Tail Ballooning Modes in Global Simulations at Substorm Onset

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EGU, Vienna/Austria, 4/23/2012

Abstract

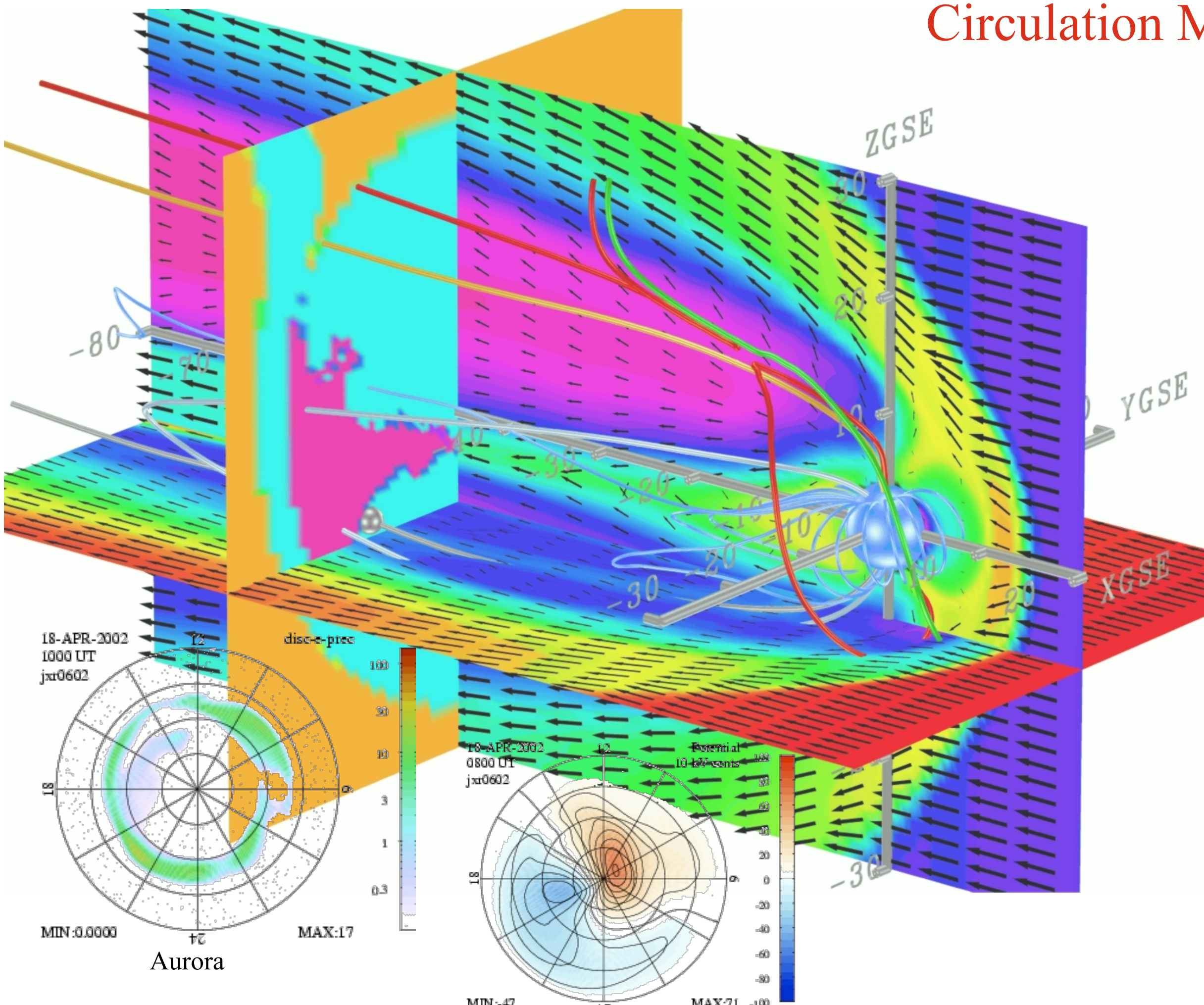
It is generally accepted that magnetic reconnection is the main mechanism that dissipates power during a substorm. It is less clear, however, whether the beginning of magnetic reconnection in the magnetotail also signifies the onset of the substorm expansion phase itself, i.e., whether the "outside-in" scenario applies, or if a different process happens first closer to Earth that triggers the reconnection onset in the magnetotail, i.e., the "inside-out" scenario. Global MHD simulations have generally supported the "outside-in" scenario. However, ideal MHD instabilities that could possibly trigger tail reconnection may have been missed due to coarse numerical resolution or due to other numerical effects. Here, we present results from OpenGGCM substorm simulations that clearly show growth of the ballooning mode (large ky) as suggested by our earlier analysis (Zhu et al., 2009), as well as growth of an ideal-like instability that is purely axial, i.e., with zero ky. The signatures of the ballooning mode in the model is in good agreement with observations, i.e., ~0.5 RE wavelength and associated auroral bead structures, whereas the axial mode appears to be related to entropy anti-diffusion and bubble-blob formation.

Introduction

- The common wisdom holds that the onset of the substorm expansion phase occurs when near-Earth reconnection reaches open field lines (NENL model).
- A competing model holds that “current disruption” initiates the onset and that reconnection occurs later.
- Others believe that tail oscillations and coupling with the ionosphere makes it happen.
- Maybe they are all wrong (or right).
- Arguments in this presentation are based on OpenGGCM simulations.

OpenGGCM: Global Magnetosphere Modeling

The Open Geospace General Circulation Model:



Aurora

Ionosphere Potential

- Coupled global magnetosphere - ionosphere - thermosphere model.
- 3d Magnetohydrodynamic magnetosphere model.
- Coupled with NOAA/SEC 3d dynamic/chemistry ionosphere - thermosphere model (CTIM).
- Coupled with inner magnetosphere / ring current models: Rice U. RCM, NASA/GSFC CRCM.
- Model runs on demand (>300 so far) provided at the Community Coordinated Modeling Center (CCMC at NASA/GSFC). http://ccmc.gsfc.nasa.gov/
- Fully parallelized code, real-time capable. Runs on IBM/datastar, IA32/I64 based clusters, PS3 clusters, and other hardware.
- Used for basic research, numerical experiments, hypothesis testing, data analysis support, NASA/THEMIS mission support, mission planning, space weather studies, and Numerical Space Weather Forecasting in the future.
- Funding from NASA/LWS, NASA/TR&T, NSF/GEM, NSF/ITR, NSF/PetaApps, AF/MURI programs.

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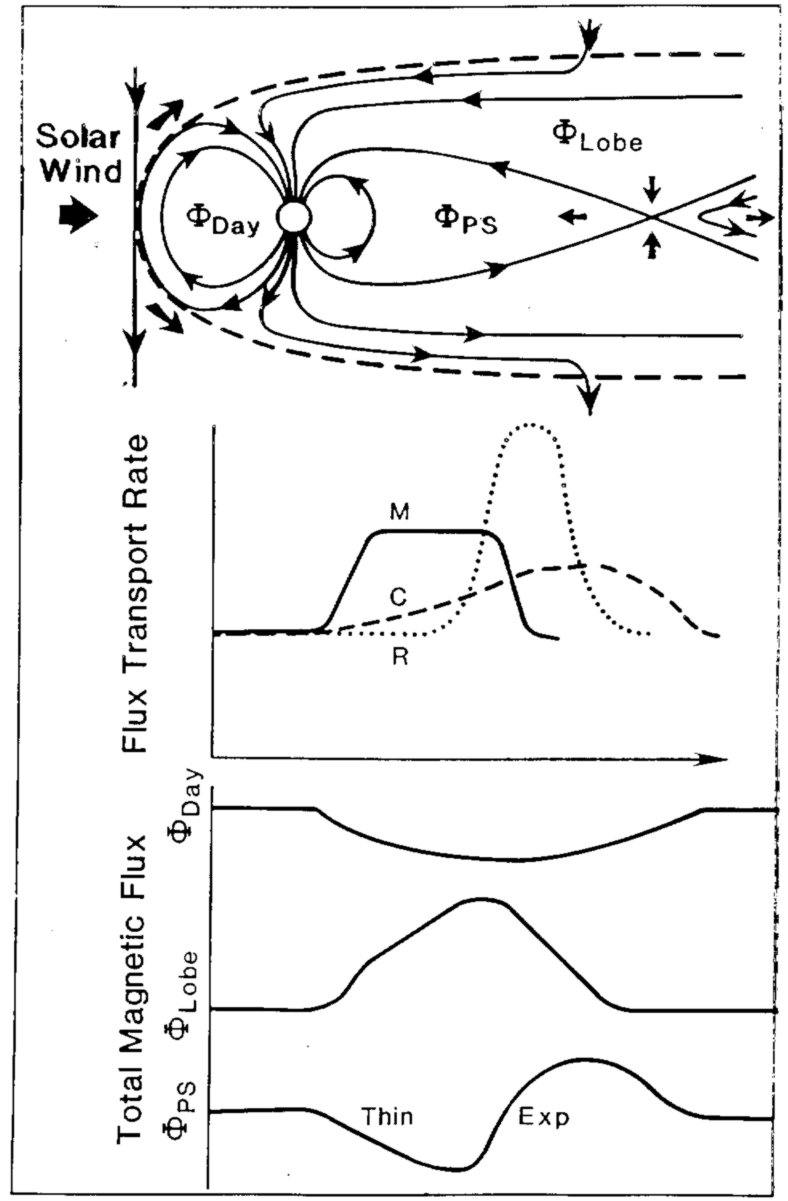
Substorms

