Guide Field Dependence of X-line Spreading in Three-Dimensional Magnetic Reconnection

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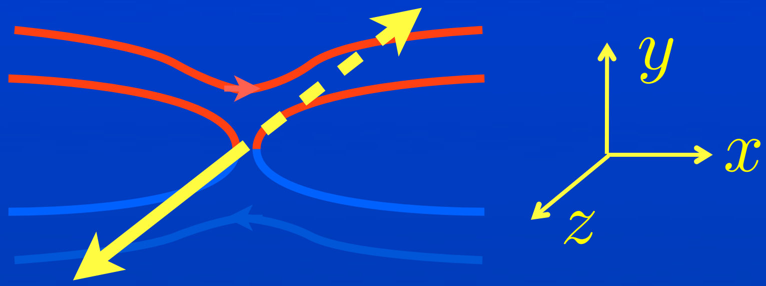
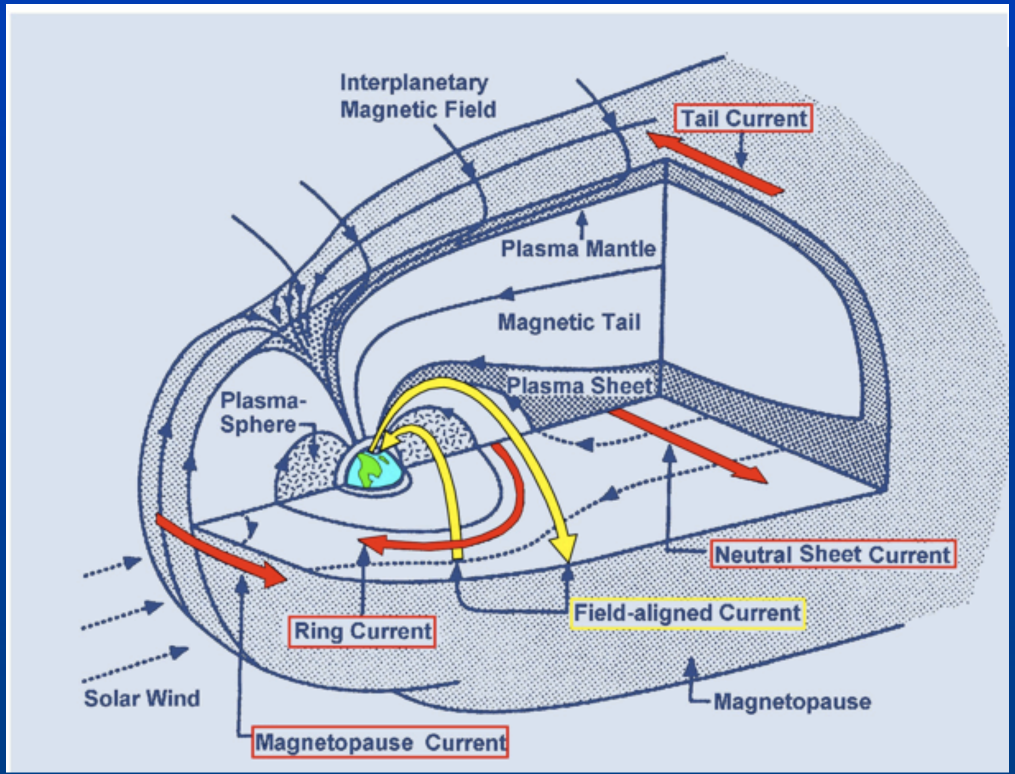
X-lines Start Locally in Substorms

- X-lines in Nature start in a localized region and spread
  - In the direction of the current

