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Two-fluid ballooning instability induced plasmoid formation in near-Earth magnetotail

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Abstract

Previous single-MHD simulations demonstrate that ballooning instability can develop in thin-current sheet configurations of near-Earth magnetotail, which would in turn induce plasmoid formation and three-dimensional magnetic reconnection in absence of inward solar wind flow from magnetopause [1,2]. Our recent two-fluid MHD simulations find that such a mechanism for plasmoid formation in magnetotail remains viable in regimes and scales where Hall and finite-Larmor-radius (FLR) effects become no longer negligible. Both linear and nonlinear calculations are carried out to evaluate the two-fluid effects on the ballooning instability and its consequence, based on a generalized Harris sheet configuration of the magnetotail. Whereas FLR effects reduce and stabilize linear growth of ballooning instability at ion gyroradius scale, Hall effects can significantly increase the number of plasmoids formed along the Earth and tail-ward direction after the nonlinear growth of ballooning instability. The emergence and presence of multiple plasmoids induced by nonlinear ballooning instability suggests a potential origin of the series of neighbouring magnetic islands in magnetotail observed during a substorm expansion phase [3]. References [1] P. Zhu and J. Raeder, Phys. Rev. Lett. 110, 235005 (2013). [2] P. Zhu and J. Raeder, J. Geophys. Res. Space Physics 119, 131-141 (2014). [3] L.-J. Chen et al, Phys. Plasmas 16, 056501 (2009).

Two-fluid ballooning instability induced plasmoid formation in near-Earth magnetotail

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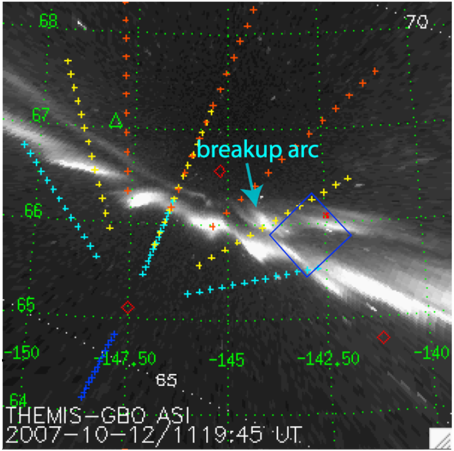
Poster SM51E-1810, Friday

Auroral beads across Milky Way [Courtesy of J. Liang 2017]

Bead structure prior to aurora substorm onset: Projection of near-Earth tail ballooning instability?

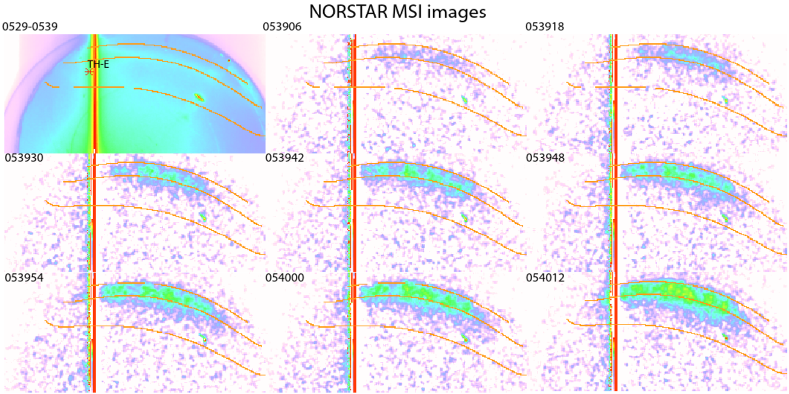


Aurora breakup onset time 1119:42 UT [Zou *et al.* 2009]

Beading features are closely associated with signatures of ballooning instability

