Convection and Substorms

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Magnetosphere Seminar Online Series
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Overview

So much cool stuff, so little time…

- "Your talk will be the beginning of the series transitioning to the night side so an overview of convection and substorms would be great."

- There's a lot more material on convection…and a lot more material on substorms…I tried to look at each through the lens of the other

- Goal: To make convection and substorm concepts accessible to graduate student audience, but use some recent studies as example to update and promote discussion amongst all career levels.

- Introductory material: Definitions and Broad Overview
  - *Dungey Cycle*
  - *Particle motion lite*
- Convection on large scales
- Convection on mesoscales
- Convection and Substorms

Convection: The Dungey Cycle

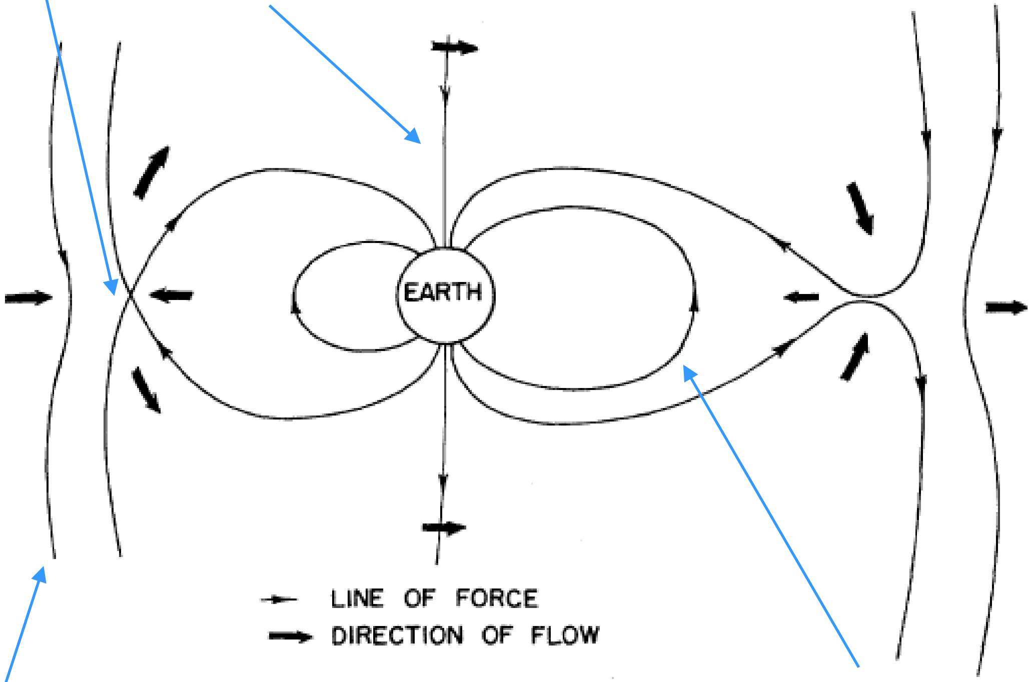
Magnetic Flux Transport: In a steady state, all rates must be equal