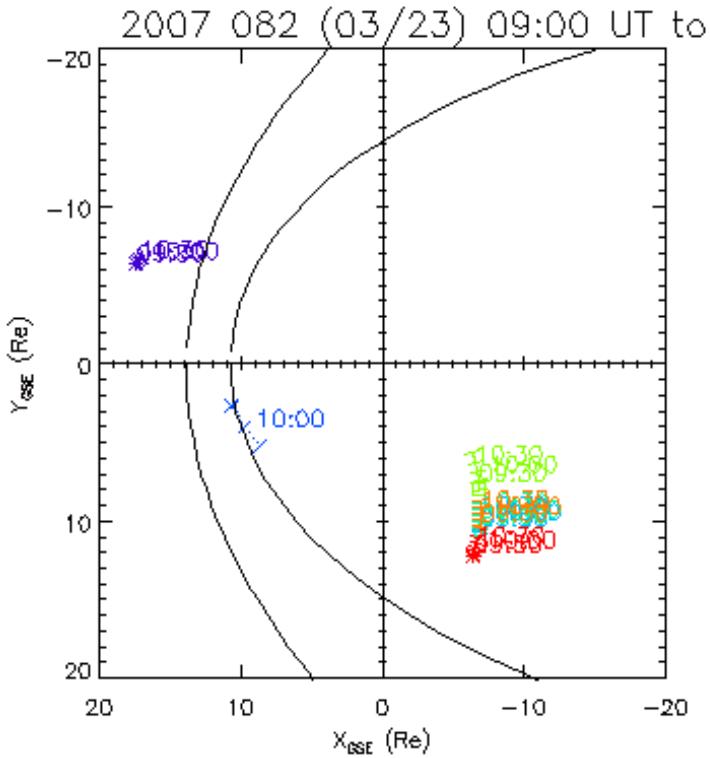
- Substorms are a consequence of reconnection rate imbalance: the nightside rate must balance dayside rate, at least on long scales (>1h) to return flux back to the dayside.
- During a substorm, first the dayside reconnection rate exceeds the nightside rate: growth phase.
- Explosive reconnection in the nightside signals the expansion phase with auroral brightening and westward traveling surge.
- It remains an open question what triggers the expansion phase onset: 2 minute question.
- If rates balance: steady magnetospheric convection (SMC).

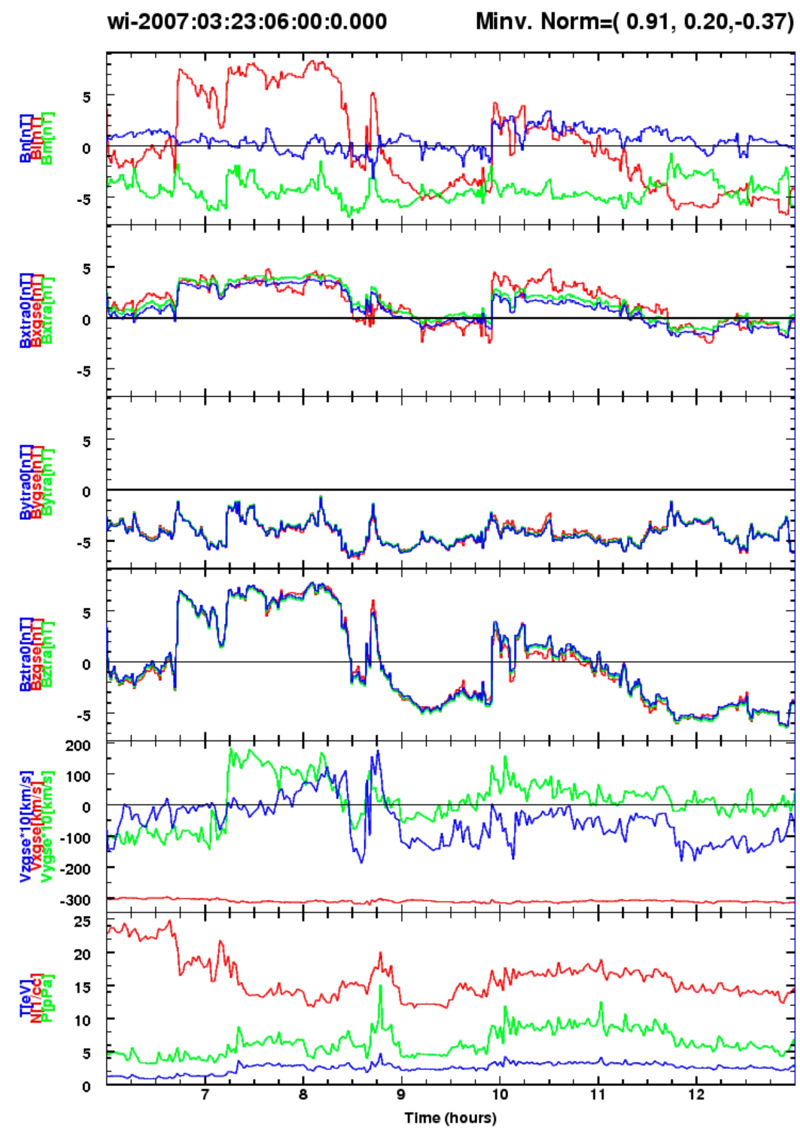


Russell, 1993

March 23, 2007 substorm

- Northward IMF turn at ~1000 UT at Wind
- Wind located at L1, 200RE upstream, ~1h time delay.