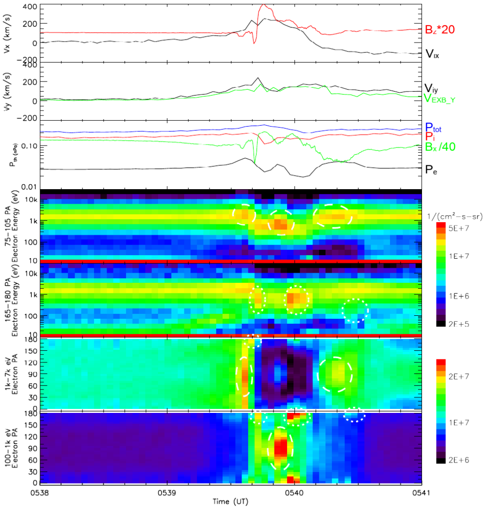
- Spatial aspect: Periodic structure along dusk-dawn direction
  - Ballooning instability only possible for non-zero k_y.
  - Intrinsically 3D, unlike other 2D instabilities/processes.
- Temporal aspect: Exponential growth of beading arc intensity
  - Exponential growth not limited to linear instability.
  - Ballooning instability is one of few MHD instabilities that grows exponentially even in early to intermediate nonlinear stage [Zhu *et al.* 2009].
- Increasing evidence suggests near-Earth tail ballooning instability a likely mechanism for onset instability.

Both auroral beading and dipolarization front events observed in a same transitional stage [Liang 2017]



Development of beading and intensification occur around 0540 UT

In-situ measurement from TH-E shows DF feature right around beading [Liang 2017]



- Wave like activities superimposed on the DF.
- The concurrent appearance of beads and DF suggests connection between ballooning and reconnection prior to substorm onset.

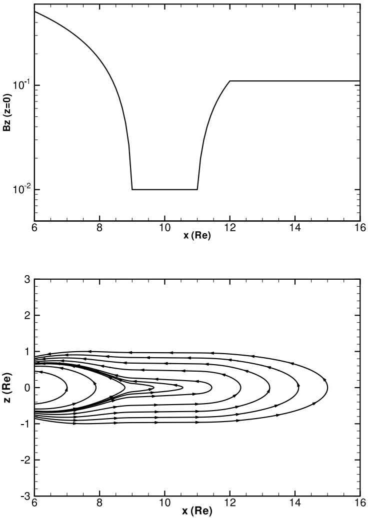
How can ballooning instability lead to the formation of plasmoids and onset of reconnection in near-Earth magnetotail?

- Can plasmoid spontaneously form without external drivers?
  - Drivers: in-flow (solar wind) or foot-point motion (corona).
  - Can internal instabilities generate plasmoids?
- Can plasmoid spontaneously form in realistic Lundquist number regime?
  - Many previous work were in low Lundquist number regime, which would need to explain sources of localized anomalous resistivity.
- This work is about
  - How ballooning instability may lead to plasmoid formation in the high Lundquist number regime in near-Earth magnetotail, and
  - How previous resistive MHD model is extended to two-fluid MHD regime.

Outline

- Observational evidence for ballooning instability in magnetotail
- Ballooning instability induced plasmoid formation
- Two-fluid effects (Hall, FLR, etc) on the ballooning-induced plasmoid formation

Generalized Harris sheet with a minimum in B_z profile along x axis used to model the near-Earth magnetotail prior to substorm onset [Zhu *et al.* 2013]



- Generalized Harris sheet

$$\mathbf{B}_0(x,z) = \mathbf{e}_y \times \nabla\Psi(x,z),$$

$$\Psi(x,z) = -\lambda \ln \frac{\cosh\left[F(x)\frac{z}{\lambda}\right]}{F(x)},$$

$$\ln F(x) = -\int B_{0z}(x,0)dx/\lambda.$$

- Harris sheet: $F(x) = 1$.
- The region of minimum B_z corresponds to an embedded thin current sheet in near-Earth magnetotail.

