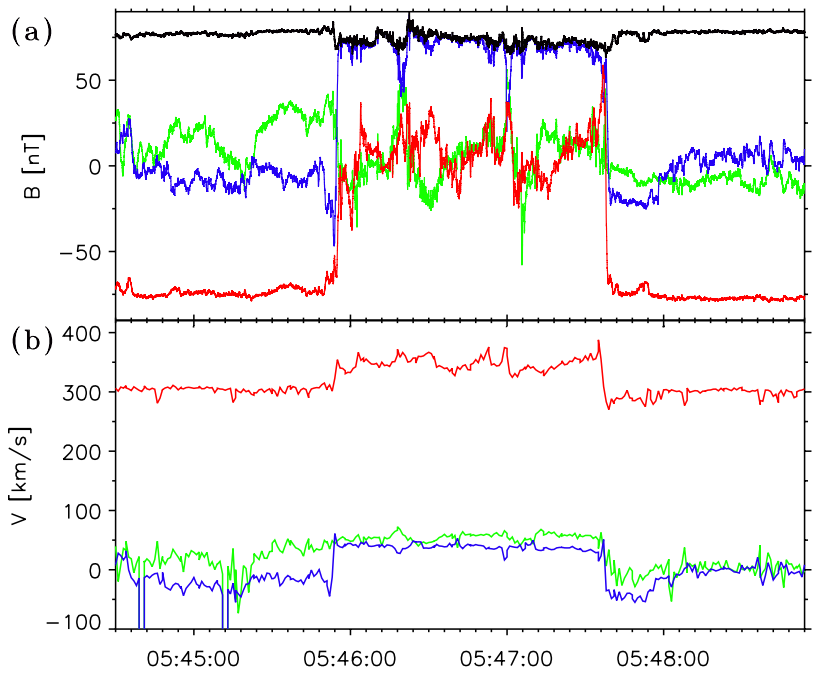
Switchbacks as signatures of magnetic flux ropes generated by interchange reconnection in the corona

