Nonlinear wave propagation and reconnection at an X-point in Hall MHD

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March 29th, 2012

Introduction

- Fast-waves and large-scale disturbances (e.g. EIT waves) seen to travel large distances in the corona, often across different magnetic field structures/environments.
- Through interaction with local environment, these waves can trigger energy release through *magnetic reconnection*.
- Significant energy release often only achieved for collisional models via large current densities & small lengthscales - *MHD model self-consistent*?
- Potential solution: include additional terms in generalised Ohm's Law.
- Focus on Hall term - study *wider range of scales* than MHD, with *minimal additional complexity*.

Q: How does the Hall term affect MHD waves and (wave-triggered) reconnection?

Fast-wave/X-point interaction in MHD

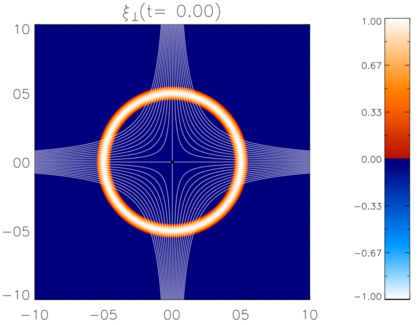
- McLaughlin et al. (2009) studied interaction of initial nonlinear fast-wave with an X-point.
- Benchmark using `Lare2d code` (Arber et al., 2001)

◇ Equilibrium:
$\mathbf{B} = B_0[-x, y, 0]$, $\beta = 0$,
$T = 0$, $(x, y) \in [-20, 20]$,
5120×5120 grid

◇ $\xi_\perp(t) = (\mathbf{v}\times\mathbf{B})_z = v_x B_y - v_y B_x$
$(v_\perp = \xi_\perp/|B|)$

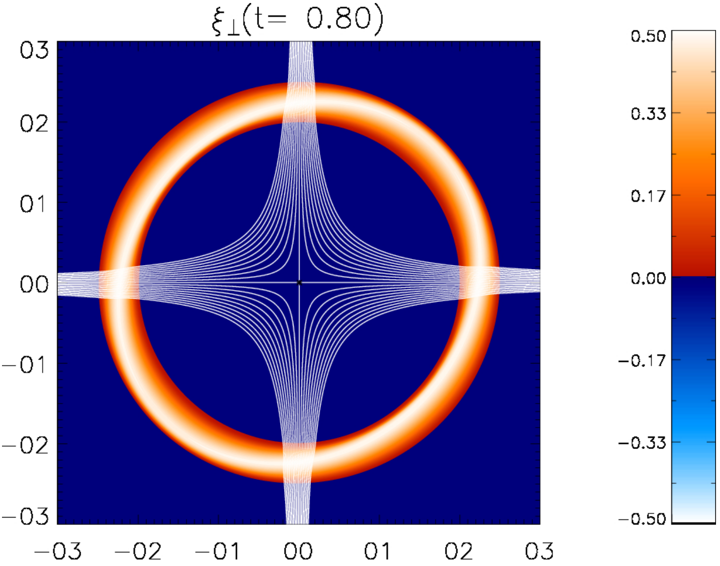
◇ Initial Perturbation:
$\xi_\perp(0) = 2C \sin(\pi[r - 4.5])$

◇ Nonlinear amplitude ($C = 0.5$) allows pulse to reach the null.



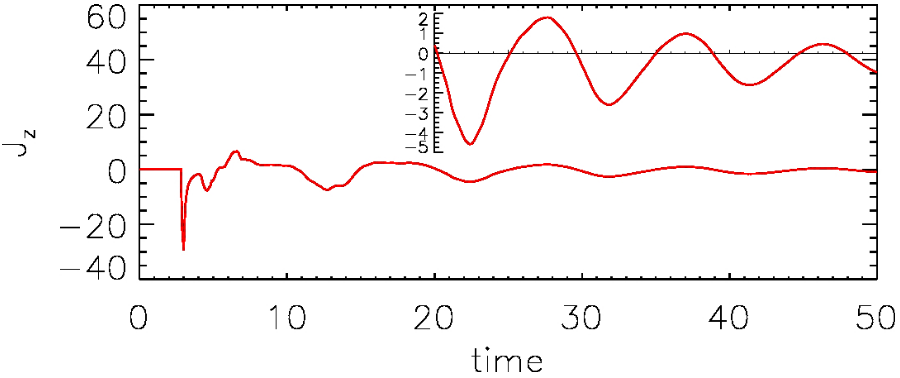
◇ $t = 0.8$: replace outward travelling pulse with initial config. & damping layer

Oscillation of collapsed X-point - **MHD**



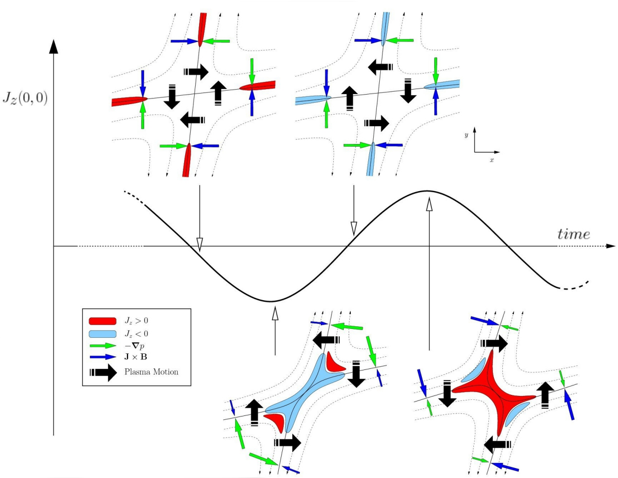
Current oscillations - MHD

Like McLaughlin et al. (2009), find distinctive oscillations of current at the null, which decrease with time:



What drives later oscillatory behaviour?