Full set of resistive Hall-MHD equations are solved in 3D domain as an initial-boundary value problem using NIMROD code [Sovinec *et al.* 2004]

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \mu \nabla \cdot (\rho \nabla \mathbf{u}) \tag{2}$$

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\gamma p \nabla \cdot \mathbf{u} \tag{3}$$

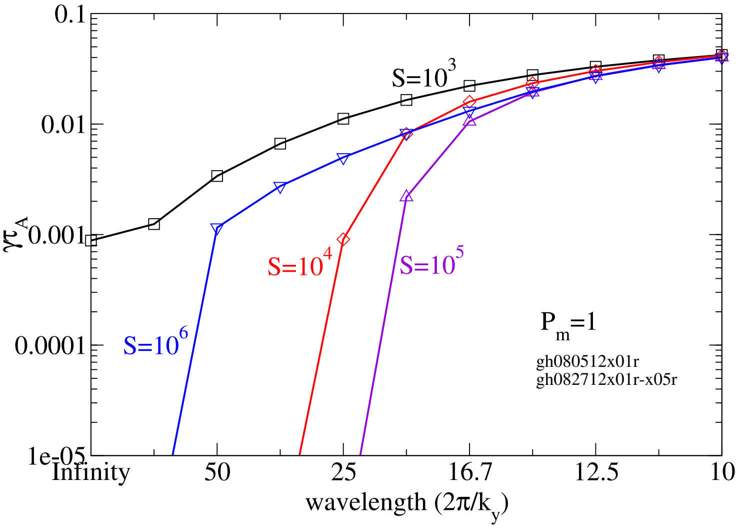
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{4}$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne} (\mathbf{J} \times \mathbf{B} - \nabla p_e) \tag{5}$$

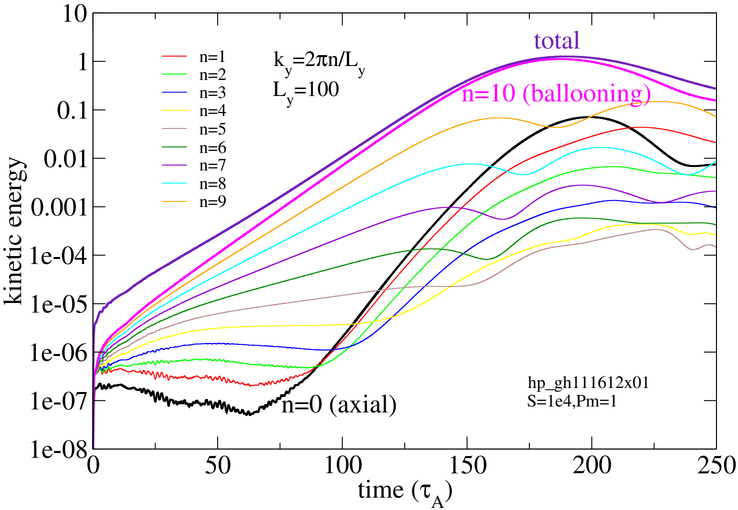
$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B} \tag{6}$$

- Boundary conditions: Solid, no-slip walls in x, z; periodic in y.

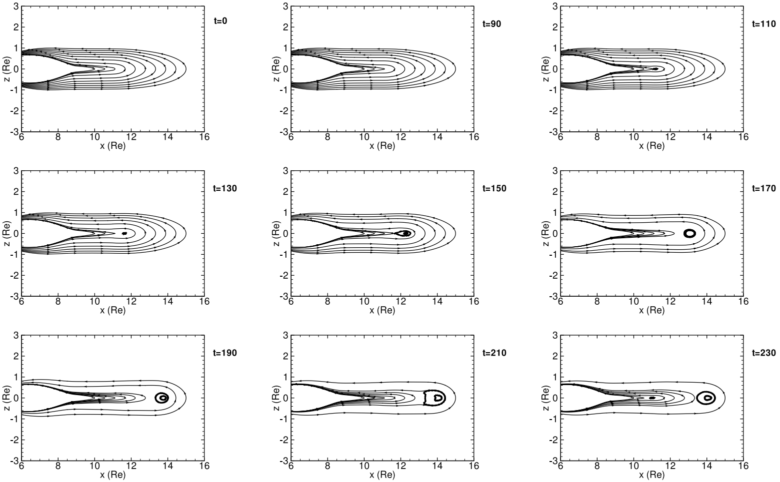
3D effects can significantly enhance growth of (axial) tail instability through coupling to ballooning instability in finite k_y regime



