively similar to 2D asymmetric reconnection (though with a curved current sheet - color background)
      - Side note: Beidler et al., in prep, used a similar approach in 3D toroidal extended-MHD simulations (bottom plot)



Towards Quantifying Local Reconnection

- To compare to 2D models of reconnection, we need to measure *local* plasma parameters in reconnection planes (all of them!) (Komar and Cassak, in prep.)
  - Inflow direction (left plot):
    - HWHM of $J_{z'}$ in y' direction is thickness δ
      - 0.76 R_E here
    - Measure plasma parameters 2δ upstream from peak in current
      - $B_{SH,x'}$ = -61 nT, n_{SH} = 57 cm^{-3} $B_{MS,x'}$ = 64 nT n_{MS} = 11 cm^{-3}
  - Outflow direction (right plot):
    - In cuts, find max of $J_{z'}$ as a function of θ
    - HWHM of $J_{z'}$ along sheet is length L
      - 5.84 R_E
    - Find v_{out} at same location



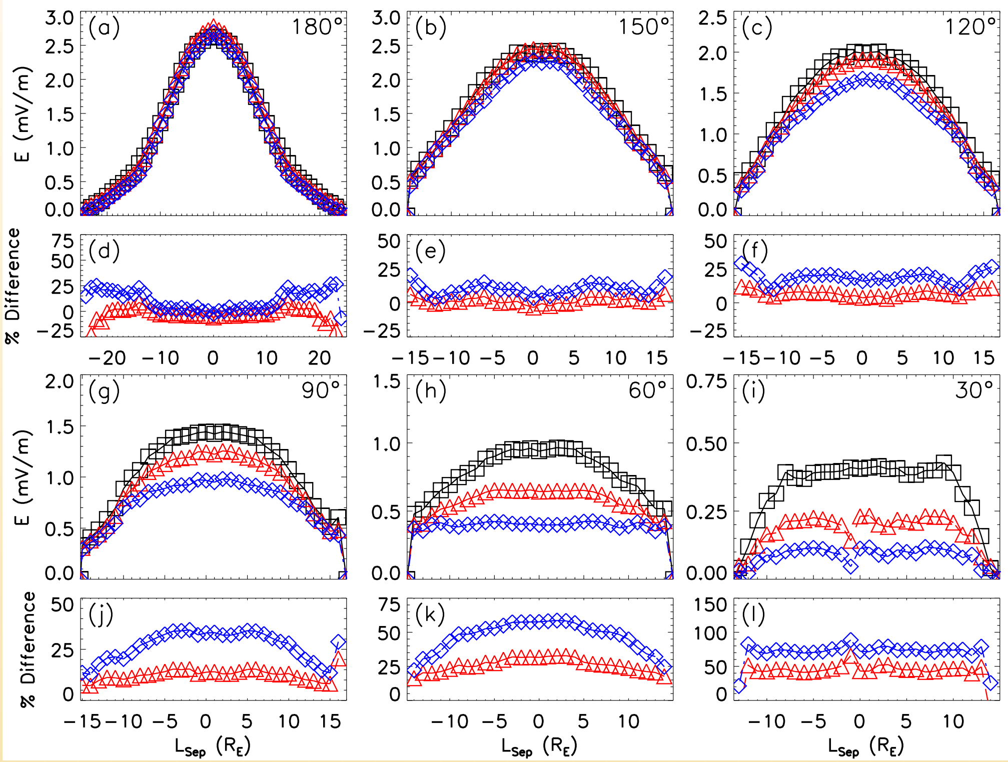
Quantifying Dayside Reconnection

- Now armed to test local reconnection models (Komar and Cassak, in prep.)
  - Simplest asymmetric reconnection model (Cassak and Shay, PoP, 2007)

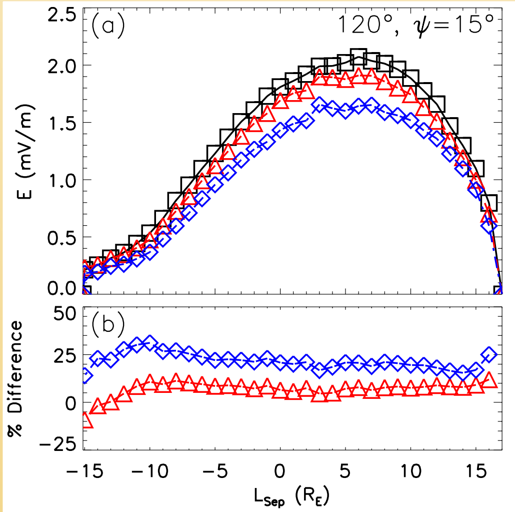
$$E \sim \frac{B_{MS,x'} B_{SH,x'}}{B_{MS,x'} + B_{SH,x'}} c_{A,out} \frac{2\delta}{L}$$

$$E \sim \sqrt{\frac{\eta c_{A,out}}{\mu_0 L} B_{MS,x'} B_{SH,x'}}$$

$$c_{A,out}^2 \sim \frac{B_{MS,x'} B_{SH,x'}}{\mu_0} \frac{B_{MS,x'} + B_{SH,x'}}{\rho_{SH} B_{MS,x'} + \rho_{MS} B_{SH,x'}}$$