Oscillatory behaviour - MHD



- Whether $-\nabla p$ or $\mathbf{J} \times \mathbf{B}$ dominates in one quadrant depends on initial config.
- Each restores overshoot brought on by other.
- Successive responses progressively smaller.
- **Could the inclusion of the Hall term affect this cycle?**

Hall MHD - recap!

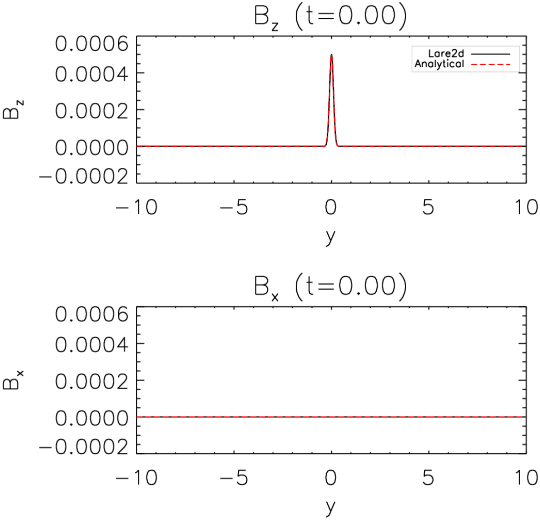
$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne} \mathbf{J} \times \mathbf{B}$$

- Hall MHD appropriate for high frequency perturbations ($\omega \sim \Omega_i$) and small lengthscales ($L \sim \delta_i$).
- Two distinct wave-branches emerge as $k\delta_i$ increases:
  - whistler wave (super-Alfvénic) - dispersive
  - ion-cyclotron wave (sub-Alfvénic, ultimately constant frequency)
- Branches introduce circular polarisation and dispersive effects when applied to waves/pulses

[Details given in **Section 2** of **Threlfall et al. (2011, A&A 525 A155)**]

- Initially shear waves *quickly couple to fast waves* (and vice-versa) and *rapidly broaden* - how quickly determined by δ_i.

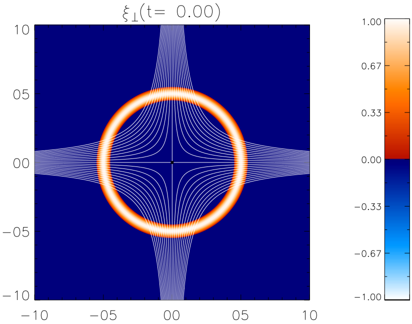
Hall MHD - single pulse, uniform field



- Example: initially shear pulse, $k\delta_i \ll 1$.
- Shear Alfvén wave no longer plane polarised for finite δ_i.
- Implications for wave annulus and shock formation in X-point field.
- **How are X-point collapse (and resulting reconnection) affected?**

Fast-wave/X-point interaction - **Hall MHD**

- $k\delta_i \ll 1$ limit yields near-identical behaviour to MHD in X-point simulations.
- $k\delta_i \gg 1$ limit difficult to simulate.
- $k\delta_i \sim 1$ simulations show *significant differences in initial wave behaviour* affecting X-point collapse.
- NB. "Diffraction-like pattern" caused by Hall effects and initial conditions (**not** interaction with boundary)!

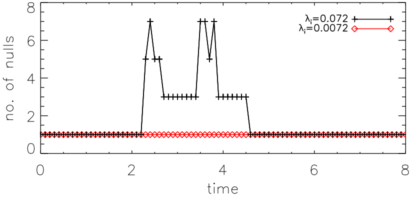


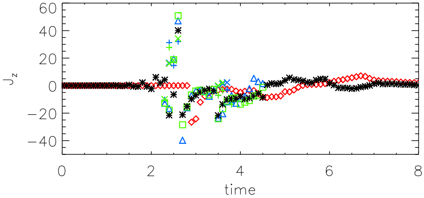
Fast-wave/X-point interaction - **Hall MHD** $(k\delta_i \sim 1)$

Reconnection in Hall MHD

Two distinct categories of reconnection:

1. **Initial X-point collapse**:
   - Highly dependent on δ_i.
   - Whistler waves destabilise X-point earlier.
   - Additional null pairs generated.
   - Wide range of currents (inc. planar, $\mathbf{J}_x,\mathbf{J}_y$) at each null.
2. **Oscillatory reconnection**:
   - Frequency appears independent of δ_i (for values tested).
   - Cycle still driven by gas and magnetic pressures (as with MHD).





Summary

- Wave-triggered X-point collapse relaxes via oscillatory reconnection.
- Relaxation caused by competition of magnetic and gas pressure forces, restoring successive overshoots brought about by the other.
- In Hall MHD, whistlers and circular polarisation significantly modify initial wave and resulting X-point collapse for large values of δ_i.
- Whistlers cause rapid oscillations of field near original null, generating multiple additional null pairs.
- Arrival of main body of pulse causes additional nulls to recombine - system then relaxes through oscillatory relaxation, with identical frequency to MHD case.
- Presence of additional nulls and planar currents prevents definitive conclusions regarding rate of reconnection.

[Submitted to A&A, Threlfall et al. (2012, arXiv: 1202.3648v2)]

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