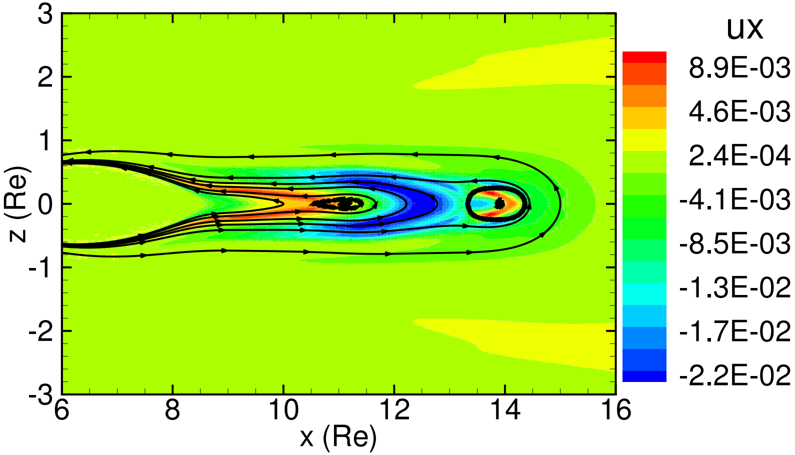
Single-fluid MHD: nonlinearly the higher k_y ballooning instability can drive growth of lower k_y (including zero-k_y axial tail) modes even when they are linearly stable



Nonlinear evolution of ballooning instability induces formation of tailward receding plasmoids in certain $x - z$ planes



Stagnation points in tailward flow are in general not the same locations as the magnetic x-points or o-points in reconnection



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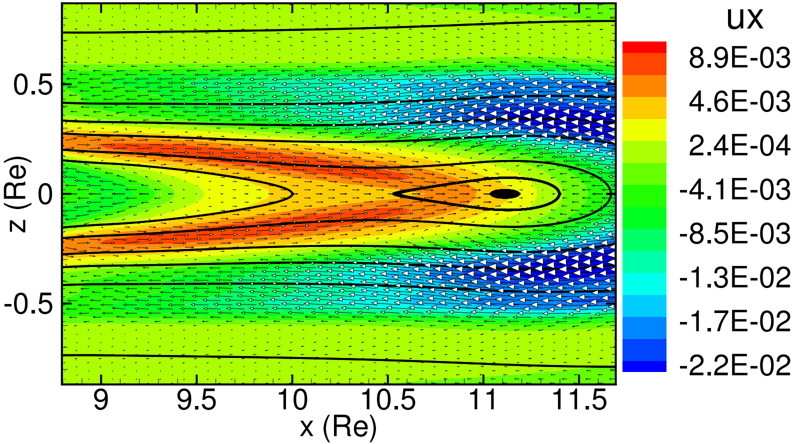

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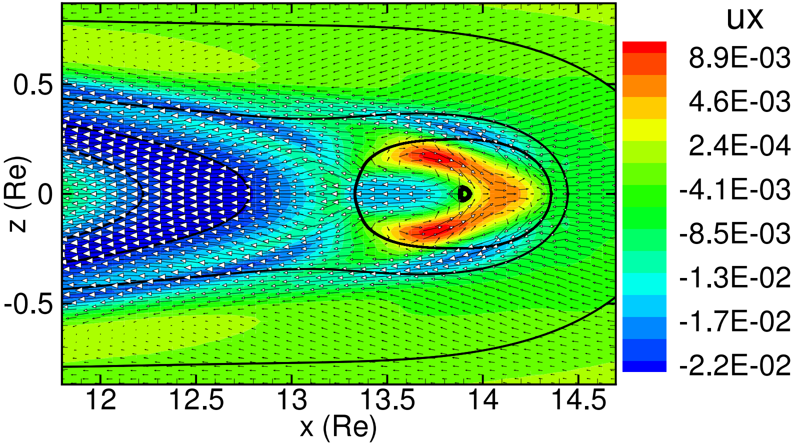