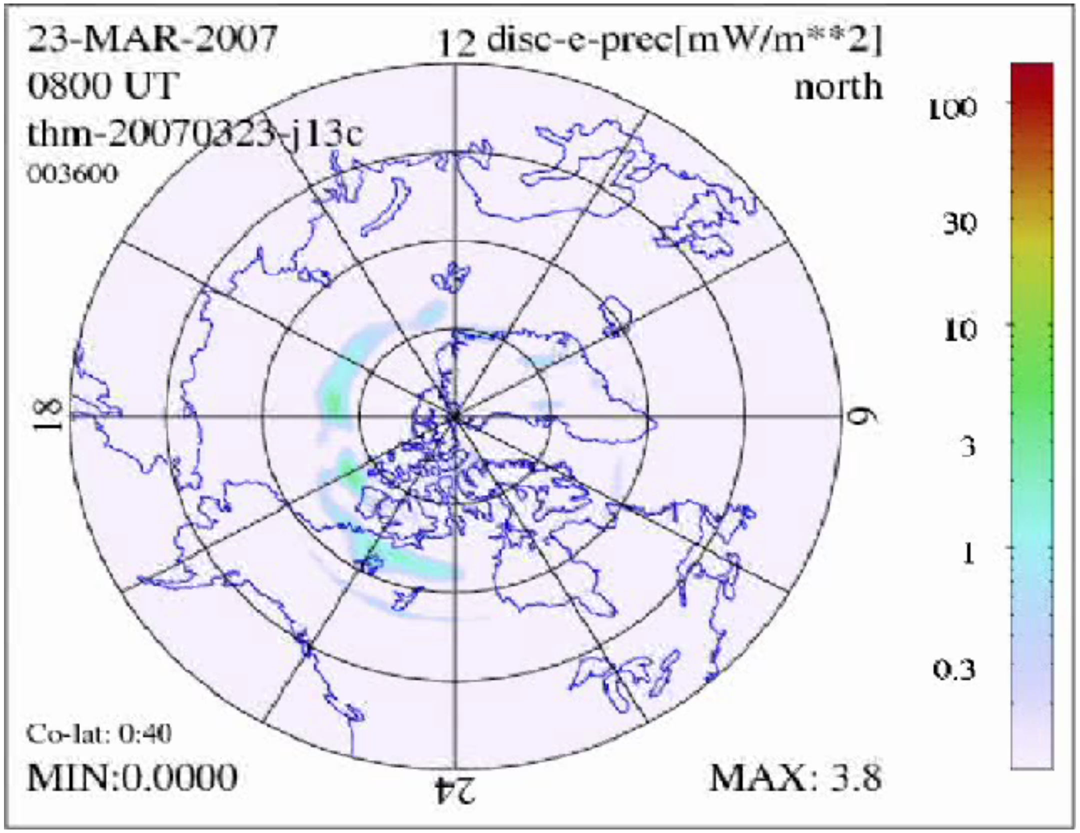




Aurora in the Simulation

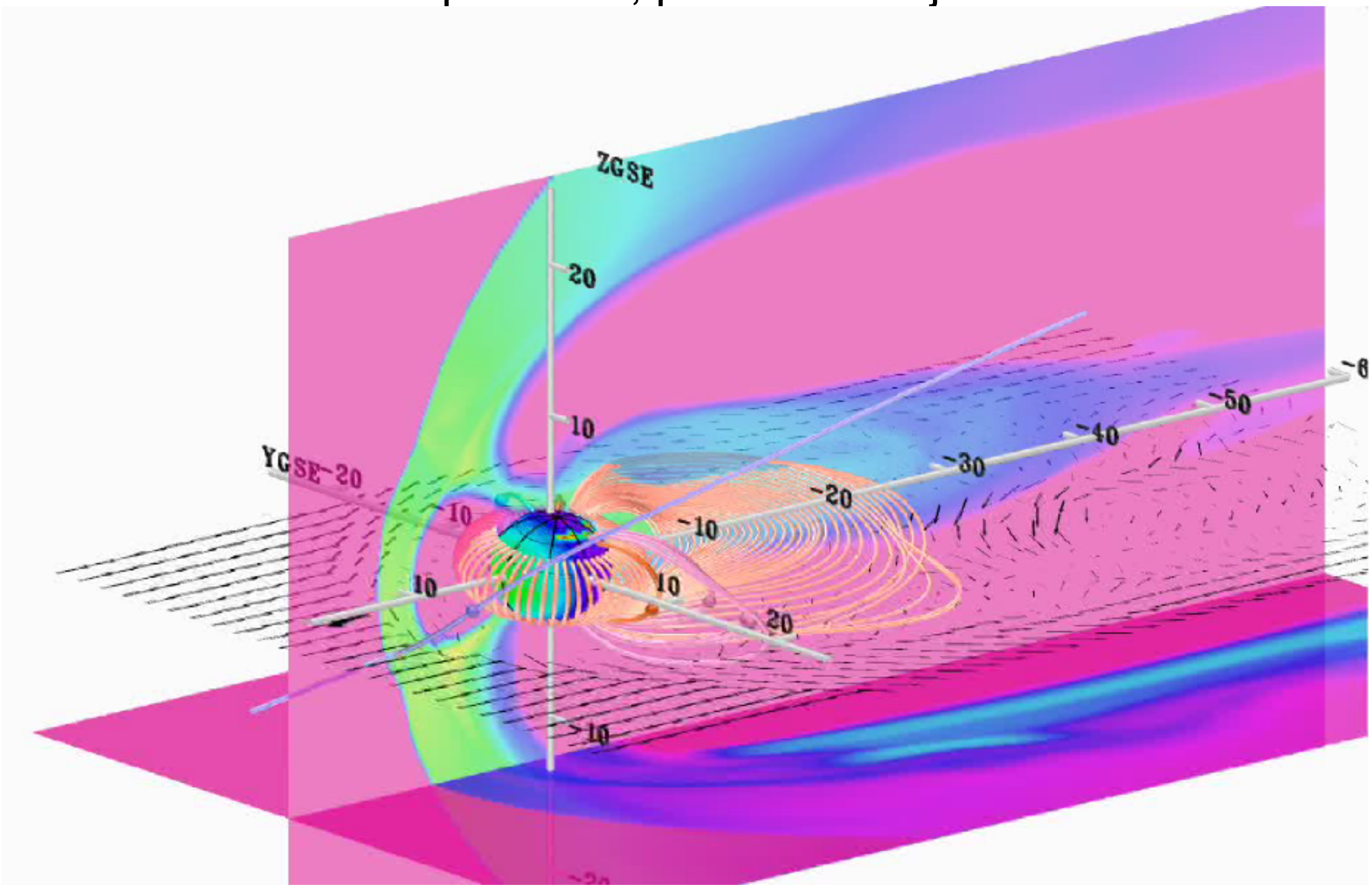
- OpenGGCM discrete e- precipitation energy flux.
- First onset near midnight, just as observed, but a bit too early, ~1045 UT.
- Second onset, ~2100 MLT, 11:20 UT.
- WTS expansion all the way to 1800 MLT, not quite right.

→ Yes, it is a substorm ➔ see movie.



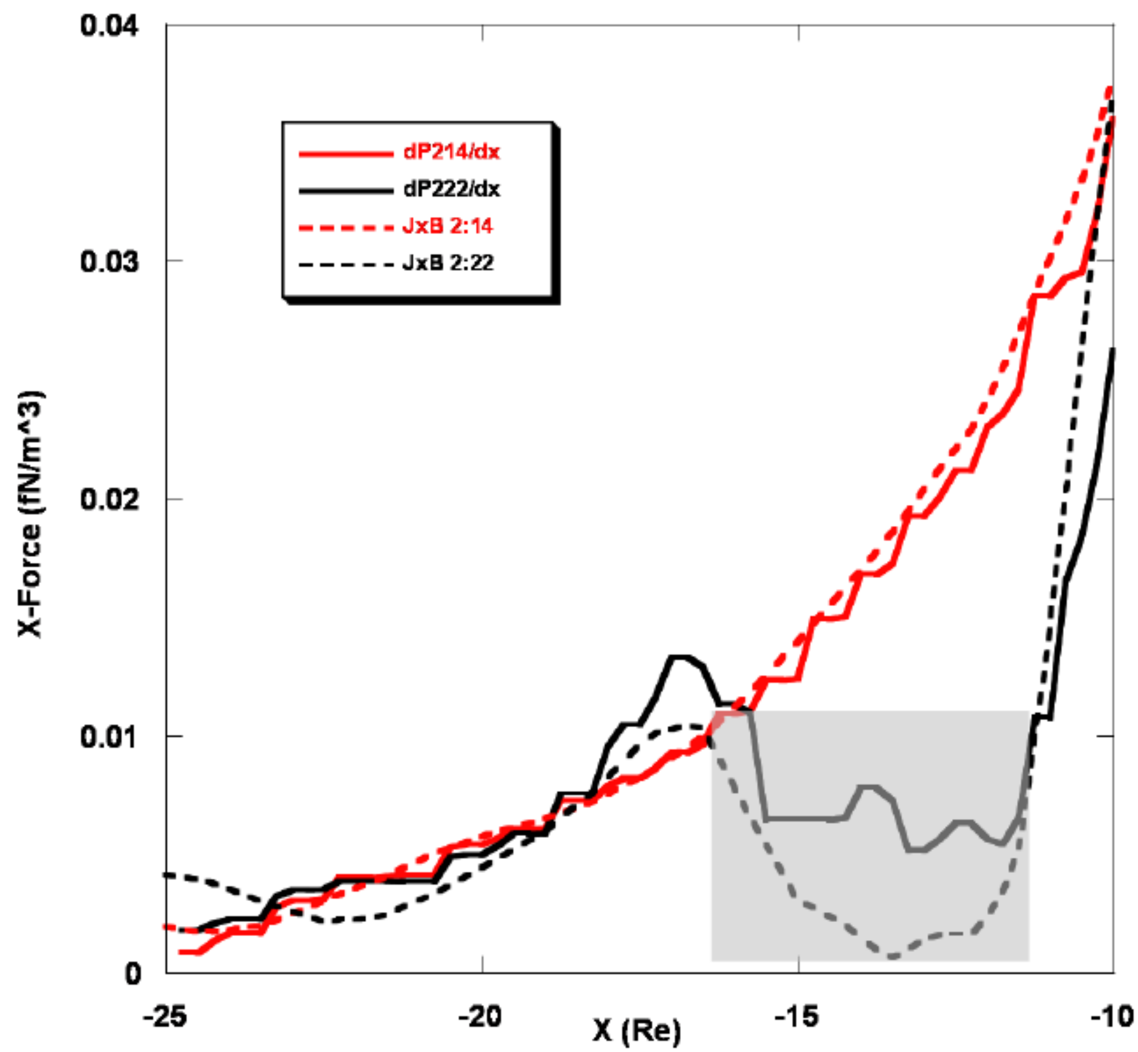
What triggers the substorm?