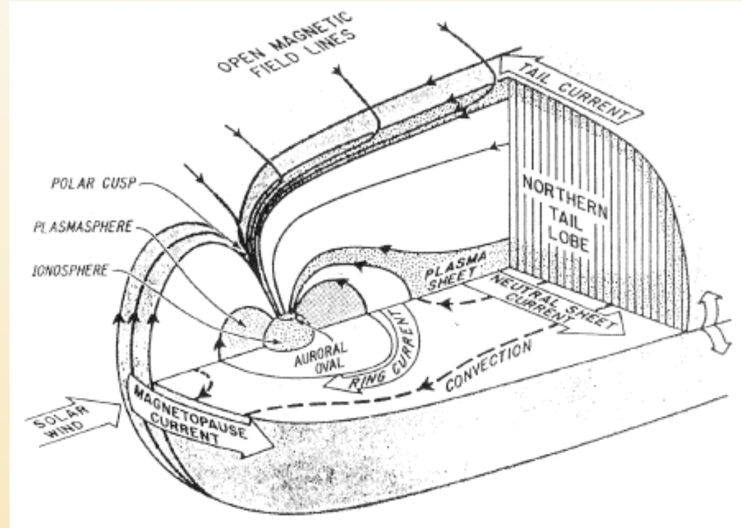


  - Test for various clock angles (top plot) Black - measured *E*, blue - top prediction, red - bottom prediction
    - Agreement for $\theta_{IMF} = 180^o$ is excellent!
      - Agrees with Borovsky et al., JGR, 2008; Ouellette et al., JGR, 2014
    - Agreement in absolute sense becomes worse for lower clock angles
    - % difference relatively flat in subsolar region; implies agreement in scaling sense
  - Test of robustness: for $\theta_{IMF} = 120^o$ introduce a dipole tilt of 15^o with northern hemisphere towards sun (breaks symmetry)
    - Similar scaling agreement to no dipole tilt case (bottom plot)



Effect of Flow Shear on Reconnection

- Long standing model of effect of flow shear on dayside reconnection (Cowley and Owen, Planet. Space Sci., 1989)
  - If flow difference Δv between magnetospheric flow (usually small) and magnetosheath flow exceeds double the Alfvén speed ($\Delta v > 2c_A$), then reconnection cannot take place
    - "Alfvén speed" c_A in reference to the magnetosheath side
  - If $c_A < \Delta v < 2c_A$, reconnection can occur, but X-line must move to make flow in reference frame sub-Alfvénic
  - If $\Delta v < c_A$, reconnection occurs with a stationary X-line



- X-line can convect tailward
  - Seen in observations (Gosling et al., JGR, 1991; Hasegawa et al., GRL, 2008; Wilder et al., JGR, 2014)
  - Tailward convection of X-line seen in global fluid (Berchem et al., Geophys. Monograph, 1995) and hybrid (Mercury) simulations (Omidi et al., Adv. Space Res., 2006)
    - However, some observations reveal steady high-latitude signatures of reconnection for hours (Fuselier et al., 2000; Frey et al., 2003)

- Theoretical developments (for *symmetric* reconnection, in 2D, no guide field, parallel flow…)
  - Theory (Mitchell and Kan, J. Plasma Phys., 1978; Chen and Morrison, Phys. Fluids B, 1990) and simulations (La Belle Hamer et al., JGR, 1994) suggest reconnection is suppressed by flow shear if it is *super-Alfvénic*

$$v_{\rm shear}^2 > c_A^2 \qquad\qquad (v_{\rm shear} = \Delta v/2)$$

  - The reconnection rate $E_{shear,sym}$ *for sub-Alfvénic* flow shear scales with v_{shear} as (Cassak and Otto, Phys. Plasmas, 2011)

$$E_{\rm shear,sym} \sim E_0 \left(1 - \frac{v_{\rm shear}^2}{c_A^2}\right)$$

where E_0 is reconnection rate without flow shear (~0.1)