Outline

- Observational evidence for ballooning instability in magnetotail
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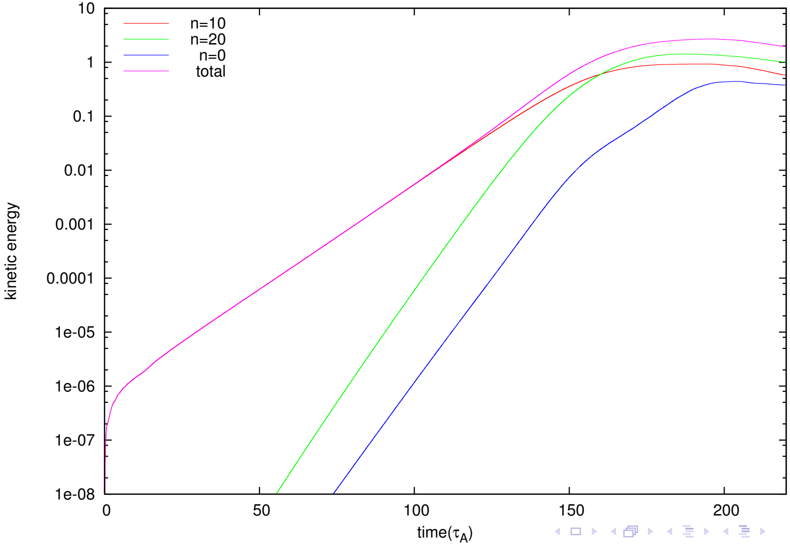
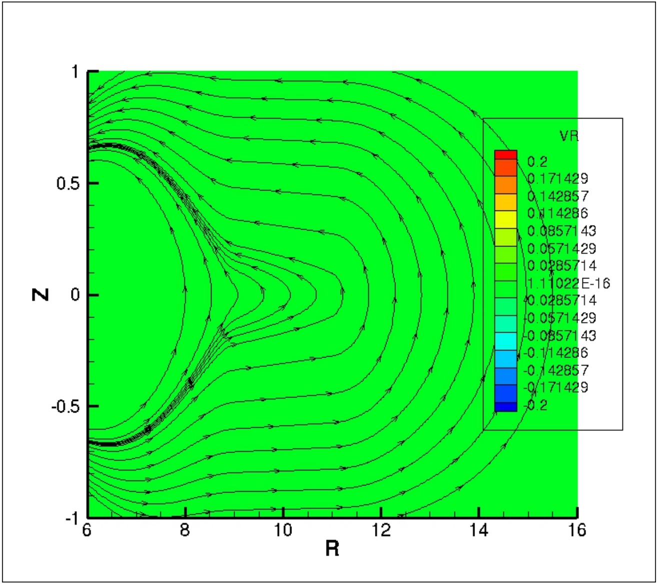
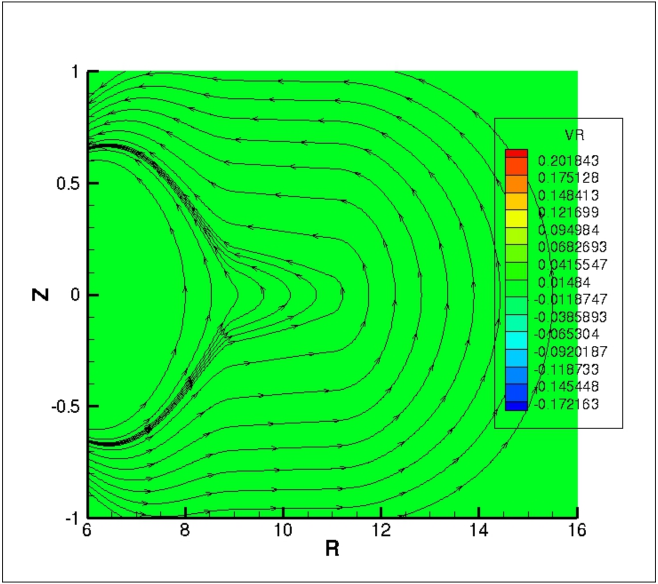
Hall MHD: for monochromatic initial perturbation, nonlinear ballooning instability goes through an exponential growth phase before saturation