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Switchback details

- Sample of single switchback event during the 1st Perihelion



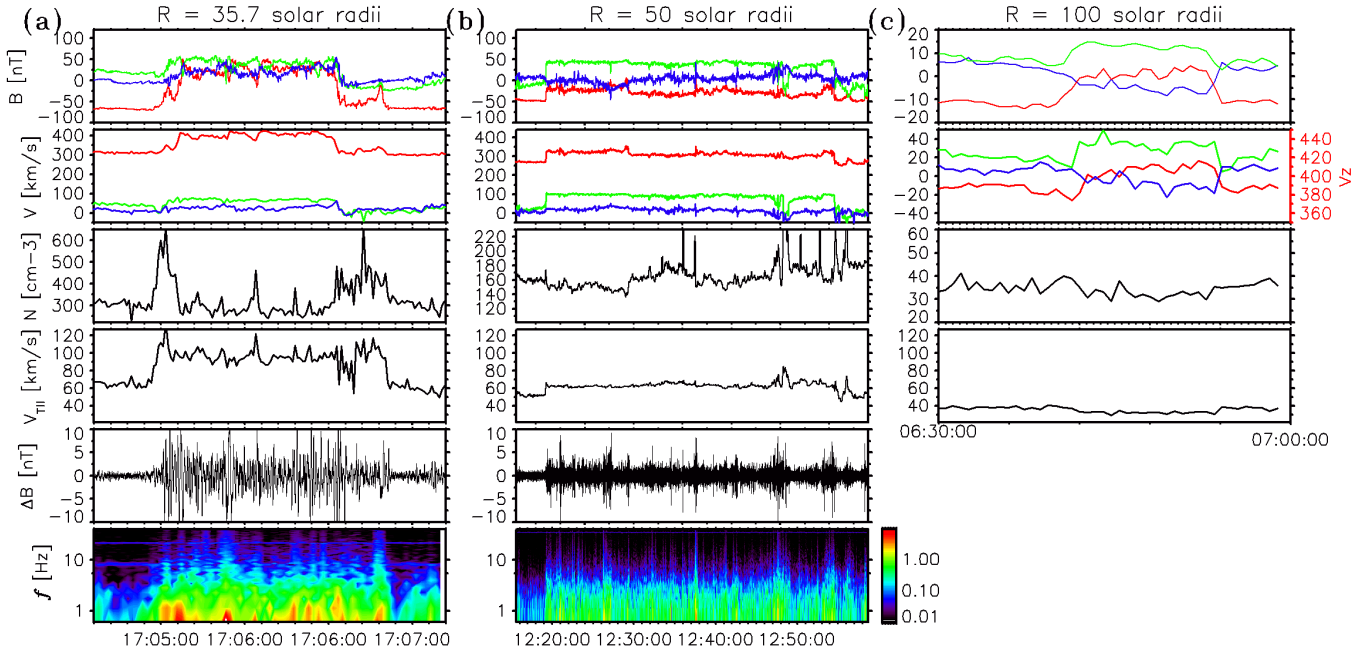
B_T

B_R

B_N

Thermal Structure of Switchbacks

- The temperature typically increases sharply within the switchback
  - Dominated by an increase in $T_{||}$ with T_{perp} being nearly constant (Mozer+ '20)
  - Temperature increment decreases with radial distance
  - Suggests that SBs form close to the sun and decay as they convect outward