Calculation - Drift Speed of X-line

- In a steady-state, conservative form of momentum equation is

$$\oint d\mathbf{S} \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{8\pi}\right)\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi}\right] = 0$$

- Evaluate x-component (L in boundary normal coordinates) on all four sides:

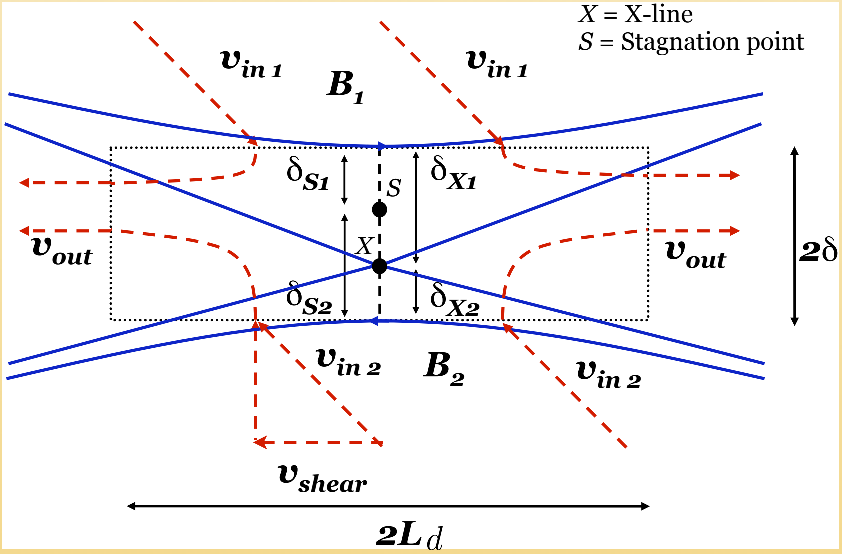
$$2L_d\rho_1[v_{in,1}(v_{L,1} - v_{\rm drift})] + 2L_d\rho_2[v_{in,2}(v_{L,2} - v_{\rm drift})] \sim 0$$

- Solve for $v_{\rm drift}$, using $v_{in,1}\, B_1 \sim v_{in,2}\, B_2$:

$$\boxed{v_{\rm drift} \sim \frac{\rho_1 B_2 v_{L,1} + \rho_2 B_1 v_{L,2}}{\rho_1 B_2 + \rho_2 B_1}}$$

  - As a check - Convects at average speed if symmetric

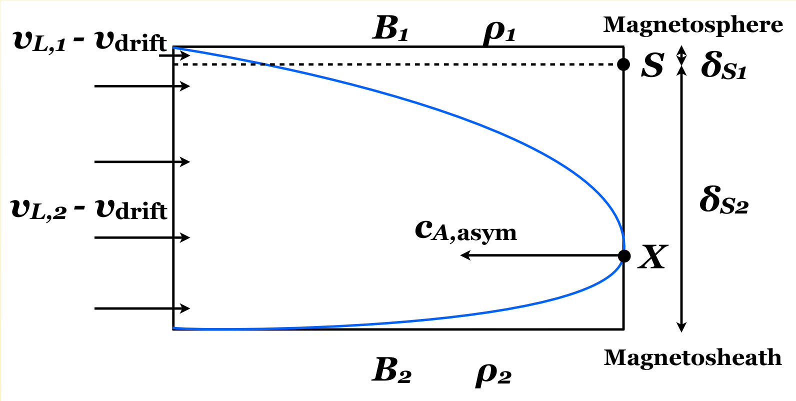
- What is the physics?
  - In asymmetric reconnection, the X-line and stagnation point are not in the center of the dissipation region (Cassak and Shay, 2007)
    - The upstream plasmas carry momentum
  - The side away from the stagnation point contributes more to the momentum of the dissipation region
    - Weighted in relation to its mass flux $\rho\, v_{in} \sim \rho / B$



Calculation - The Reconnection Rate

- The reconnection rate is slowed by flow shear due to the momentum of the upstream plasma working against the tension of the reconnected field line
  - Analogous to suppression of reconnection by diamagnetic drift effects (Swisdak et al., 2003)

- For asymmetric reconnection, the outflow speed in the absence of flow shear (due to field line tension) is



$$c_{A,\rm asym}^2 \sim \frac{B_1 B_2}{4\pi} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$

  - In asymmetric reconnection, the offset of the stagnation point means that upstream plasmas do not impede the flow equally; see the diagram. Therefore, we expect

$$v_{\rm out}^2 \sim c_{A,\rm asym}^2 - \frac{\delta_{S1}}{2\delta}(v_{L,1} - v_{\rm drift})^2 - \frac{\delta_{S2}}{2\delta}(v_{L,2} - v_{\rm drift})^2$$