- Ignoring the red and green surfaces:
- Obviously a new x-line forms ~15RE.
- Near-Earth fields dipolarizes, plasmoid is ejected.



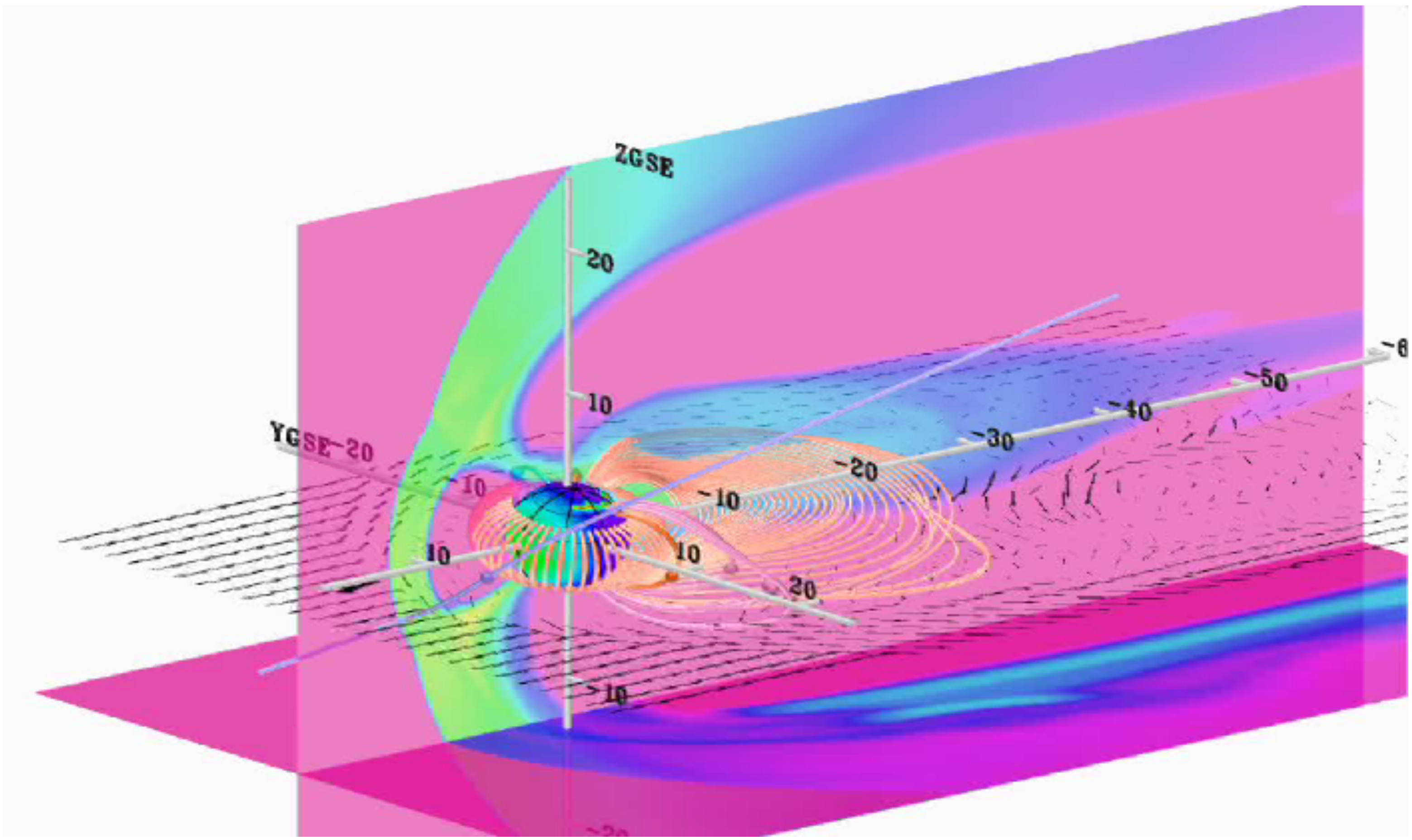
What happens before reconnection?

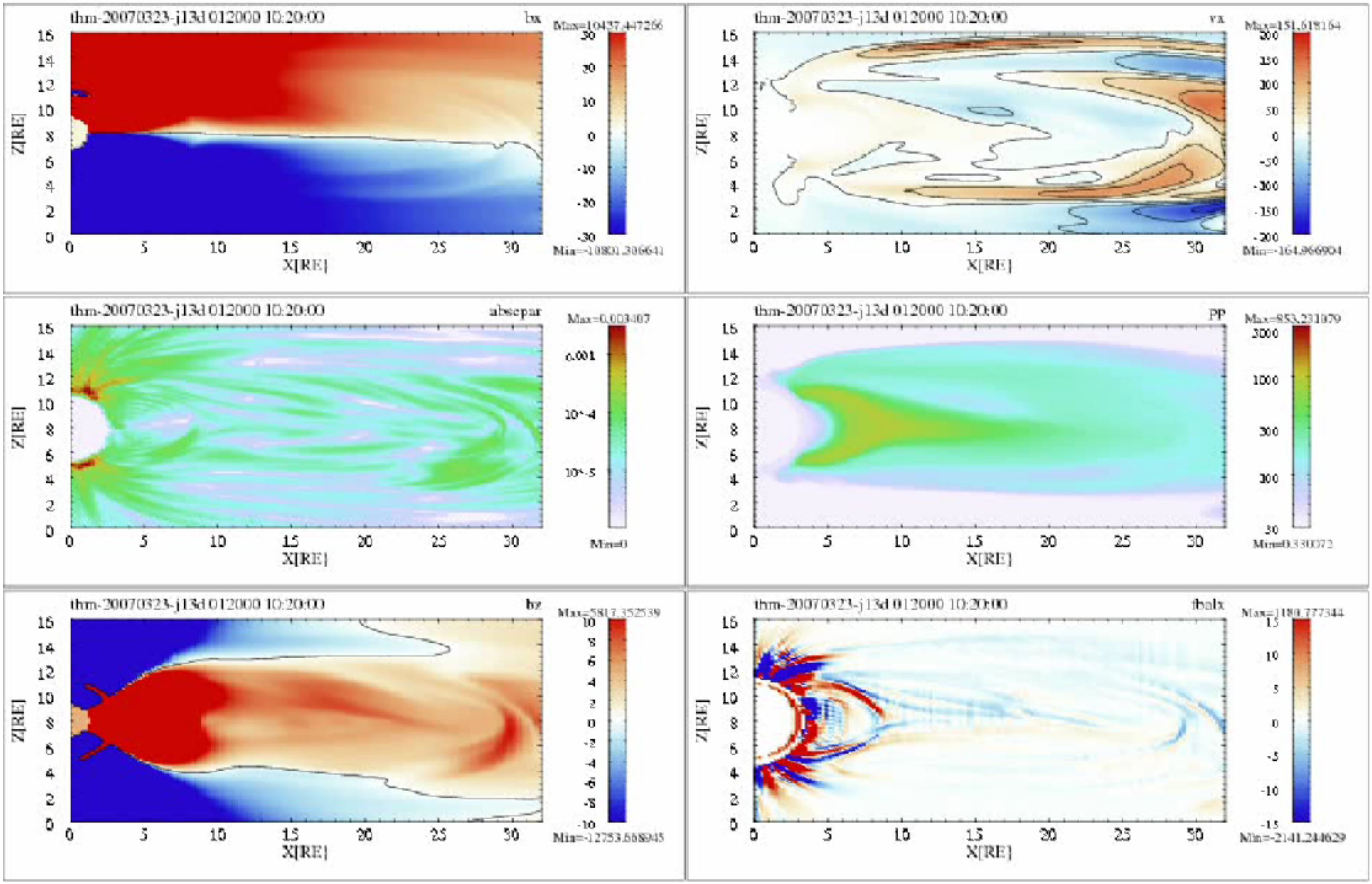
- Different simulation, idealized (no dipole tilt, constant SW/IMF, run at CCMC), symmetric. Recently published, and all credit to: Siscoe, Kusnetzova, and Raeder, Annales Geophysicae, 27, 3142, 2009.
- Red lines: before equilibrium loss: dp/dx (solid) and JxB (dashed) match.
- Black lines: after equilibrium loss: both forces reduced, but JxB more so.



