Global MHD simulation and analysis of Feb. 22, 2009 THEMIS substorm event

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in collaborations with

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Periodic black aurora was observed in Feb 22 2009 substorm event [Sakaguchi and Shiokawa 2009]

Optical substorm onset: Fort Yukon 0814 UT (∼ 2314 LT)
Periodical black aurora: Gillam and Sanikiluaq 0830 UT (∼ 0230 LT)
Torch structure of periodic aurora resembles “Rayleigh-Taylor finger” pattern of interchange type of modes [Sakaguchi and Shiokawa 2009]
An initial effort to explore possible connections between ionosphere aurora features and plasma sheet instabilities

Question:
- Is the periodic black aurora structure a signature or consequence of a certain plasma sheet instability or reconnection process?

Approach:
- Reconstruct the Feb 22 2009 substorm event using global MHD simulations (OpenGGCM).
- Analyze (ballooning) instabilities of near-Earth tail configuration prior to onset.
- Look for links (correlations and causal relations) between aurora structures and plasma sheet instabilities.
- Initial results focus on correlational links.
THEMIS Feb 22, 2009 substorm event: 0700-0930 UT, first onset around 0810 UT (from OpenGGCM)

- Grid: $630 \times 200 \times 300$;
  Domain $x : [20, -500]$, $(y, z) : [-36, 36]$

- Ionosphere B.C.: Coupled Thermo-Ionosphere Model
  [Fuller-Rowell et al., 1996]

- Dayside B.C.: Solar wind data from ACE
  (left: bottom panel)

- Maximum ionosphere discrete electron flux at night side indicates first onset around 0810 UT
  (left: top panel)
Ionosphere discrete $e^-$ precipitation shows initial intensification around 0810 UT (OpenGGCM)
Timings and locations of discrete $e^-$ precipitation intensification are consistent with observations

- **Prior to onset expansion:** initial intensification at 0810 UT ($\sim 2300$ LT); Observation: optical onset at 0814 UT ($\sim 2314$ LT).

- **During recovery phase:** subsequent intensification starts at 0830 UT ($\sim 0200$ LT); Observation: periodic black aurora at 0830 UT ($\sim 0230$ LT).
Tailward flow evolution shows plasma sheet stretching and dipolarization around onset expansion (OpenGGCM)
Early growth phase ($\sim UT0750$): Plasma sheet is highly stretched in middle tail region with multiple reconnection sites.
Pre-onset phase ($\lesssim$ UT0810): Reconnection sites recede tailwards and near-Earth region becomes stretched.
Onset expansion phase ($\sim$ UT0815 – 0830): Entire plasma sheet stretching stops and dipolarization starts from near-Earth region.
Recovery phase (⏰ UT0835): Dipolarization front propagates from near-tail region to mid-tail region.
Pre-onset phase, as well as other phases, near-Earth plasma sheet region ($\lesssim 15 \, R_E$) is marginally stable to ballooning.
Pre-onset phase: plasma sheet becomes highly unstable to ballooning in a narrow transition region (near-to-middle distance from Earth)
Recovery phase: entire plasma sheet returns to marginally ballooning stable state
Discussion

The relation between the tail ballooning instability and the periodic black aurora has yet to be rigorously established.

- The discrete electron flux structure in ionosphere needs to be further resolved to demonstrate the periodic aurora structure.
- 3D ballooning analysis is required to map the unstable tail region to ionosphere.
- Resolving and tracing the dynamic ballooning process in global MHD simulations remains challenging.
Summary

- The Feb 22 2009 substorm event has been reconstructed using ACE solar wind data and OpenGGCM simulations.
  - The initial intensification of discrete electron flux (DEF) in ionosphere is consistent with observations of onset in both time and location.
  - Subsequent intensification of DEF in recovery phase may relate to the appearance of black aurora in observations.