- Using the expression for $v_{\rm drift}$ from before and some algebra gives

$$v_{\rm out}^2 \sim c_{A,\rm asym}^2 - (v_{L,1} - v_{L,2})^2 \frac{\rho_1 B_2 \rho_2 B_1}{(\rho_1 B_2 + \rho_2 B_1)^2}$$

- We expect the reconnection rate to generalize the symmetric result as

$$\boxed{E_{\rm shear,asym} \sim E_{\rm asym,0}\left(1 - \frac{v_{\rm shear}^2}{c_{A,\rm asym}^2} \frac{4\rho_1 B_2 \rho_2 B_1}{(\rho_1 B_2 + \rho_2 B_1)^2}\right)}$$

Calculation - Suppression via Flow Shear

- From the expression for the reconnection rate, the condition for suppression of reconnection by flow shear ($E_{shear,asym} \rightarrow 0$) is

$$\boxed{v_{\mathrm{shear,crit}} \sim c_{A,\mathrm{asym}} \frac{\rho_1 B_2 + \rho_2 B_1}{2(\rho_1 B_2 \rho_2 B_1)^{1/2}}}$$

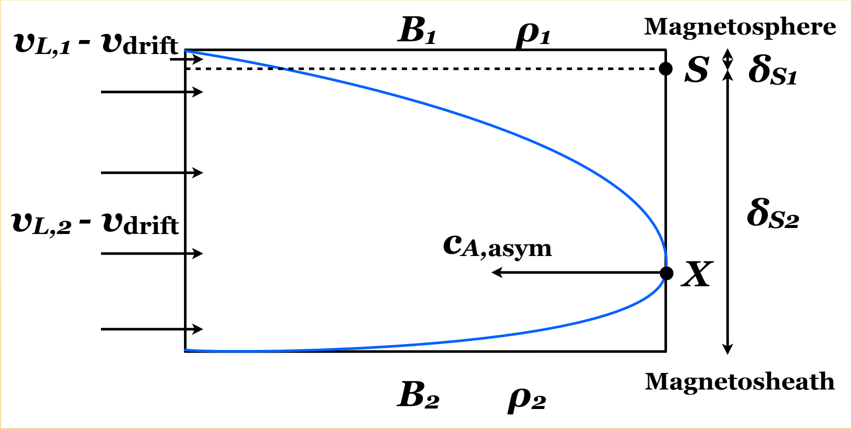
  - Related to the asymmetric outflow speed, but it is always larger!

- The physics (at Earth's magnetosphere)
  - the stagnation point is almost all the way to the magnetospheric side of dissipation region
  - the X-line moves essentially with the magnetosheath flow;
    - in the reference frame of the X-line, the magnetosheath is almost stationary, and the magnetosphere moves at the solar wind speed, but the density of the magnetosphere is so small that there is almost no effect!
      - *Effect on reconnection rate should be very small too!*

- Consider magnetospheric parameters ($\rho_{ms} \gg \rho_{sh}$)
  - Critical speed for suppression is

$$v_{L,sh} > c_{A,\mathrm{asym}} \left(\frac{\rho_{sh} B_{ms}}{\rho_{ms} B_{sh}} \right)^{1/2}$$

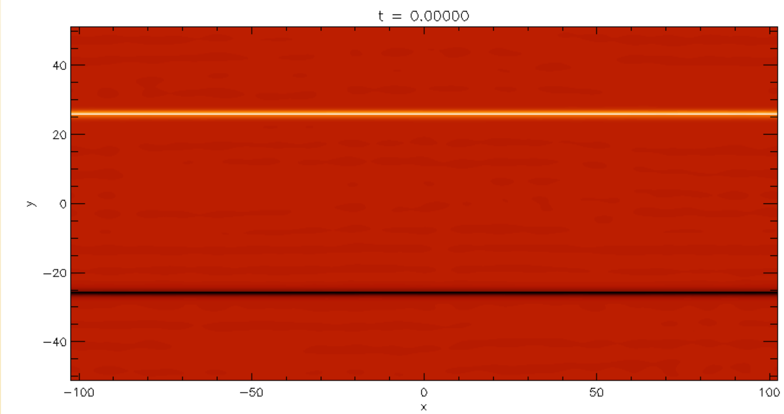
    - For event with B_{sh} ~10-15 nT, n_{sh} ~ 60-70 cm^{-3}, B_{ms} ~ 60 nT, n_{ms} ~ 0.5 cm^{-3} (Wilder et al., JGR, 2014), this implies critical magnetosheath flow of 22 x the asymmetric Alfven speed!!!
    - Much more difficult for flow shear to suppress asymmetric reconnection (of an isolated X-line) than thought!