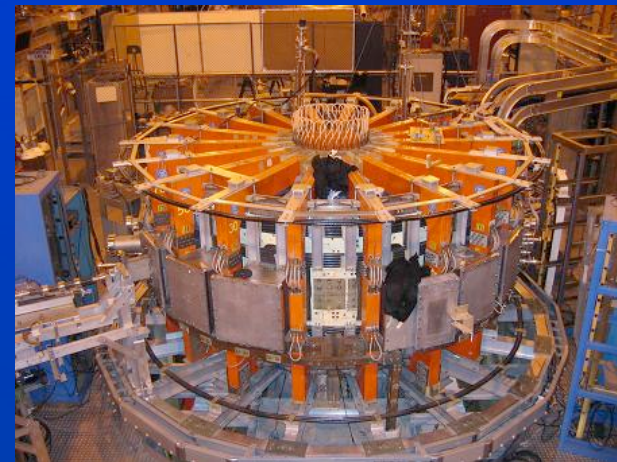


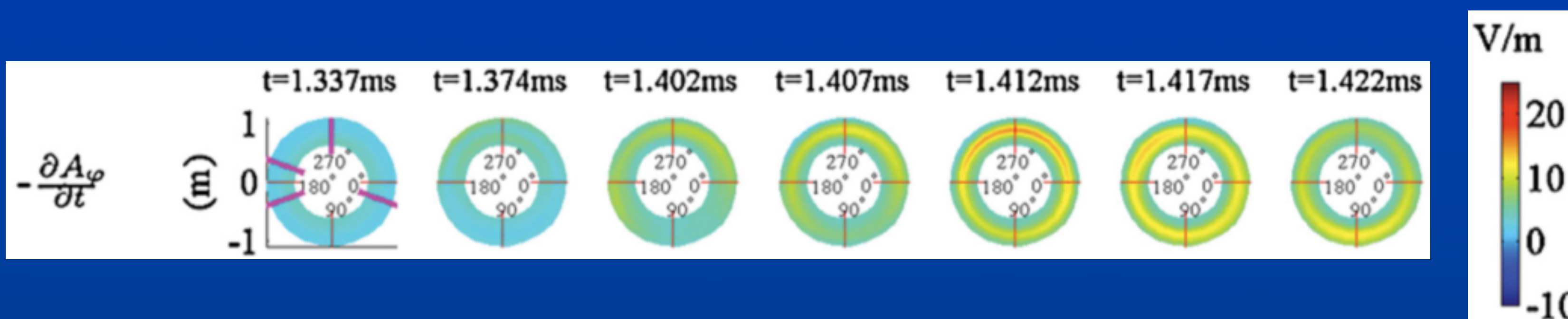
- Example - magnetotail reconnection
  - Auroral brightenings display dawn-dusk asymmetry, surges go westward (in direction of plasma sheet current (McPherron et al., 1973)
  - The pre-substorm plasma sheet has cross-tail current carried by both ions and electrons. At substorm onset, the cross-tail current is carried mostly by the electrons (Asano et al., 2004).



… and Laboratory Experiments …

- Experiments using **V**ersatile **T**oroidal **F**acility (VTF) at MIT (Katz et al., 2010; Egedal et al., 2011) show a reconnection site starting at one location and spreading toroidally in time



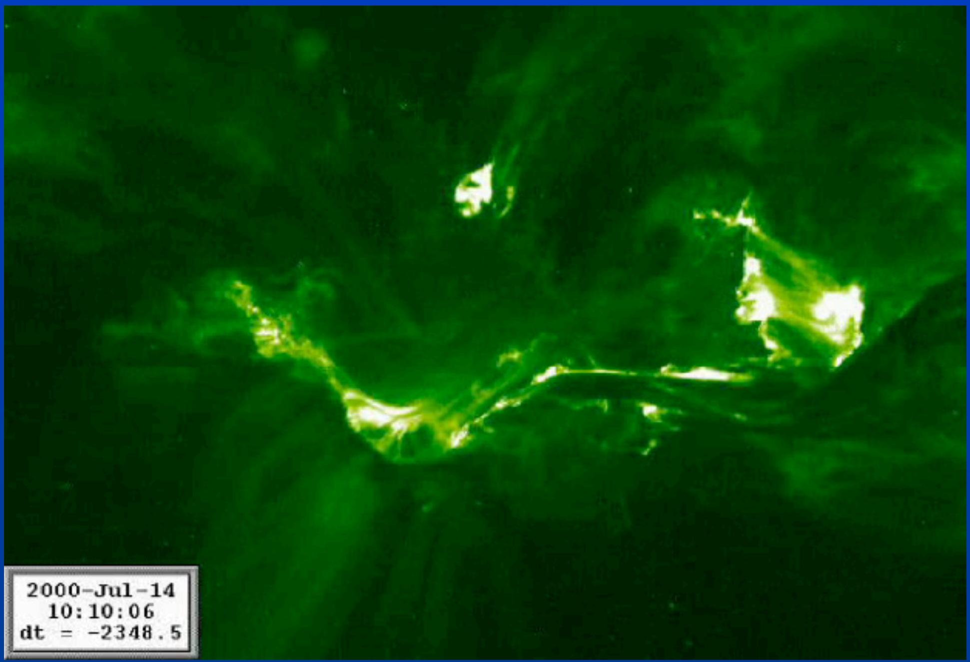


Katz et al., 2010

 - X-line spreads in both directions!
   - Spreading speed is the Alfvén speed

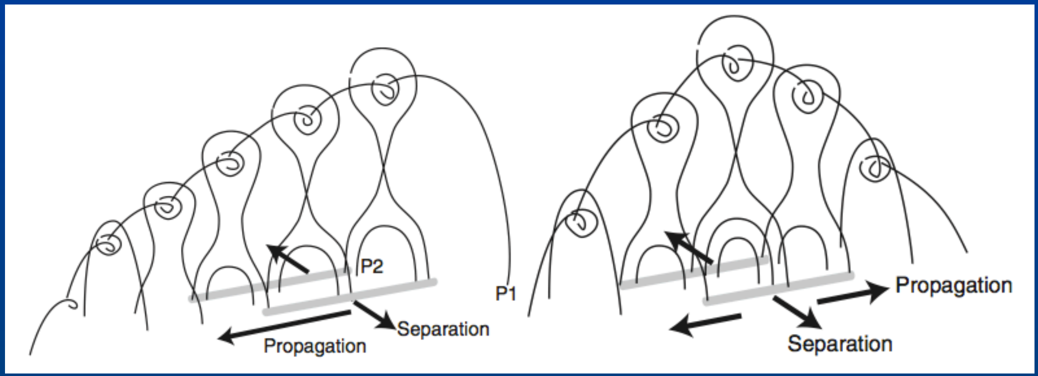
… and Solar Flares!