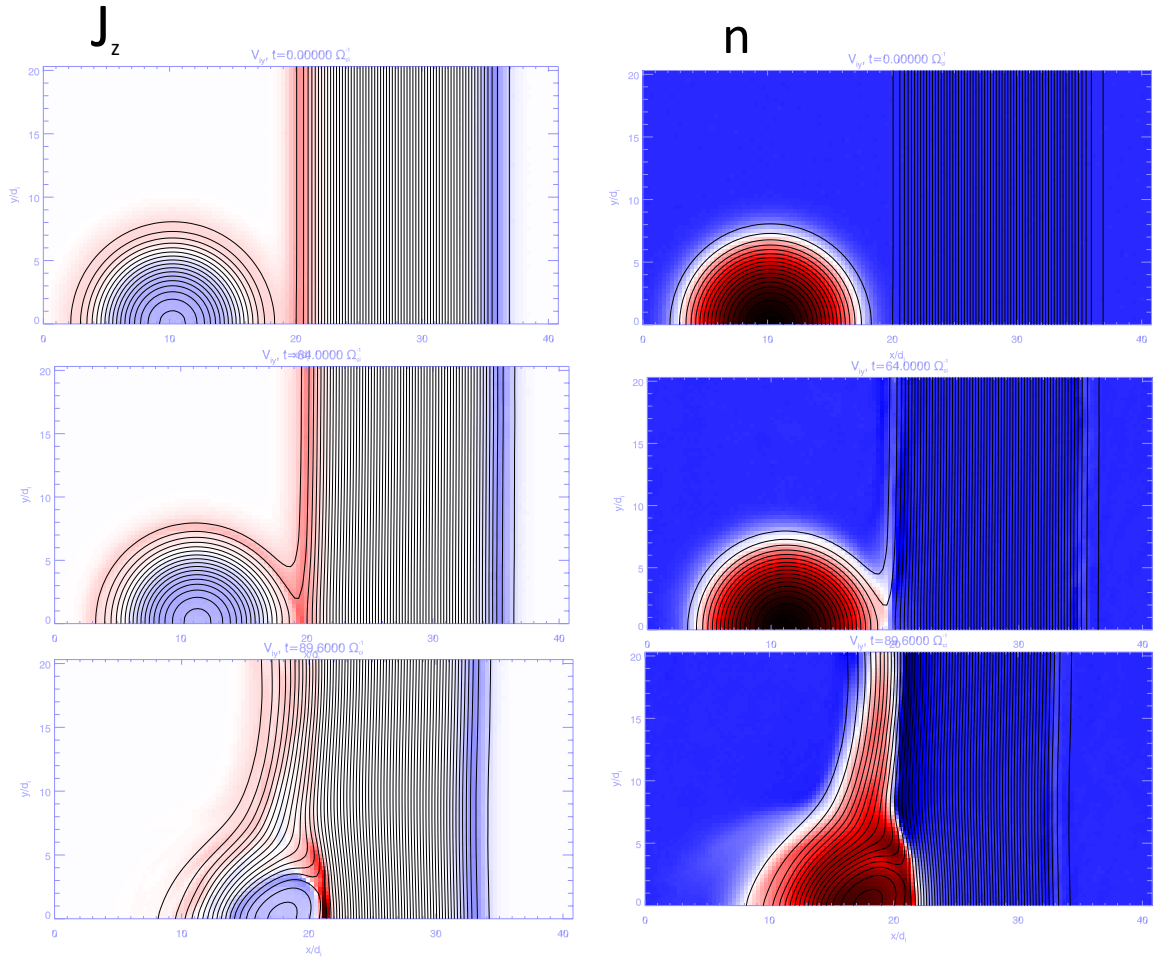


Alfvenicity: a key observation

- Fluctuations exhibit strong correlations of velocity and magnetic field over extended time periods
  - e.g. $V_{pR} - B_R/(4\pi\rho)^{1/2} = \text{const.}$
- Do switchback models based in interchange reconnection and flux rope formation relax to Alfvenic states?

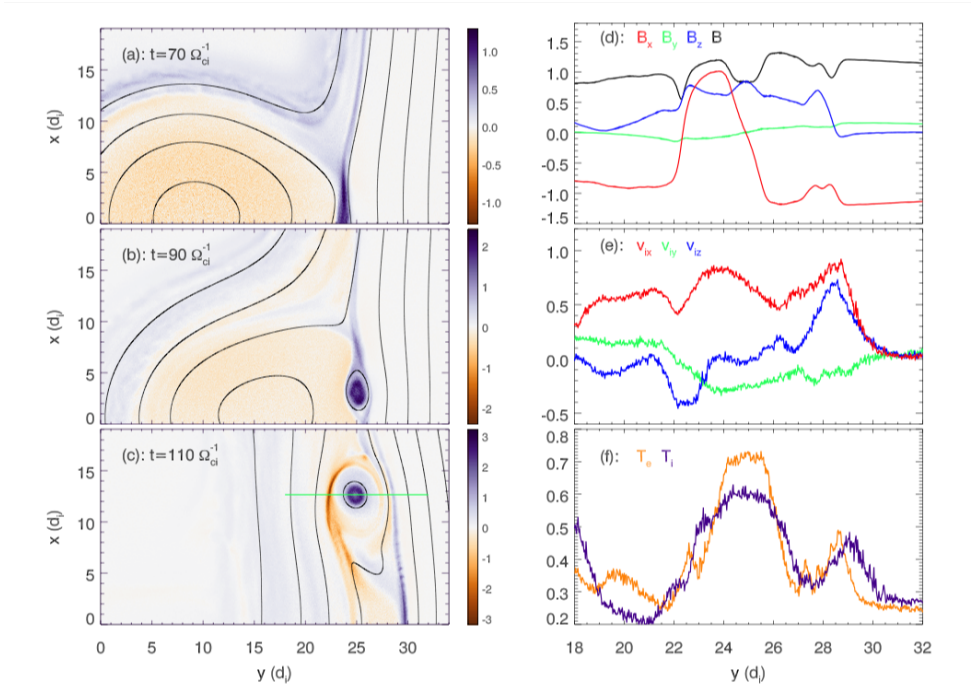
Simulation interchange reconnection

- A simulation testing interchange reconnection as a source of switchbacks (Fisk & Kasper ‘20)
- Initial state with a closed flux region adjacent to open flux
  - Strong initial guide field
- Reconnected field lines straighten as they expand outward
  - Relaxation of field line tension
- Simple interchange reconnection model is not likely to produce the reversals in B_R seen in the data