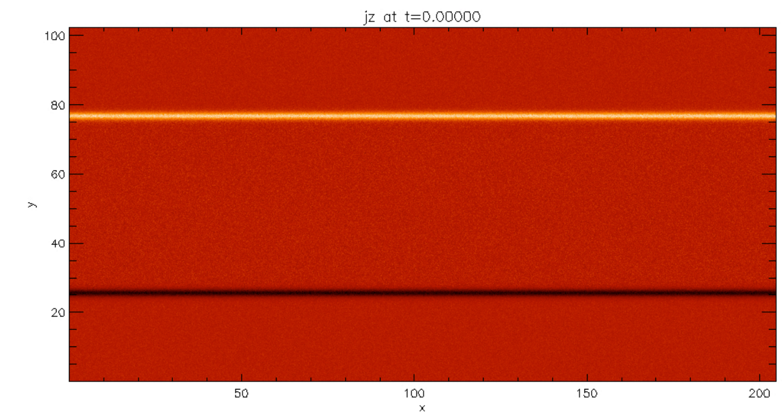


Testing Theory with Simulations

- We have tested the predictions in simulations with both two-fluid (Doss et al., JGR, submitted) and particle-in-cell (Doss and Cassak, in prep.)
  - Two-fluid simulations with F3D (Shay et al., 2004)
    - Adiabatic ions, cold electrons
    - 2D, 204.8 x 102.4 d_i, grid 0.05, Electron mass 1/25
    - Series of simulations with $B_1 = 3$, $B_2 = 1$ with symmetric density ($\rho = 1$) and $\rho_1 = 1$, $\rho_2 = 3$ for symmetric magnetic fields ($B = 1$) with varying flow shear
  - PIC simulations with P3D (Zeiler et al., 2002)
    - 2D, electron mass 1/25
    - Simulations with $B_1 = 1.5$, $B_2 = 0.5$ with symmetric density ($\rho = 0.2$) with 204.8 x 102.4 d_i, grid 0.025 with varying flow shear
    - Series of simulations with $\rho_1 = 0.6$, $\rho_2 = 0.2$ for symmetric magnetic field ($B = 1$) with 102.4 x 51.2 d_i, grid 0.05 with varying flow shear

- Sample results (movies of out-of-plane current)
  - Top movie - two-fluid with asymmetric magnetic field $B_1 = 3$, $B_2 = 1$, flow shear of 1.2
  - Bottom movie - PIC with asymmetric magnetic field $B_1 = 1.5$, $B_2 = 0.5$, flow shear of 2.0
    - X-line is not stationary, as expected