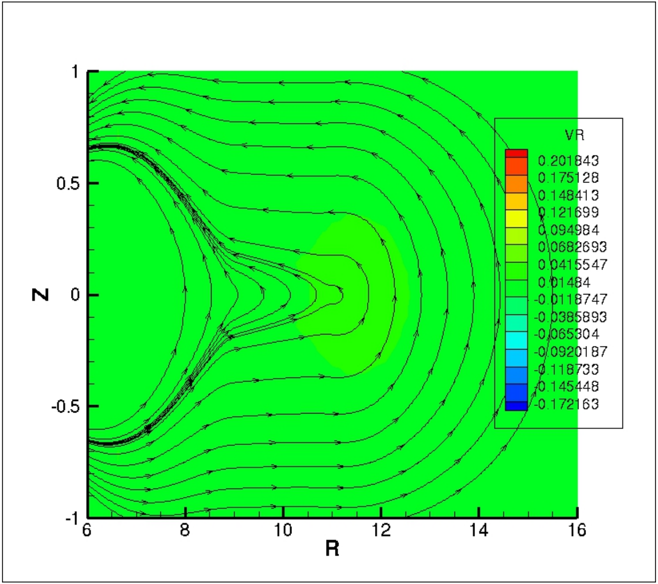
Hall MHD simulation starts with the same Harris sheet configuration without in-flow ($t = 0$)



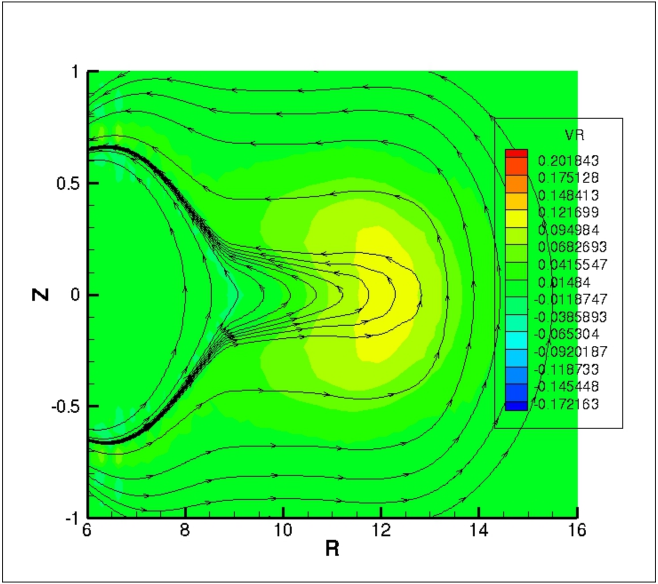
Hall MHD: Current sheet thinning starts in near-Earth region around $10\ R_{\mathrm{E}}$ ($t = 90$)



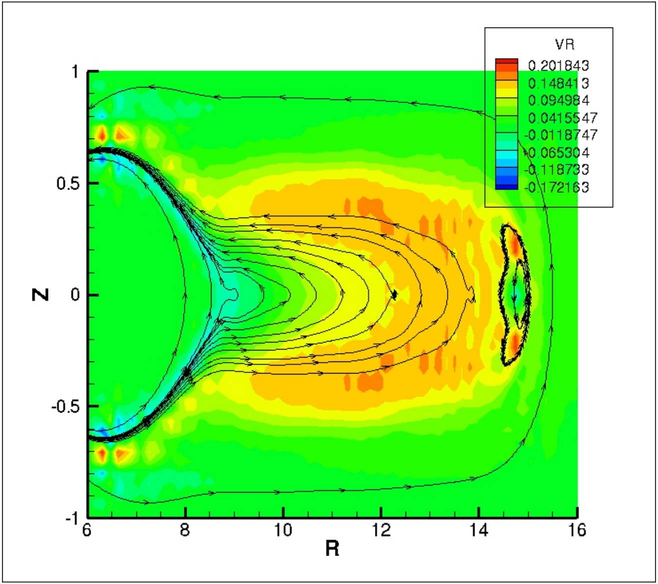
Hall MHD: Current sheet continues thinning as ballooning starts to grow around 11 R_E ($t = 120$)