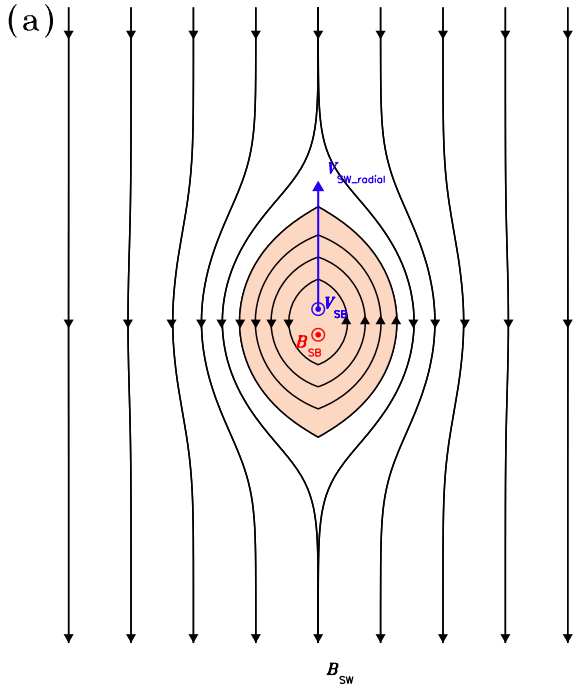
Interchange reconnection and flux rope formation

- PIC simulation of interchange reconnection in a larger domain
  - Longer current layers form flux ropes
  - Flux rope is injected into the ambient ”solar wind”
- Flux rope characteristics
  - Reversal in radial field B_x
  - Strong axial magnetic field
  - Increase in T_e and T_i in the flux rope
    - Mostly parallel heating



Structure of outward propagating flux rope

- Flux rope propagates outward
  - Sandwiched within uni-directional field lines
- Reconnection in the current layer at the right edge of the bubble is suppressed because of Alfvenic shear flow between the ambient solar wind and the outward propagating flux rope



Rest frame of solar wind

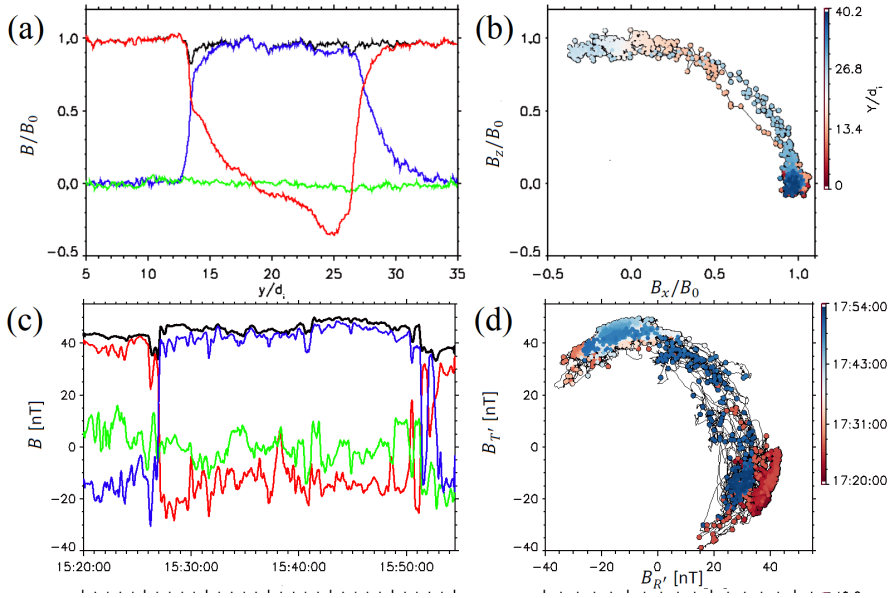
Comparison of the flux rope structure with observations

- Cuts through the center of the flux rope (simulation coordinates)
  - Sharp rotation of B into the azimuthal direction
  - Magnitude of B nearly constant across the flux rope
  - Surprisingly good agreement between simulation cuts and observational data
  - Data is not sensitive to the angle of the trajectory because the flux ropes are highly elongated