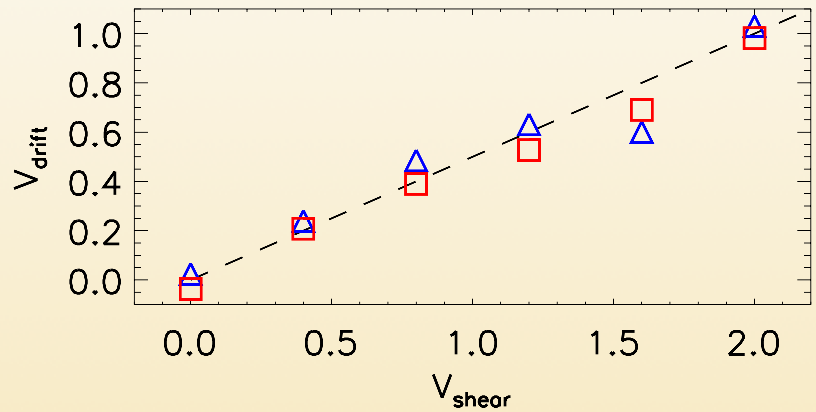


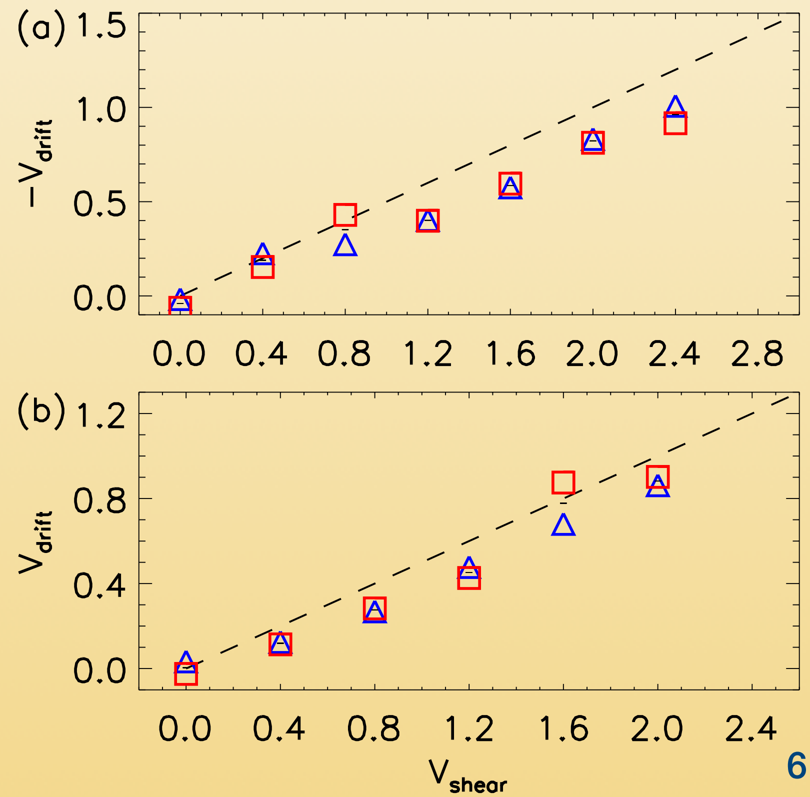
Scaling of X-line Convection Speed

- Two-Fluid: varied flow shear for $B_1 = 3$, $B_2 = 1$ simulations (top plot)
  - Red boxes/blue triangles are data from two current sheets
  - Dashed line is from prediction
    - Asymmetric density simulations do not allow mixing; need PIC

- PIC:
  - Top plot - simulations with asymmetric magnetic field
  - Bottom plot - simulations with asymmetric density
    - Agreement is good; even better at later time

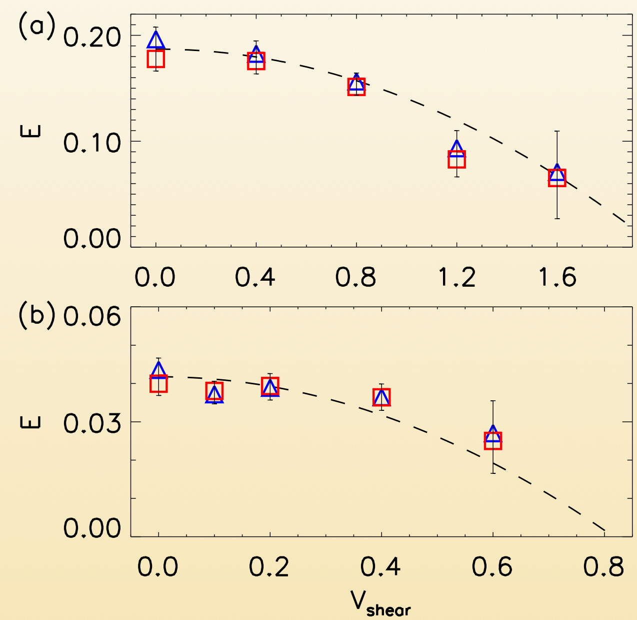
Results agree very well with theory!



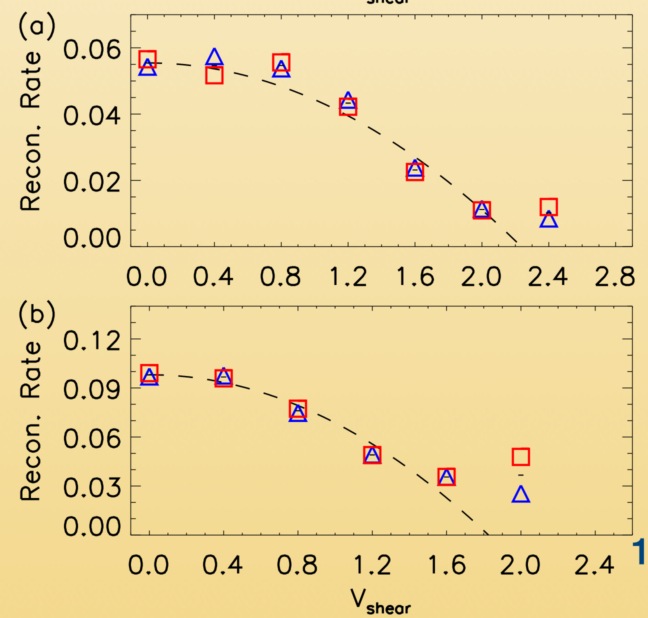


Reconnection Rate Scaling

- Measured scaling of reconnection rate E with v_{shear}
  - Red boxes/blue triangles are data from two current sheets