- Bi-directional spreading also occurs in solar flares, such as the Bastille Day flare (Qiu et al., 2010)



Courtesy of TRACE

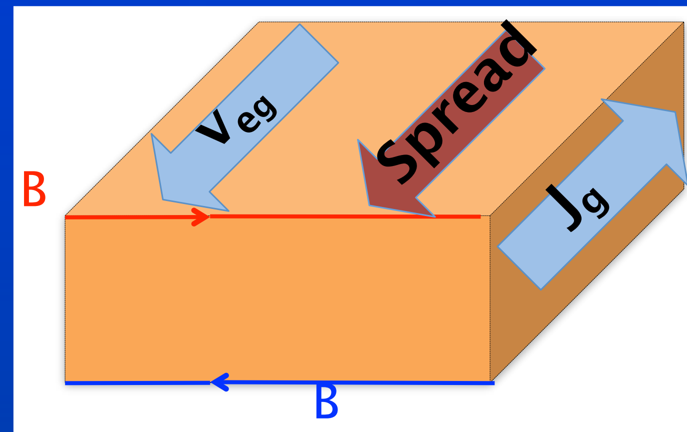
and prominences (Tripathi, Isobe, and Mason, 2006) due to emergence



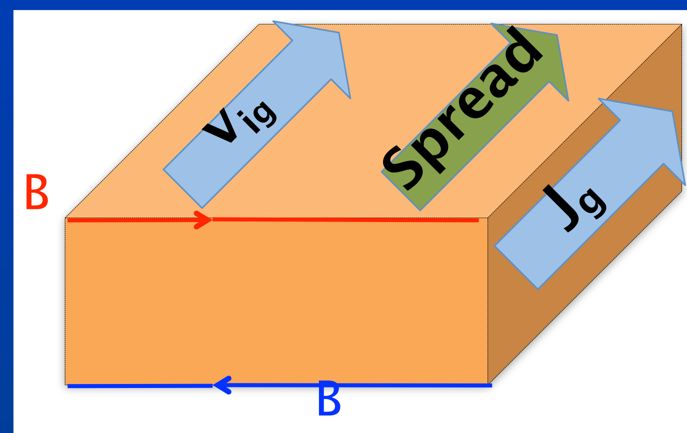
Previous Numerical Studies

- Focused on m'tail applications
- The electrons making up the current carry the signal of reconnection in direction opposite the current
  - Huba and Rudakov, 2002
    - "Reconnection wave"
  - Shay et al., 2003 (Hall-MHD, BBFs?)
  - Karimabadi et al., 2004 (hybrid)
  - Lapenta et al., 2006 (PIC)
  - Ugai, 2007 and Birn et al., 2011 (m'tail)
  - Lukin and Linton, 2011 (coalescence)
- When current is carried by both species, the X-line spreads in both directions at the speed of the current carriers.
  - Shay et al., 2003
  - Nakamura et al., 2012 (Hall-MHD)

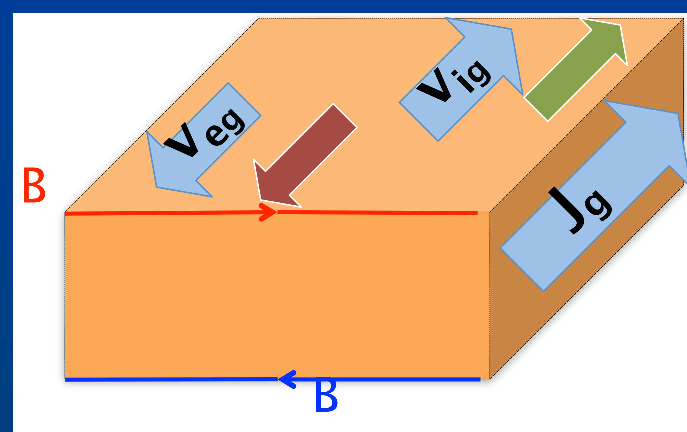
Magnetotail observations make sense!
However, these simulations
assume no or weak guide field!