B_x

B_z

B_y



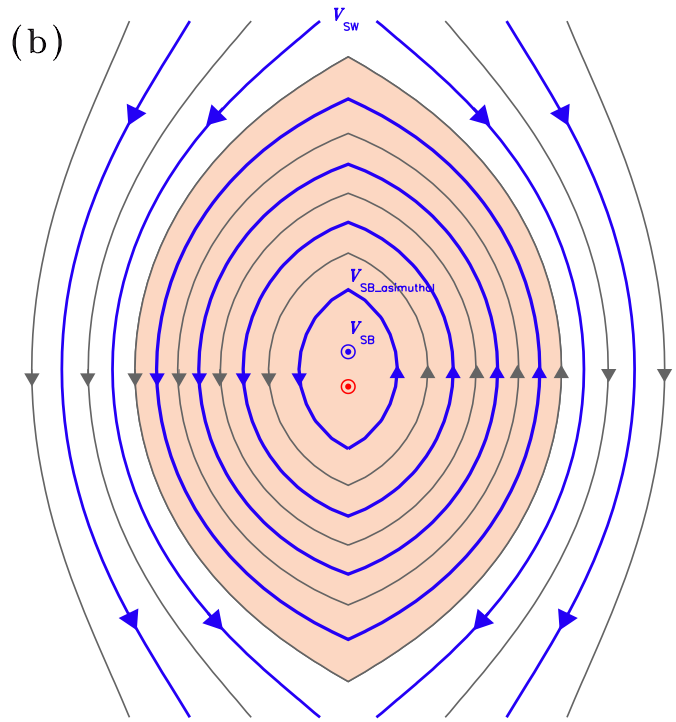
Simulation data

PSP observations

Relaxation of flows

- The observations reveal the Alfvenic character of the flows
  - e.g., $V_{pR} - B_R/(4\pi\rho)^{1/2}$ = const.
- Interchange reconnection does not typically produce flows that satisfy the Alfvenic relation
  - Large parallel as well as perpendicular flows
- The flows driven by perpendicular electric fields relax on a fast time scale
  - Leaving only parallel flows
- Flux ropes dominated by parallel flows are characterized by two distinct classes
  - Alfvenic or anti-Alfvenic flux ropes
  - Anti-Alfvenic flux ropes reconnect
  - Only Alfvenic flux ropes survive

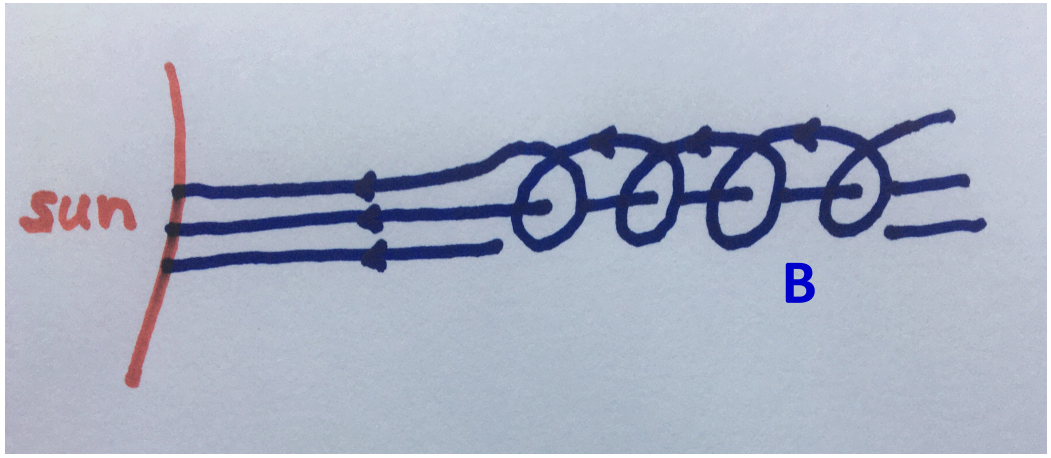
Flows in the flux rope frame

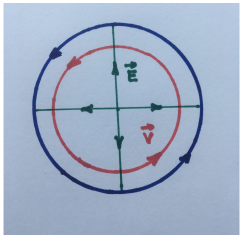


Alfvenic flux rope

Dissipation of perpendicular flows

- Perpendicular flows result from perpendicular electric fields in the flux rope
- Perpendicular electric field drive currents that close through the solar surface
  - Analogous to Region 1 currents in the Earth's magnetosphere/ionosphere
  - Flux ropes remain magnetically connected to the sun (e.g., strahl)





Circuit model of flow damping

- Flow damping modeled with an effective R-C circuit
- Energy in perpendicular kinetic energy

$$W_{SB} = \frac{1}{2} n m_i V_\perp^2 \left(\pi r_{SB}^2 L_{SB} \right) = \frac{1}{2} C \varepsilon_{SB}^2$$