- Two-fluid results
  - Varied flow shear for $B_1 = 3$, $B_2 = 1$ simulations (top plot)
  - Varied flow shear for $\rho_1 = 1$, $\rho_2 = 3$ simulations (second plot)
- PIC results
  - Varied flow shear for $B_1 = 1.5$, $B_2 = 0.5$ simulations (third plot)
  - Varied flow shear for $\rho_1 = 0.6$, $\rho_2 = 0.2$ simulations (fourth plot)



- Dashed line is from prediction
  - Using measured E_0

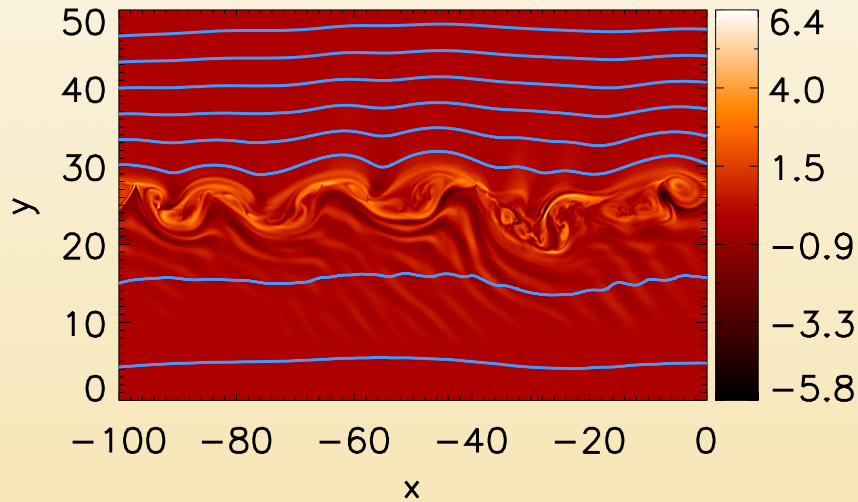
Agreement is very good!

Suppression of Reconnection

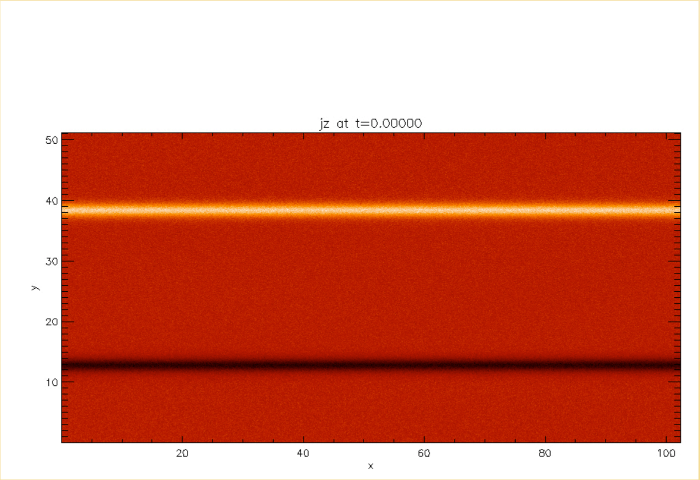
- Two-fluid simulations
  - For $B_1 = 3$, $B_2 = 1$ predicted suppression condition is

$$v_{\text{shear,crit}} \sim c_{A,\text{asym}} \frac{\rho_1 B_2 + \rho_2 B_1}{2(\rho_1 B_2 \rho_2 B_1)^{1/2}} = 2$$

  - Reconnection occurs for $v_{shear} = 1.6$; plotted is current sheet for $v_{shear} = 2.4$
    - Not reconnection; it is Kelvin-Helmholtz
    - Secondary reconnection occurs, of course
  - For $\rho_1 = 1$, $\rho_2 = 3$, condition is 2/3
    - Reconnection occurs for $v_{shear} = 0.6$; not for $v_{shear} = 0.8$



- PIC simulations
  - For $B_1 = 1.5$, $B_2 = 0.5$, condition is 2.24
    - For $v_{shear} = 2.0$, reconnection occurs
    - Interesting - for $v_{shear} = 2.8$; reconnection does not occur early on, but does happen nonlinearly; subject of future research