If electrons carry current



If ions carry current

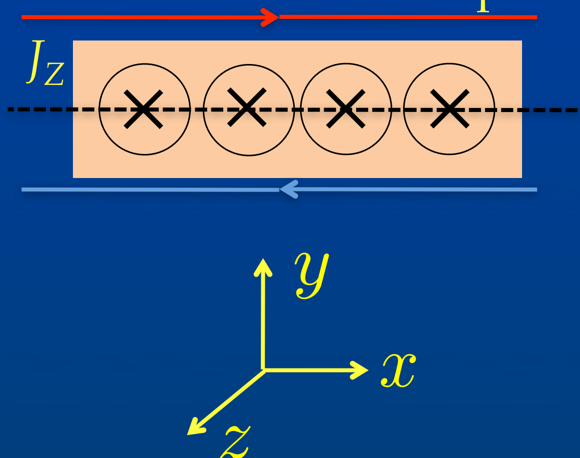


If both species carry current

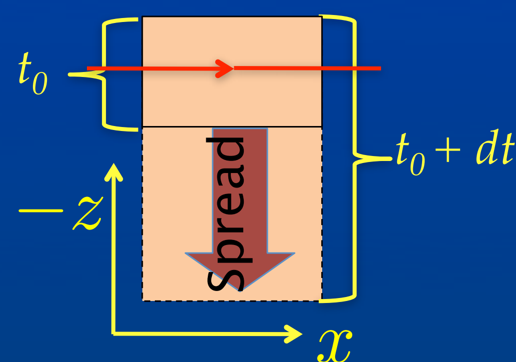
What is the effect of the Guide Field?

- Observations in the laboratory and corona have qualitatively different behavior!
  - These settings (solar and experimental) contain a significant guide field
  - The data suggests different spreading mechanisms with and without a guide field
  - How does spreading occur for system with an arbitrary guide field?
    - Has not been addressed theoretically or numerically
- Hypothesis
  - Spreads in either direction at speed of whatever mechanism is faster
  - There is a cross-over point where mechanism changes
    - We predict a condition on the guide field where the mechanism causing the spreading changes from current carriers to Alfvén waves
    - We confirm with large-scale 3D two-fluid numerical simulations

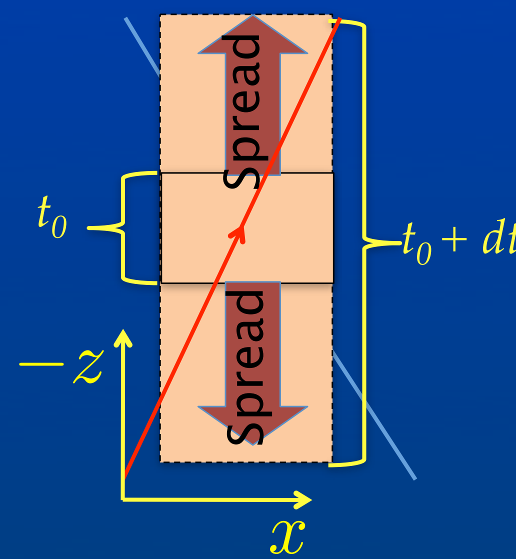
General X-line Setup



Looking from above the X-line to below the X-line



No Guide Field (Electron Current)



With Guide Field

What is the spreading speed?

- Spreading speed due to Alfvén waves in a guide field
  - $$c_{Ag} = \frac{B_g}{\sqrt{4\pi m_i n}}$$
- Spreading speed due to current carriers (assumed to be electrons)
  - $$v_{eg} \sim \frac{J_g}{ne} \sim \frac{cB_{rec}}{4\pi n e \delta}$$

δ = current sheet thickness

- Spreading speed in direction of electron and ion flow is greater of the two

$$v_{Xe} = \max\{v_{eg}, c_{Ag}\}$$
$$v_{Xi} = c_{Ag}$$

  - Straight-forward to allow ions to carry a fraction α of the current as in Nakamura et al., 2012; see Shepherd and Cassak (JGR, submitted) for details

What is critical guide field?

- The spreading in the direction of the electrons switches from current carriers to Alfvén waves when