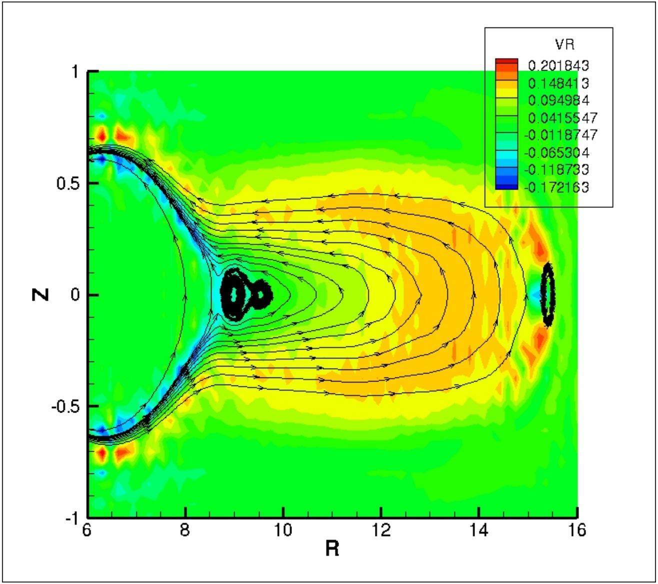
Hall MHD: Near-Earth CS extends tailward as a consequence of ballooning growth ($t = 150$)



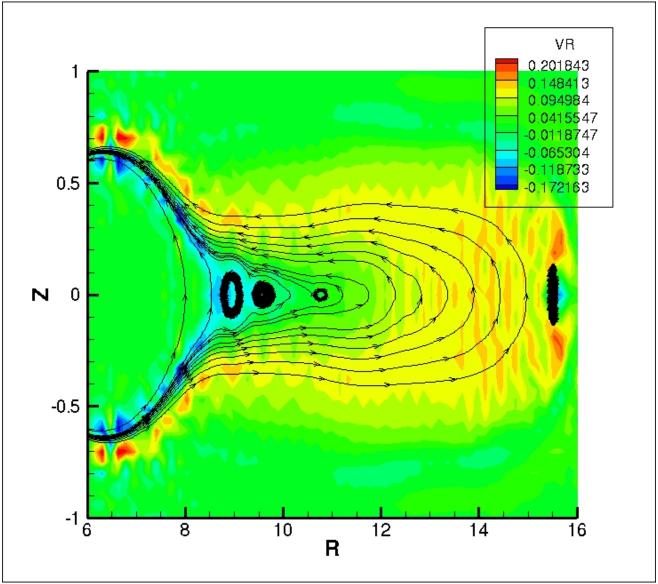
Hall MHD: Plasmoid forms at the tip of extending ballooning structure ($t = 180$)



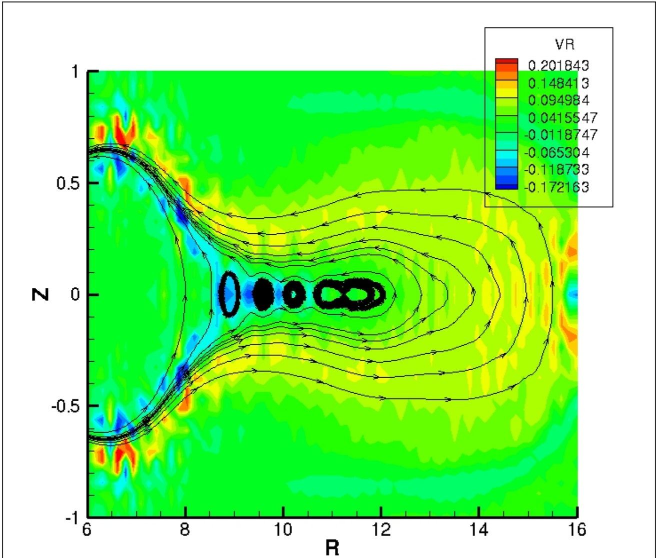
Hall MHD: Plasmoids start to form in near-Earth region as finger-tip plasmoid shrinks ($t = 190$)