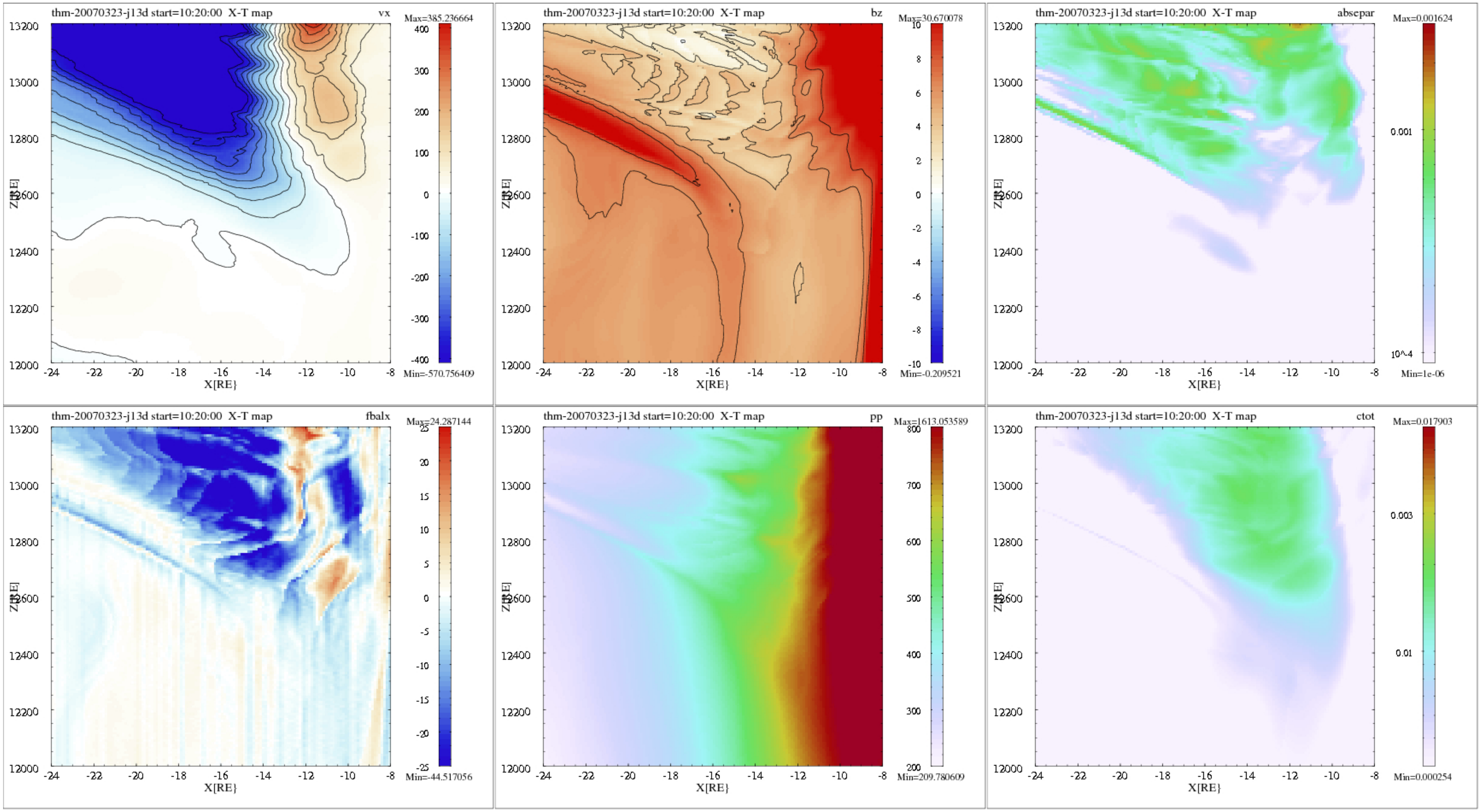
What happens before reconnection?

- Red iso-surface: force imbalance lgrad(p)-JxBl.
- Green iso-surface: parallel E (what is reconnection?).
- → loss of equilibrium before reconnection sets in!
- ➔ see movie.





X-Z cuts in the onset meridian, top row: Bx and Vx, middle row: E_parallel and pressure, bottom row: Bz and net force (grad(p)-JxB)_x, blue is taiward ➔ movie.



Tail Keograms: top row: Vx, Bz, E_par; bottom row: F_bal_x, pressure, lJl. Taken at (x,y=0,z(Bx=0)), i.e., center of current sheet (Raeder et al., JGR, 2010).

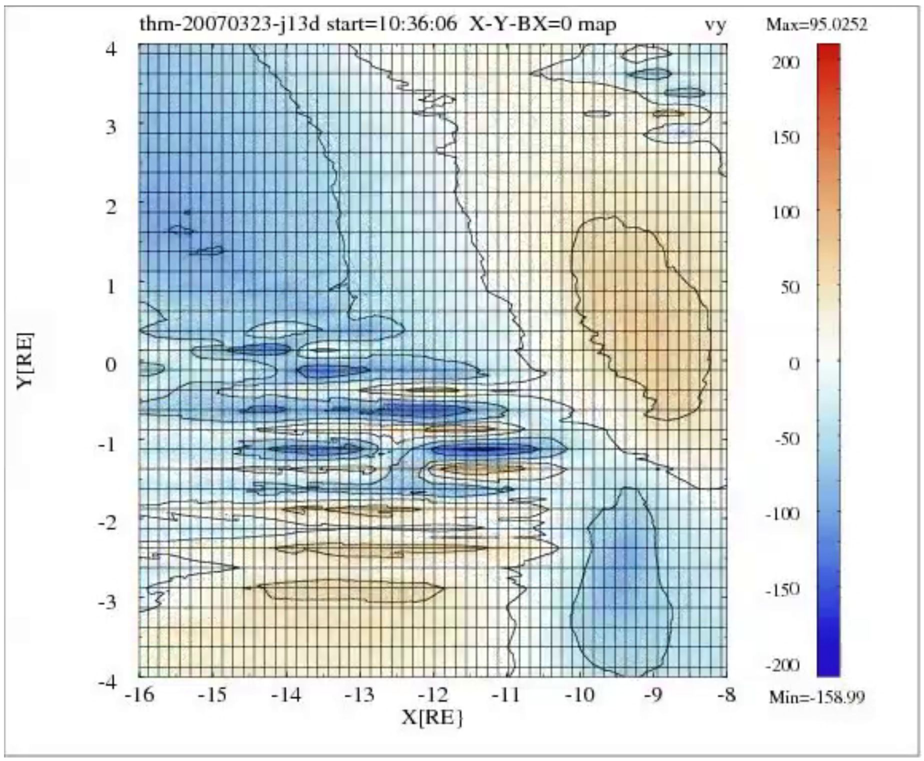
KY0 mode: tailward force imbalance → tailward acceleration and flow divergence → reduction of Bz → tearing. **2 minute** time scale: consistent with **explosive growth phase** (Ohtani) and recent ASI **faint arc growth** observations (Donovan).

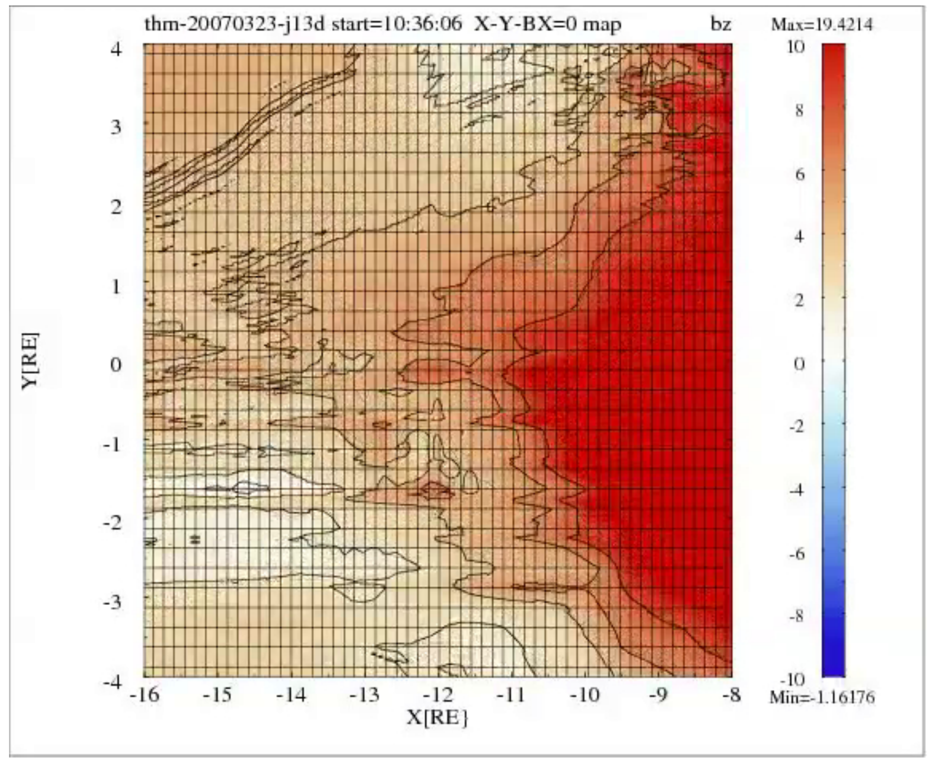
Substorm simulation synopsis

- Growth phase adds flux to the tail and squeezes PS/CS. Distribution of p, J, and Bz changes, but JxB ~ grad(p) remains in equilibrium. Consistent with various analytical equilibrium models (Birn, Schindler) and numerical models (Toffoletto, Zacharia).
- At some point JxB ~ grad(p) equilibrium is no longer possible. Plasma accelerates, but only tailward (that distinguishes it from the tearing mode). CS thins further, and much quicker than during the growth phase.
- After ~2 min significant tailward flow emanating from X~13RE. Bz decreases (explosive growth phase?).
- After ~4 min Bz → 0, signs of tearing mode, earthward acceleration and significant E_par.
- After ~6 min tearing mode fully developed. Strong tailward AND earthward flows.