- Ballooning instability of the reconstructed configurations during the pre-onset and recovery phases are evaluated.
  - Tail configuration is most ballooning unstable in stretched plasma sheet region ($\sim 20-25 \, R_E$).
  - Tail configuration is most ballooning unstable in late growth, pre-onset phase.
  - The timing suggests the periodic aurora observed in recovery phase could be developed from the most unstable tail ballooning instability started in pre-onset phase.
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Ballooning analysis starts with ideal MHD ballooning mode equations in a general configuration

For general magnetic configuration $B = \nabla \psi \times \nabla \alpha$

$$\rho B^2 \partial^2_{t} \xi_{\parallel} = B \partial_l \left[ \frac{\gamma p}{1 + \gamma \beta} \left( B \partial_l \xi_{\parallel} - 2 e_{\perp} \cdot \kappa \xi_{\psi} \right) \right]$$

$$\rho |e_{\perp}|^2 \partial^2_{t} \xi_{\psi} = B \partial_l (|e_{\perp}|^2 B \partial_l \xi_{\psi}) + 2 e_{\perp} \cdot \kappa e_{\perp} \cdot \nabla p \xi_{\psi} + \frac{2 \gamma p e_{\perp} \cdot \kappa}{1 + \gamma \beta} \left( B \partial_l \xi_{\parallel} - 2 e_{\perp} \cdot \kappa \xi_{\psi} \right)$$

where

$$e_{\perp} \equiv e_{\psi} \cdot (I - bb) = \frac{\nabla \alpha \times B}{B^2}, \quad \kappa \equiv b \cdot \nabla b.$$ 

For ballooning eigenmodes $\partial^2_{t} \rightarrow \Gamma^2_{b}$, solve above two coupled ODEs along each flux tube with proper end boundary conditions to find growth rate $\Gamma^2_{b}$. 


Quasi-static condition need be satisfied in order to apply conventional ballooning analysis

- Quasi-static condition:

\[
\frac{\tau_A^2}{\tau_{eq}^2} = \frac{L_{eq}}{B^2} |J \times B - \nabla p| \ll 1, \quad \text{or} \quad \frac{|J \times B - \nabla p|}{\rho L_{eq}} \ll \Gamma_b^2
\]

where \( L_{eq} \approx L_p \), and \( L_p^{-1} = |d \ln p / dx| \).

- The MHD ballooning time scale \( \tau_A \) is an order of magnitude faster than the configuration evolution time scale \( \tau_{eq} \) prior to onset in the near-tail region reconstructed from OpenGGCM simulation:

\[
\tau_A^2 \sim 10^2 \ll \tau_{eq}^2 \sim 10^3 - 10^4
\]
Ballooning analyses are performed on reconstructed near-tail configurations

- For 2D magnetotail configuration \( \mathbf{B} = \nabla \psi(x, z) \times \hat{y} \), near marginal stability, under quasi-static condition and for line-tied boundary condition, the coupled ballooning mode equations is reduced to one equation

\[
\frac{\rho}{B^2} \frac{\partial^2 \xi}{\partial t^2} = B \frac{\partial}{\partial l} \left( \frac{1}{B} \frac{\partial \xi}{\partial l} \right) + \frac{2\kappa \psi}{B} \frac{dp}{d\psi} \xi - \frac{4\gamma p \kappa \psi}{B} \frac{\langle \kappa \psi \xi \rangle}{\langle 1 + \gamma \beta \rangle}
\]

or \( \Gamma_b^2 = -\Gamma_{ben}^2 + \Gamma_{int}^2 - \Gamma_{com}^2 \)

where in local approximation

\[
\Gamma_{int}^2 = \frac{2\kappa \psi}{B} \frac{dp}{d\psi}, \quad \Gamma_{ben}^2 \lesssim \left( \frac{u_A}{R_E} \right)^2 = \frac{B^2}{\rho R_E^2}.
\]

- The time scale of bulk flow effects: \( \Gamma_{con}^2 \simeq (u_x/L_p)^2 \).