$$v_{eg} = c_{Ag}$$

- Solving gives

$$B_g \sim B_{rec}\frac{d_i}{\delta}$$

$$d_i = c/\omega_{pi}$$

Ion Inertial Length

- In our simulations,

$$B_{rec} \sim 0.4\ B_0 \quad \text{and} \quad \delta \sim d_e = 0.2\ d_i$$

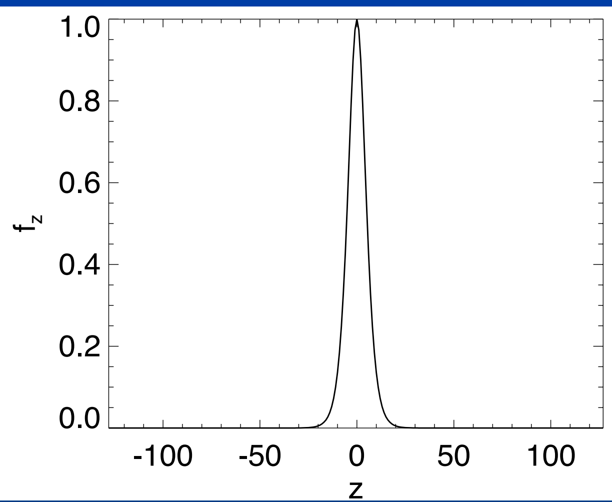
so, $$B_g \sim 2.0\ B_0$$

Numerical Simulations

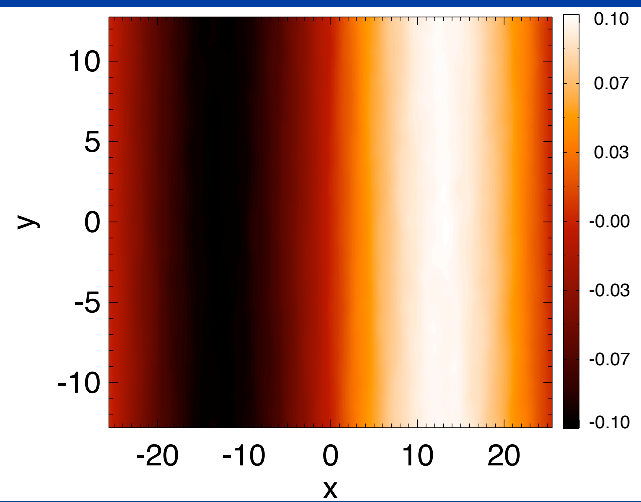
- 3D double Harris sheet, $51.2 \times 25.6 \times 256\ d_i$ box
- Performed six simulations with different guide fields B_g of
  - $B_g = 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3\ B_0$
- Localized initial perturbation around z = 0

$$B_{y1} = \sum_{k_x, k_z} B_1 \sin(k_x x + k_z z) f_z(z)$$

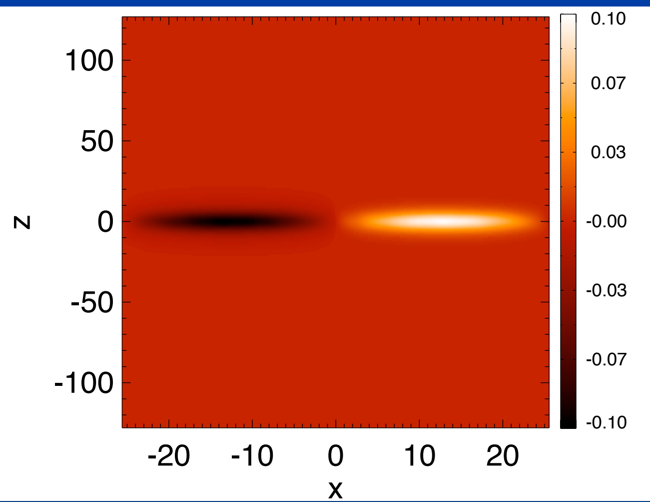
$$f_z(z) = .5[\tanh[(z + W_{0z})/6] - \tanh[(z - W_{0z})/6]$$