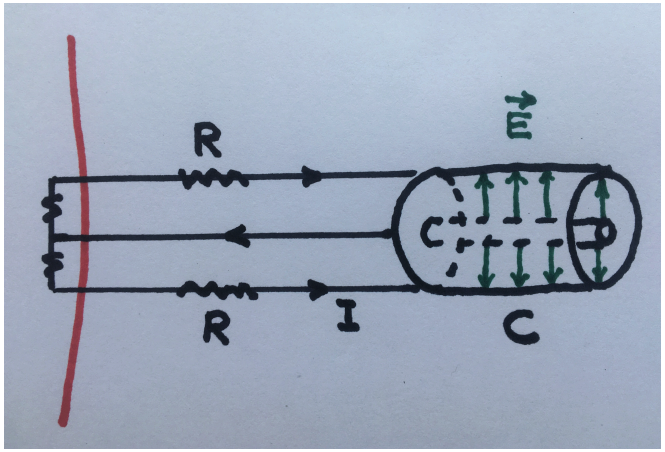
- Yields an effective capacitance C and current I

$$C = \frac{c^2}{4 c_A^2} L_{SB} \qquad I = C \frac{d}{dt} \varepsilon_{SB}$$

- Dissipation of energy

$$\frac{d}{dt}\left(\frac{1}{2} C \varepsilon_{SB}^2 \right) = -I^2 R_{eff}$$

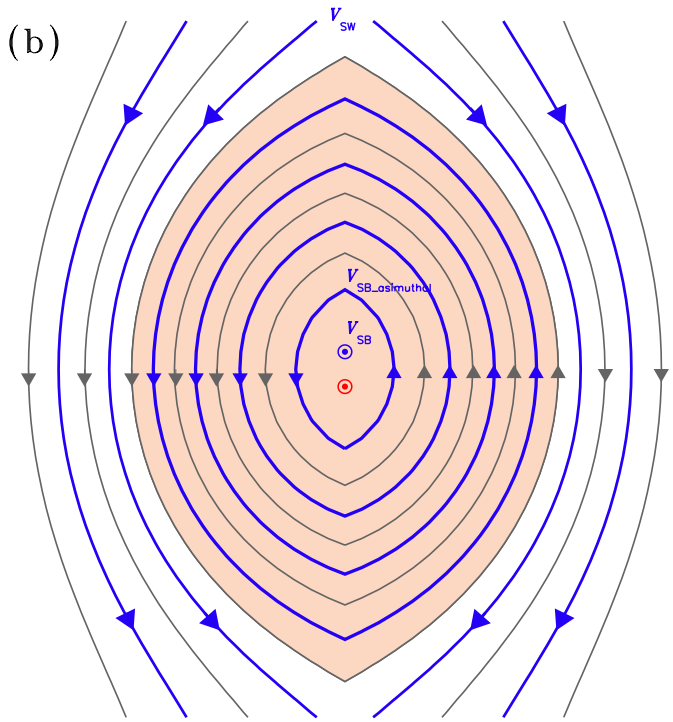
- Non-classical resistivity R_{eff} from Buneman instability
- Flow damping is fast – close to the solar surface



$$V_\perp = \frac{c E_r}{B} = \frac{c \varepsilon_{SB}}{B r_{SB}}$$

Relaxed states of flux ropes

- De Hoffmann-Teller frames of the flux rope and solar wind should match
  - Required since perpendicular electric fields dissipate
- Flows within the flux rope are magnetic field aligned
- Two possible final states: Alfvenic and anti-Alfvenic
  - Alfvenic flux rope stable to reconnection
  - Anti-Alfvenic flux rope has reversed parallel flows in the flux rope
    - Reconnection with the solar wind magnetic field eliminates anti-Alfvenic flux ropes



Alfvenic flux rope

Conclusions

- Velocity spikes in the solar wind may be the result of flux ropes injected into the solar wind as a result of reconnection between open and closed flux close to the solar surface
- Strikingly good agreement between the magnetic structure of flux ropes and that of switchbacks
- Temperature increase within flux ropes consistent with SB observations
  - Relaxation of the temperature increase with distance from the sun suggests flux rope formation close to the sun
- Perpendicular flows within a flux rope relax, leaving dominantly parallel flows
- Flows and magnetic fields in a relaxed-state flux rope are Alfvenic in character