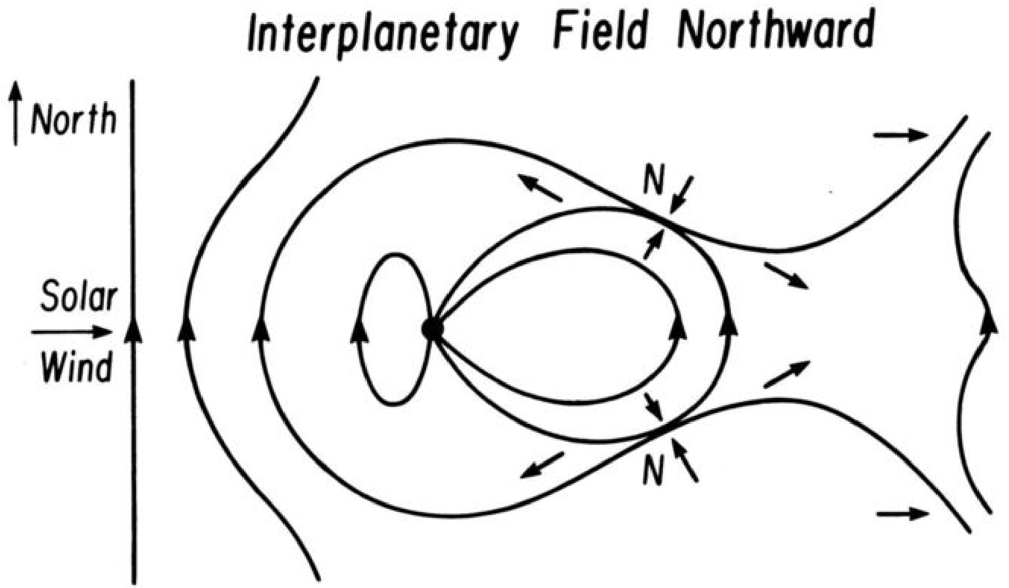
Dungey, PRL, (1961): <2 pages, 1914-4032 citations and growing

$$Magnetic\ flux = \Phi = BA\cos(\Theta)$$

Dayside reconnection

Open magnetic field lines: Earth magnetic field lines connected to IMF.





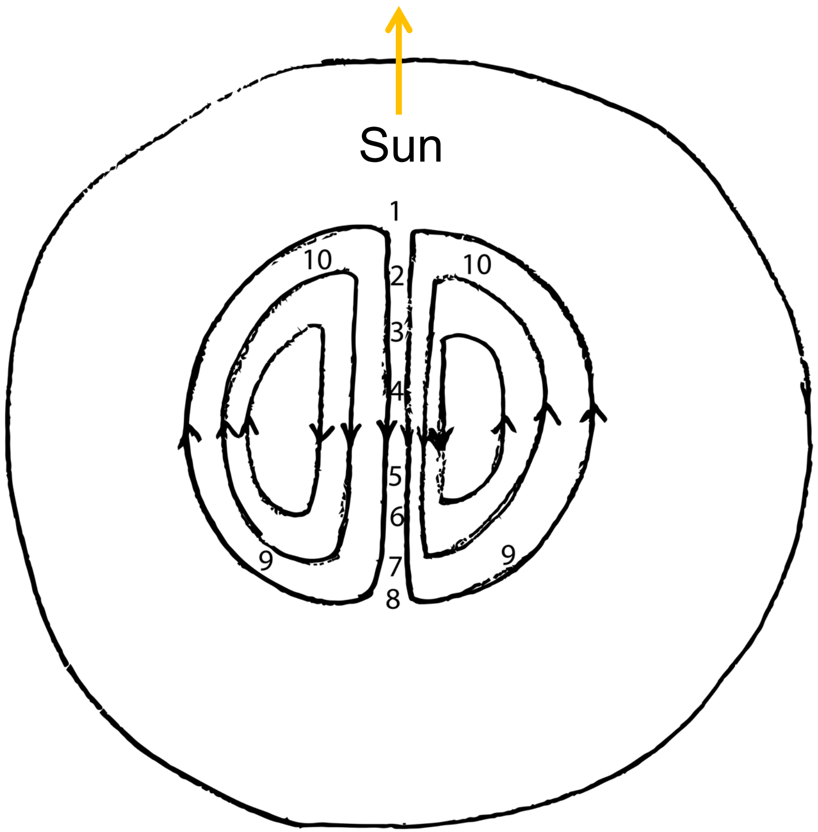
Credit: Dungey (1963?)