Form of the envelope f_z

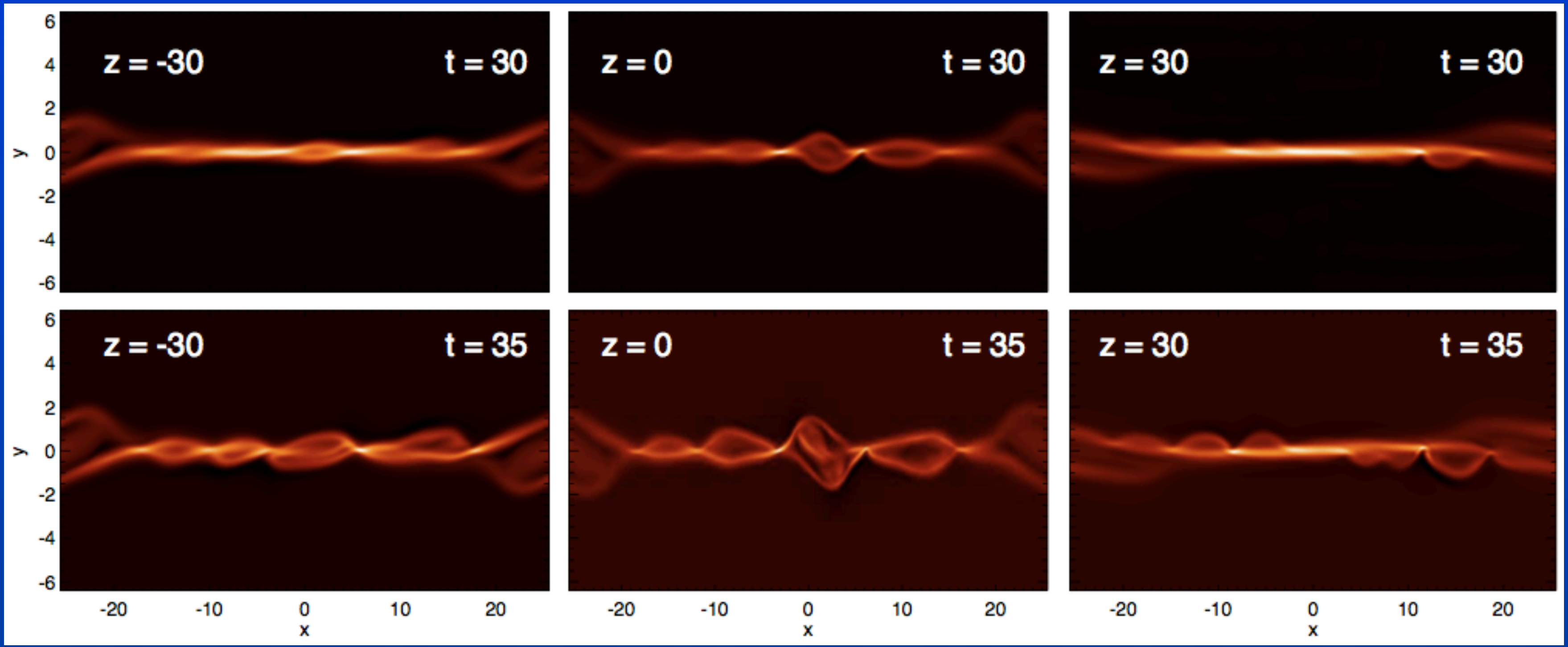


Form of B_{y1} at $t = 0$ and $z = 0$ in the *xy* plane



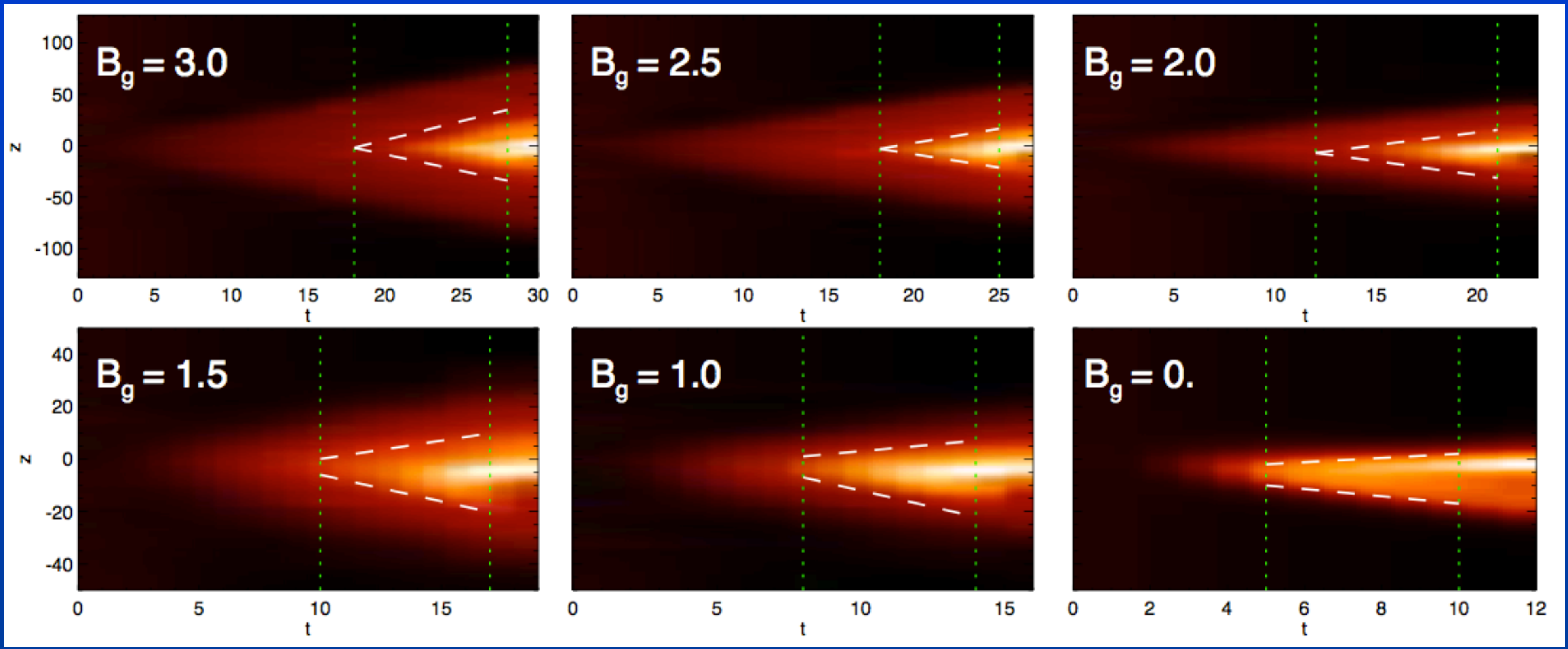
Form of B_{y1} through the X-line (y=6.4) in the *xz* plane

Results - The X-line Spreads



- X-lines spread in $B_g = 3$ case (out-of-plane current J_g)
  - Top row ($t = 30$): Hall reconnection at z = 0, not at $z = \pm 35$
  - Bottom row ($t = 35$): Hall reconnection at all three locations in z
- Guide field changes dynamics relative to anti-parallel
  - Oblique modes excited, as is well-known (Daughton et al., 2011; Baalrud et al., 2012)
  - Can prevent X-line spreading (Schreier et al., 2010)