Wait, there is more:

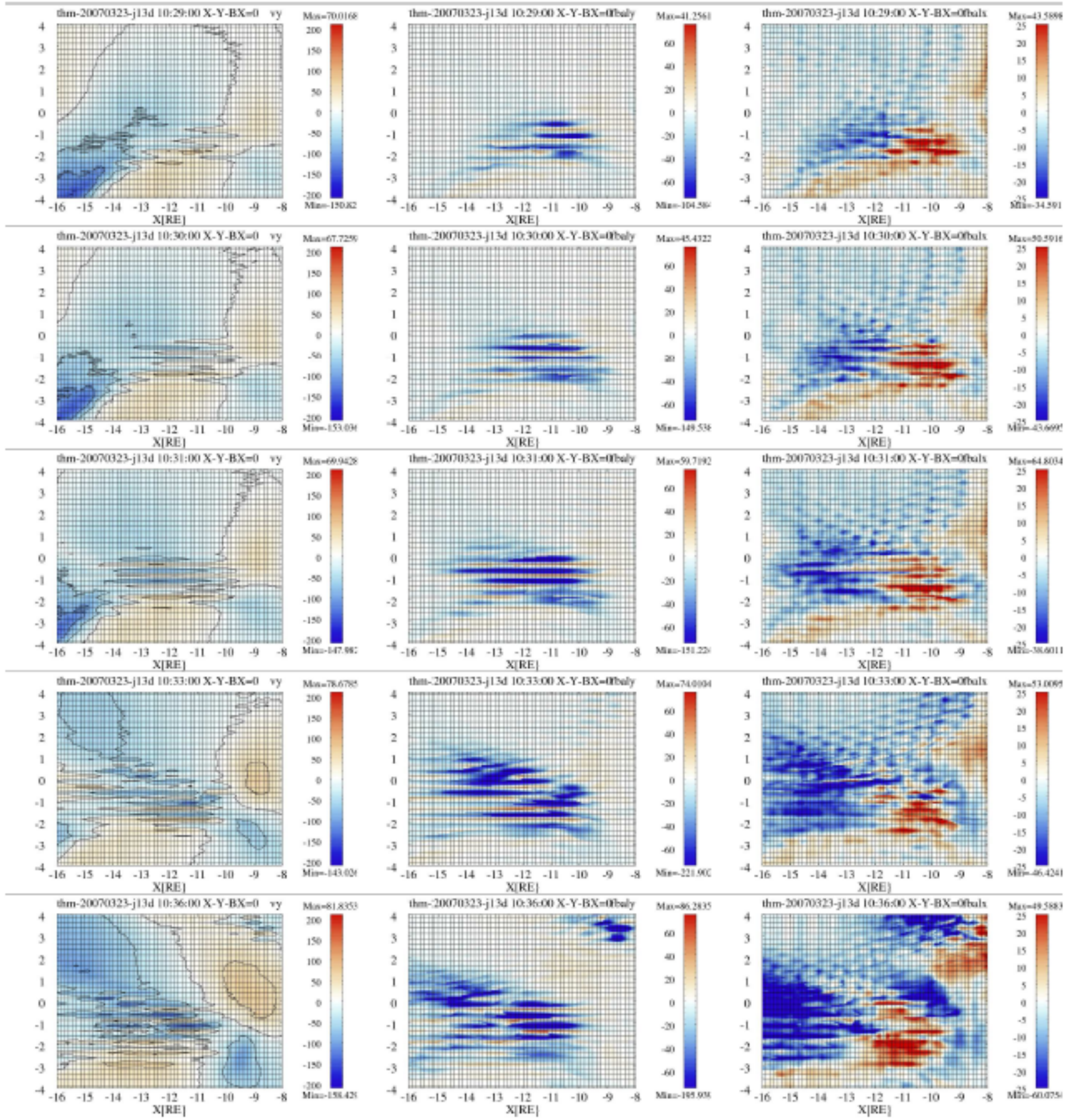
- Careful look at the center of the current sheet, defined by z(Bx=0): Clear finger-like structures in radial direction, but well aligned with numerical grid (➔ see movie): Looks like the ballooning mode, but could be numerical.





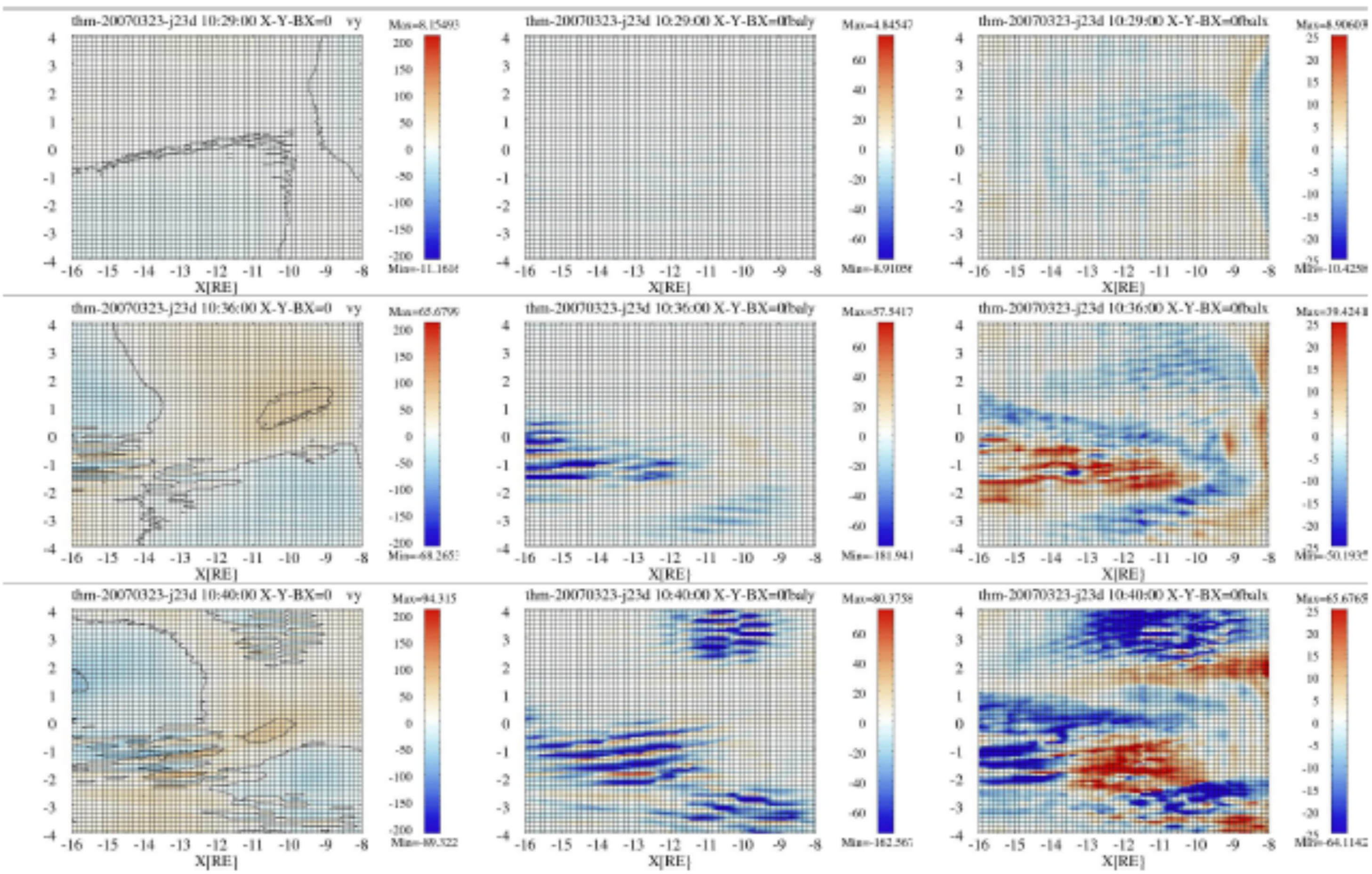
Clear signatures of "classical" ballooning mode:

- Careful look at the center of the current sheet, defined by z(Bx=0):
- Finger-like structures in radial direction, but well aligned with numerical grid. Wavelength ~ 0.5 RE. Not propagating.
- See movie how they develop.