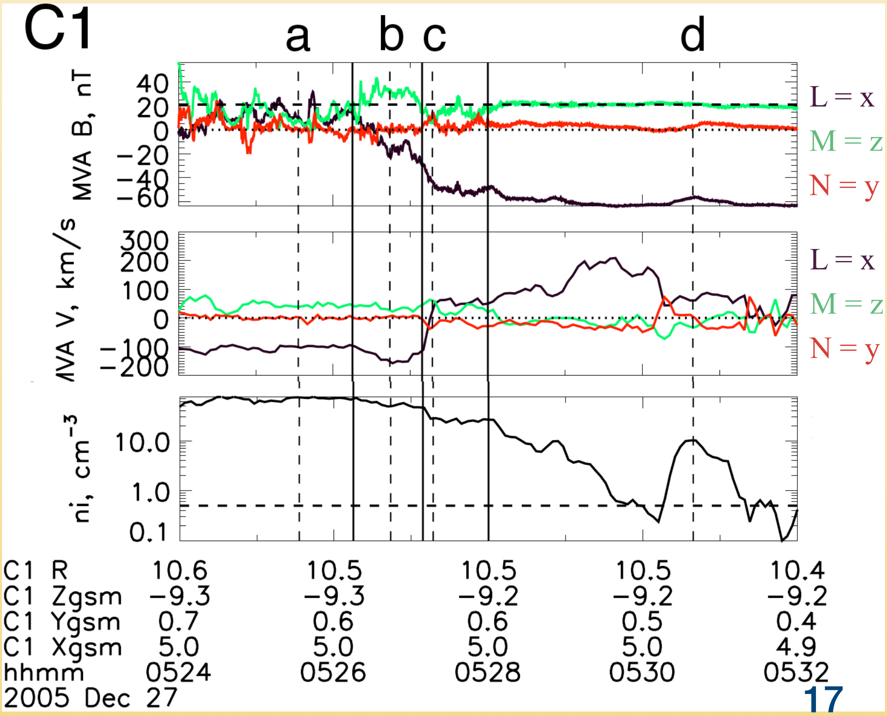


Could pin down more precisely, but agreement is very good!

Comparison to Cluster Observations

- Wilder et al., JGR (2014) recently observed an event near the cusp at the southern hemisphere with Cluster
  - C1 sees a reconnection event moving tailward, then C3 later sees the same event
    - From their separation and time delay between events, can determine how fast X-line is retreating
      - Estimate of convection speed is 105 km/s
    - L component of solar wind speed is 106 km/s

- Magnetosheath parameters are B_{sh} ~10-15 nT, n_{sh} ~ 60-70 cm^{-3}, magnetospheric parameters are B_{ms} ~ 60 nT, n_{ms} ~ 0.5 cm^{-3}
  - The theory predicts nearly identical v_{drift} and $v_{L,sh}$
    - Consistent with observations!
  - $c_{A,sh}$ ~ 28 km/s; reconnection would not happen in $v_{L,sh}$ is compared to $c_{A,sh}$
    - v_{shear} ~ 53 km/s, $c_{A,Asym}$ ~ 74.5 km/s



Wilder et al., 2014

Conclusions

- Tested 2D models of (asymmetric) reconnection at the 3D magnetopause in global simulations (Komar and Cassak, in prep.)
  - Found separator (X-line), found reconnection plane, measured local parameters
  - Agreement with simplest theory in the scaling sense is quite good
    - Systematic effect on absolute reconnection rate that increases with smaller clock angle

- Studied asymmetric reconnection with a flow shear analytically and confirmed using 2D two-fluid and PIC simulations (Doss et al., JGR, submitted; Doss and Cassak, in prep.)
  - Predicted convection speed and reconnection rate for asymmetric reconnection with arbitrary upstream parallel flows

$$v_{\rm drift} \sim \frac{\rho_1 B_2 v_{L,1} + \rho_2 B_1 v_{L,2}}{\rho_1 B_2 + \rho_2 B_1}$$

$$E_{\rm shear,asym} \sim E_{\rm asym,0}\left(1 - \frac{v_{\rm shear}^2}{c_{A,\rm asym}^2}\frac{4\rho_1 B_2 \rho_2 B_1}{(\rho_1 B_2 + \rho_2 B_1)^2}\right) \qquad v_{\rm shear} = \frac{v_{L,1} - v_{L,2}}{2}$$

    - Assumptions: isolated current sheet (no line tying), 2D, anti-parallel reconnection, no asymmetries in outflow direction, no flow in out-of-plane direction, used fluid model and simulations
  - Significant departures from standard expectations
    - Different X-line convection speed than previously thought
    - Effect on reconnection rate is minimal for typical magnetopause parameters; requires solar wind speed <u>much</u> bigger than Alfvén speed to suppress reconnection
      - Many topics for future work