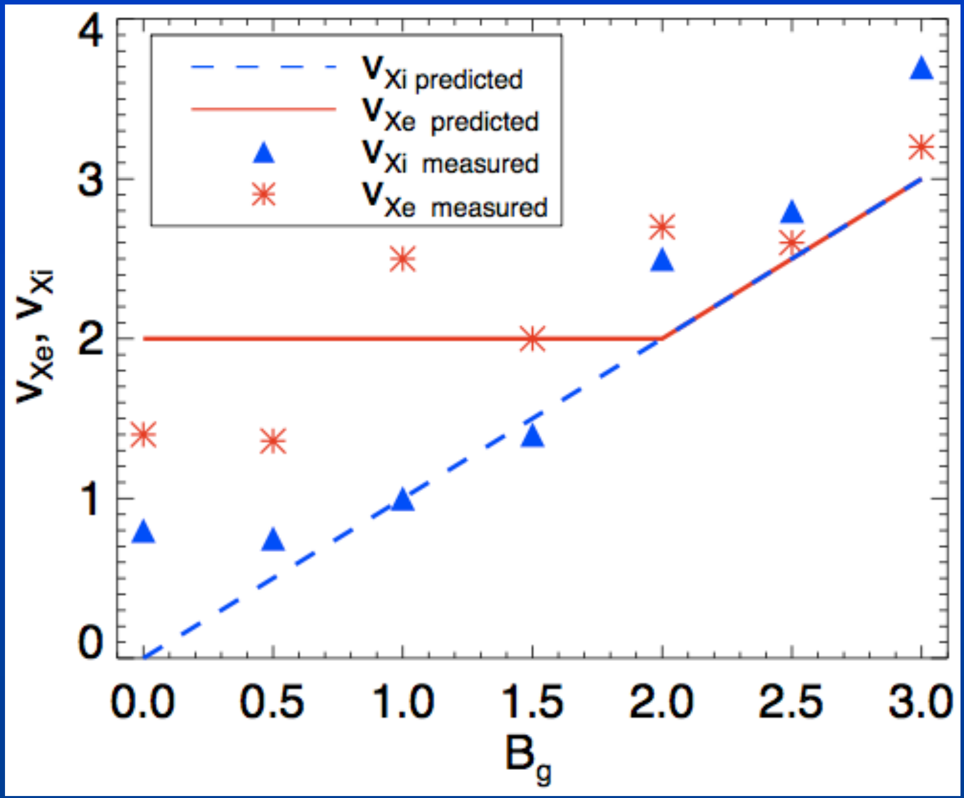
Guide Field Dependence



- A measure of the spreading - peak in out-of-plane current as a function of z and t
  - Dashed lines indicate the edge of the Hall current sheet.
- Large guide field ($B_g > 2$): bi-directional, nearly symmetric about $z = 0$
- Small guide field ($0 < B_g < 2$): bi-directional for $B_g > 0$, but asymmetric about $z = 0$
- Zero guide field: essentially uni-directional spreading (in agreement with past results)

Spreading Speeds

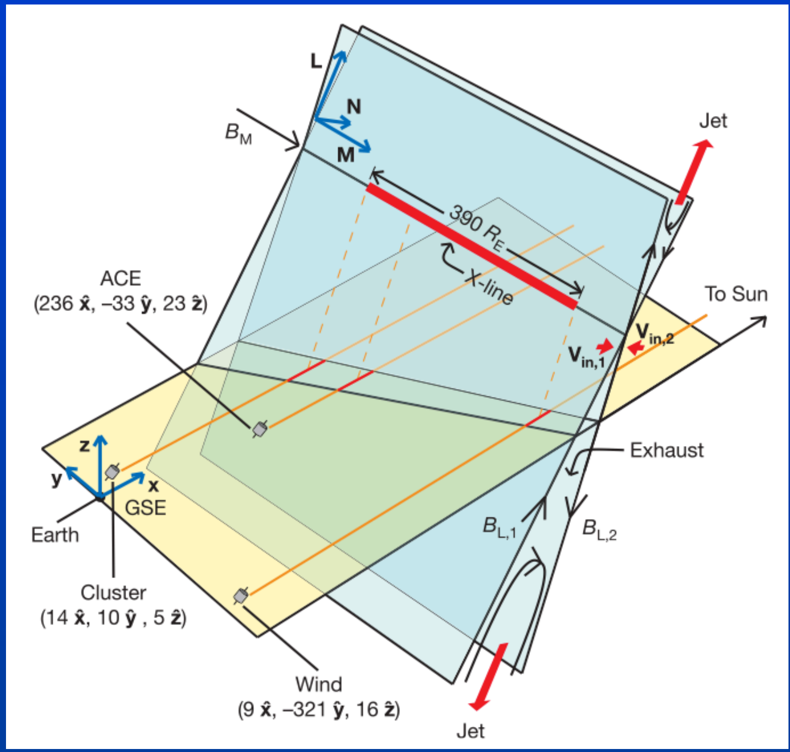
- Slope of edge of current gives the spreading speed



Speeds and existence of transition at $B_g \sim 2$ agree well with prediction!