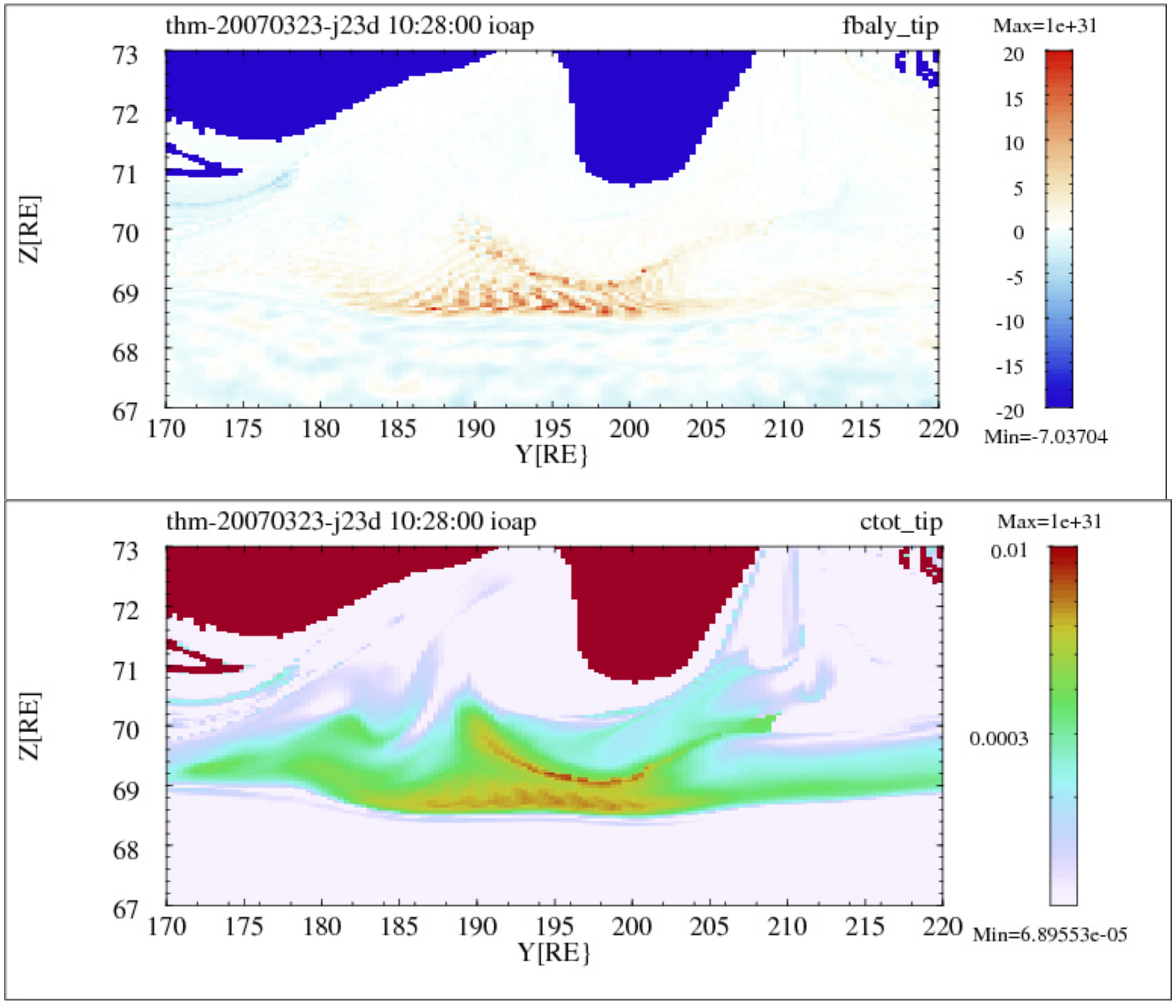
Higher resolution

- Wavelength does not change, not aligned with grid → numerically resolved.
- However, ballooning does not seem to initiate onset, but appears on the edge of the dipolarizing inner magnetosphere during expansion.



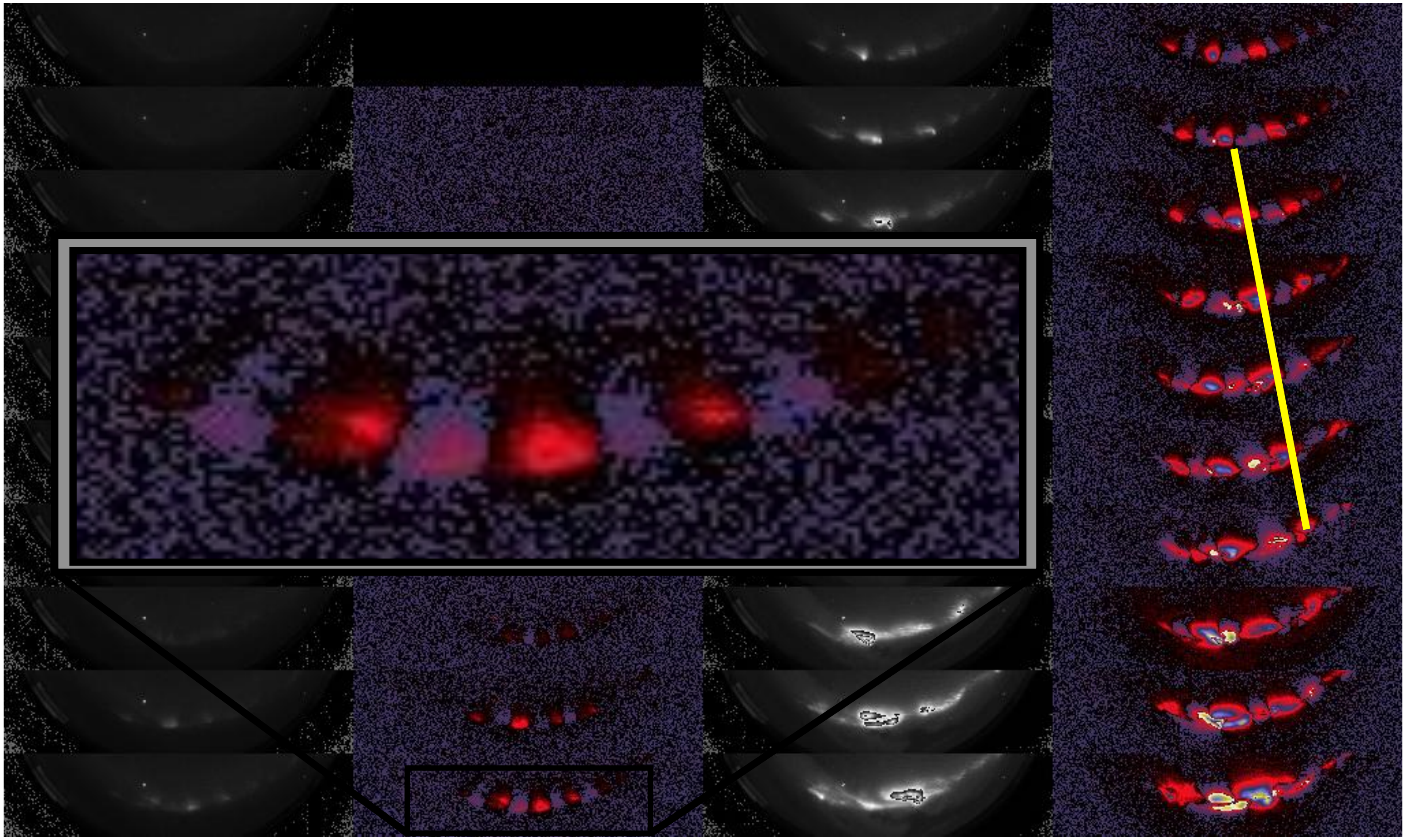
Auroral Signature

- We don't know how the ballooning mode would cause auroral emissions.
- However, it is reasonable to assume that whatever process causes aurora will map along field lines and it will produce the same periodicity.