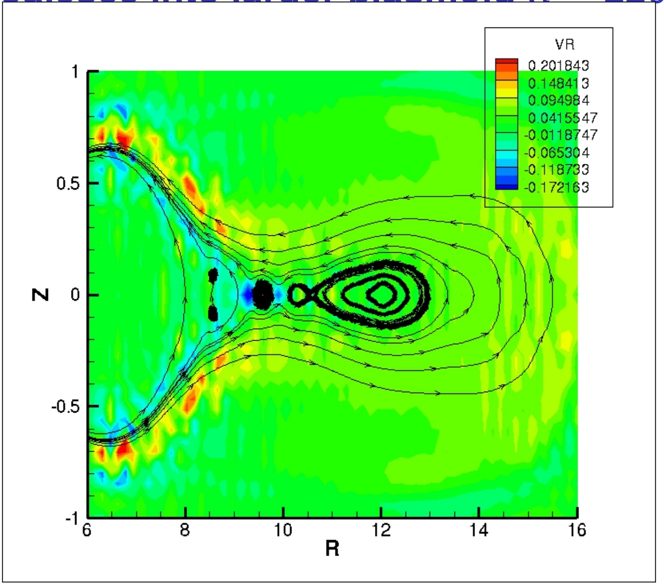
Hall MHD: Multiple plasmoids emerge and move tailward from near-Earth region ($t = 200$)



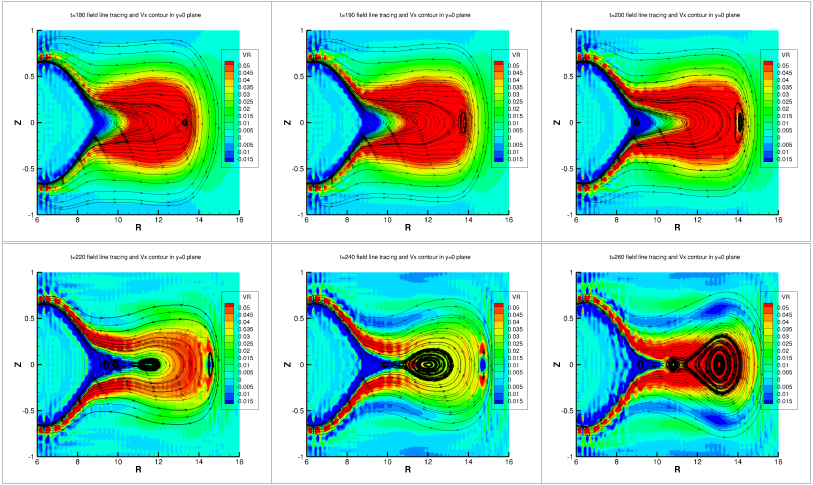
Hall MHD: More plasmoids continue to emerge forming a plasmoid chain extending from near-Earth region ($t = 210$)



Hall MHD: Eventually several plasmoids in the chain coalesce into larger plasmoid ($t = 220$)



Two-fluid MHD simulation at higher spatial resolution confirms the convergence of newly found Hall effects



Summary: Two-fluid effects may enable formation of plasmoid chain in near-Earth magnetotail

- Observations suggest causal relation between ballooning instability (“beads”) and onset of magnetic reconnection (“DFs”) in near-Earth magnetotail.
- In higher-*S* regime where linear 2D resistive tearing mode is stable, nonlinear ballooning instability can induce the formation of plasmoids in current sheet without preexisting X-line [Zhu and Raeder 2013,2014, Zhu *et al.* 2017].
- Such a mechanism of plasmoid formation induced by nonlinear ballooning instability remains valid in the two-fluid MHD model.
- Two-fluid effects may enable formation of plasmoid chain in near-Earth magnetotail region.

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