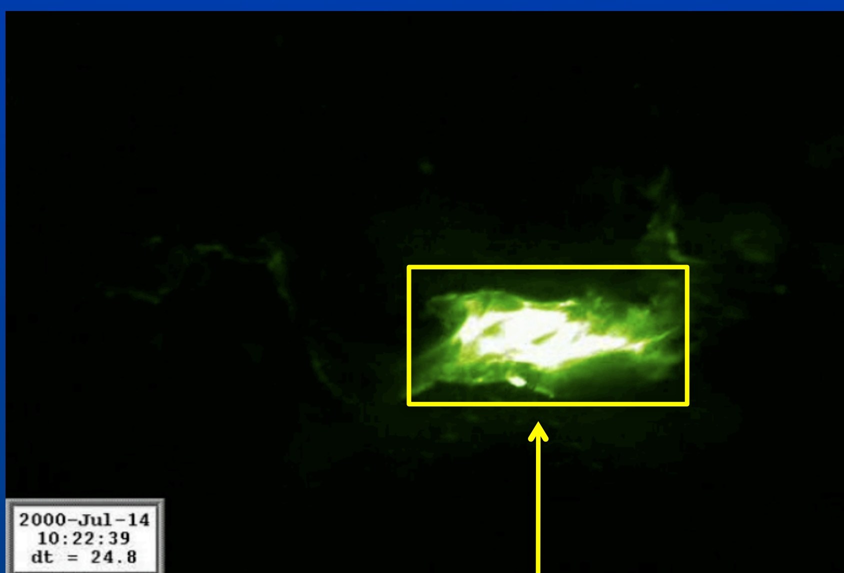
Applications - Solar Wind

- Extended X-lines inferred in the solar wind - 390 R_E! (Phan et al., 2006)
  - "Our finding also raises an interesting question: how does the reconnection X-line become so extended? We suspect that in the case of the solar wind, reconnection starts in a limited region in the solar wind current sheet closer to the Sun and spreads with time from its initiation region."
  - Their guide field was only 0.35 of the reconnecting field
    - Even if it expands at the slower guide field Alfvén speed, if it started at the corona it would be 1000 R_E long!
    - Their conclusion seems plausible (Shepherd and Cassak, submitted)
      - A more precise analysis should be undertaken

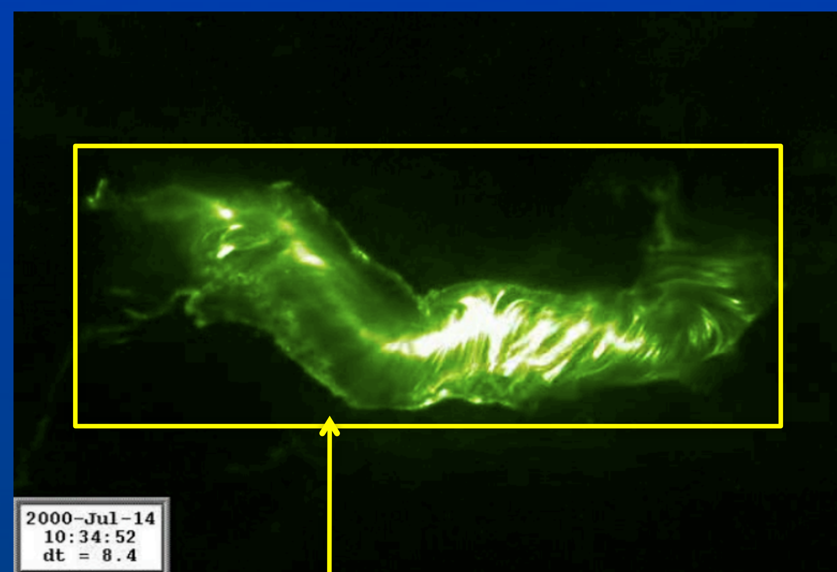


Applications - Solar Flares

- Qiu et al., 2010 suggested one can infer relative guide field from observations
  - Potentially important because guide field influences how many secondary islands are present (Drake et al., 2006a), and secondary islands may be correlated to particle acceleration (Drake et al., 2006b; Chen et al., 2008)
- For this event, this type of analysis suggests the guide field of order 1 (Shepherd and Cassak, submitted), more work necessary



Localized area of reconnection at early time



Rapid expansion in the left/right direction in a short time

Conclusions

- The mechanism of reconnection X-line spreading in the direction of the current is qualitatively different depending on the strength of the guide magnetic field (Shepherd and Cassak, JGR, submitted)
  - Strong guide field: Alfvén waves
  - Weak guide field: Current carriers
- X-line spreads at the speed of whichever mechanism is faster in that direction
- A prediction of the of the transition is when the guide field is

$$B_g \sim B_{rec} \frac{d_i}{\delta}$$

- Many potential applications:
  - Solar flares
  - Solar wind
  - Dayside magnetopause
  - Substorms
  - Laboratory experiments and fusion plasmas
- Simplifications - Current sheet initially thin (free energy present at start of simulation) and is independent of z