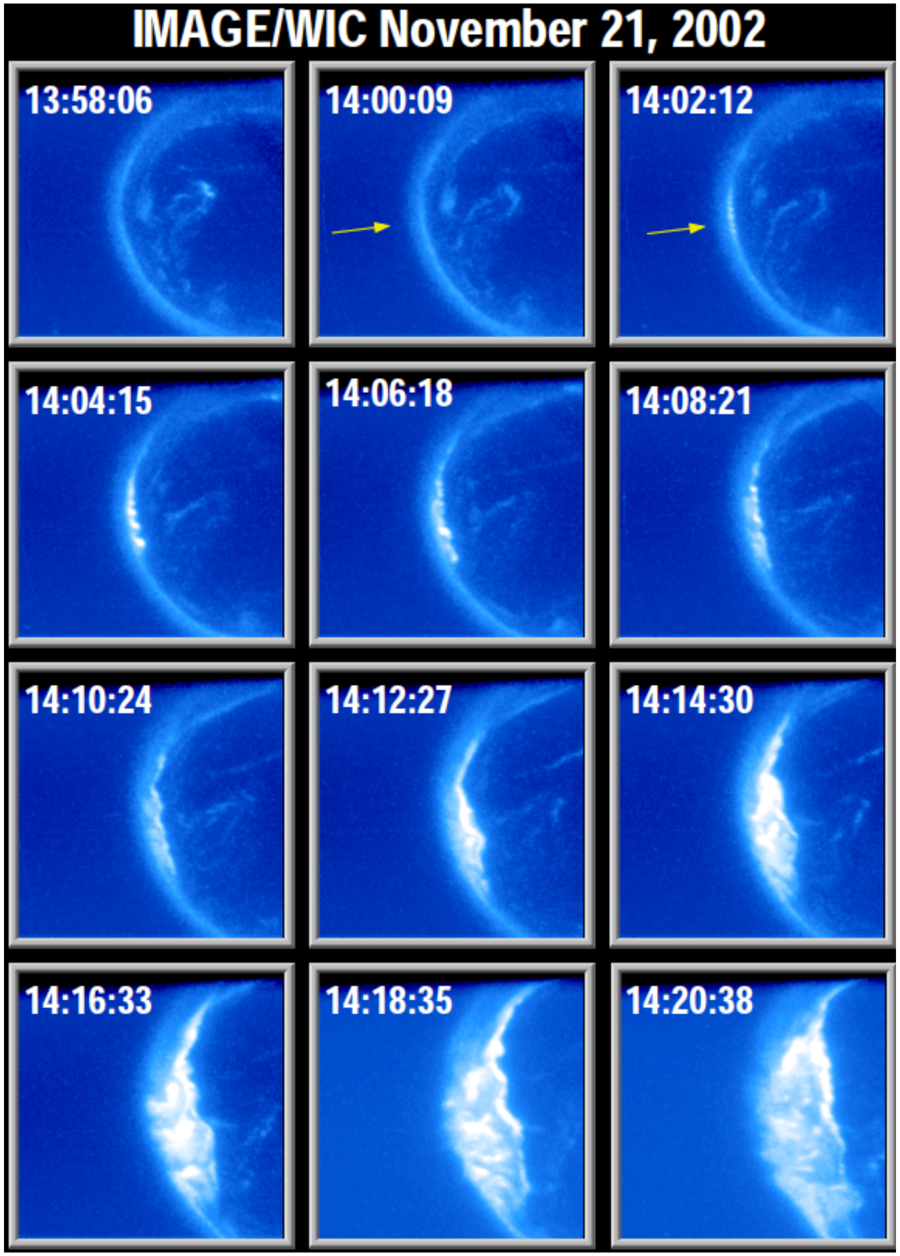
- Top: field line curvature at the tip of the field line. Bottom: Pressure imbalance at the tip of the field line.
- Auroral "beads" separation as expected.
- They are already present during the growth phase.
- The auroral breakup occurs poleward of the ballooning signature.
- Simple calculation gives wavelength in the ionosphere of 360Deg/(2*pi*13RE/Ly) ~ 2.2 Deg.
- Azimuthal wavenumber m ~ 160.
- Beads extend ~0.5 Deg in latitude and seem to fan out from a point 2-4 Deg north. ➔ see movie.

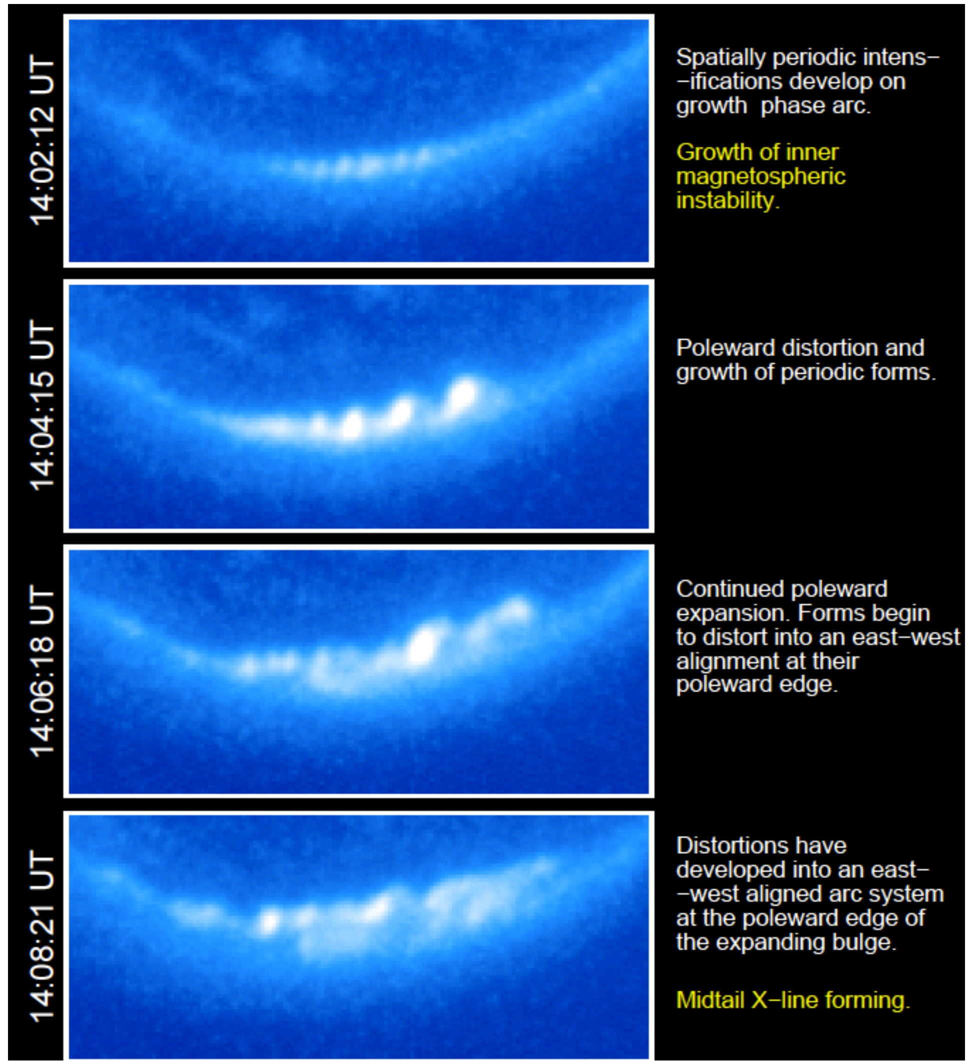
Compare to THEMIS/ASI observations



THEMIS/ASI observations courtesy of Eric Donovan and Jun Liang: Beads with wavenumber m=100-300, Ly=1.2-3.6Deg. There is even a hint of the fan-like structure. Consistent with simulation.

And older observations:





Henderson et al., AG, 27, 2129,2009. Note here: beads occur long before (~ 10 min) substorm breakup.

New substorm scenario, but also a new can of worms

- Growth phase adds flux to the tail and squeezes PS/CS → distribution of p, J, and Bz changes slowly, but JxB ~ grad(p) remains in equilibrium → At some point JxB ~ grad(p) equilibrium is no longer possible → plasma accelerates, but only tailward (that distinguishes it from the tearing mode) → CS thins further, and much quicker than during the growth phase → ~2 min later significant tailward flow emanating from X~13RE → Bz decreases (KY0 mode, explosive growth phase?) → ~4 min later: Bz → 0, signs of tearing mode (earthward acceleration and significant E_par) → ~6 min later tearing mode fully developed (strong tailward AND earthward flows) → expansion phase.
- Nature of KY0 mode not entirely clear, could be field line slippage / entropy antidiffusion.
- "classical" ballooning mode appears, but seems to be unrelated to expansion phase onset.
- But maybe the ballooning mode helps the tail become unstable?
- What determines the ky of ballooning? This is all MHD, but matches observations!
- Why do Cluster/THEMIS not observe ballooning more often?
- Do all substorms develop this way?