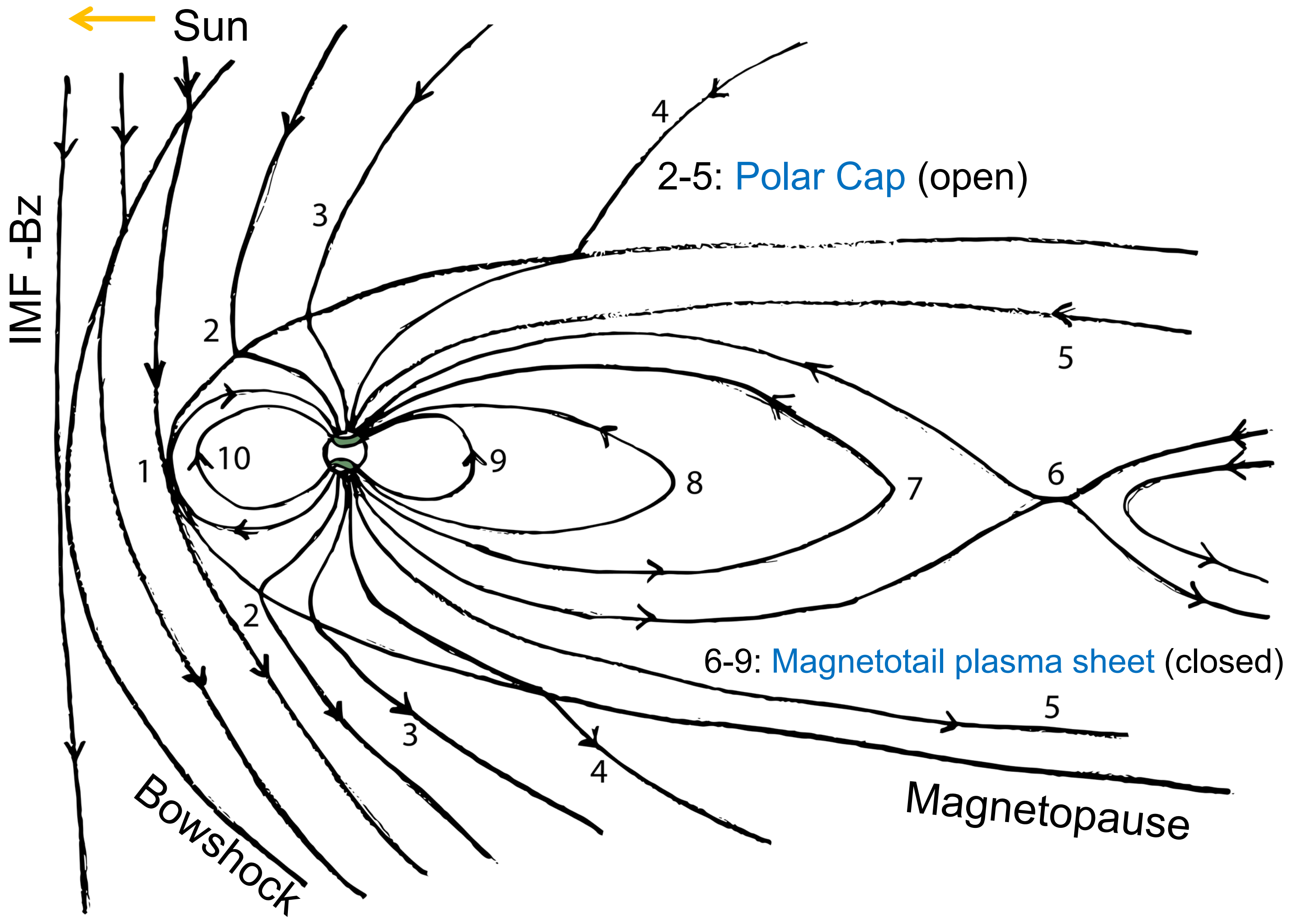
Interplanetary Magnetic Field (IMF): Sun's magnetic field embedded in the solar wind. (Southward)

Closed magnetic field lines: Earth magnetic field lines connected to only Earth.

Large-Scale Convection: Ionosphere

Polar Cap: Region poleward of aurora oval. Connected to open field lines (Earth magnetic field lines connected to IMF).



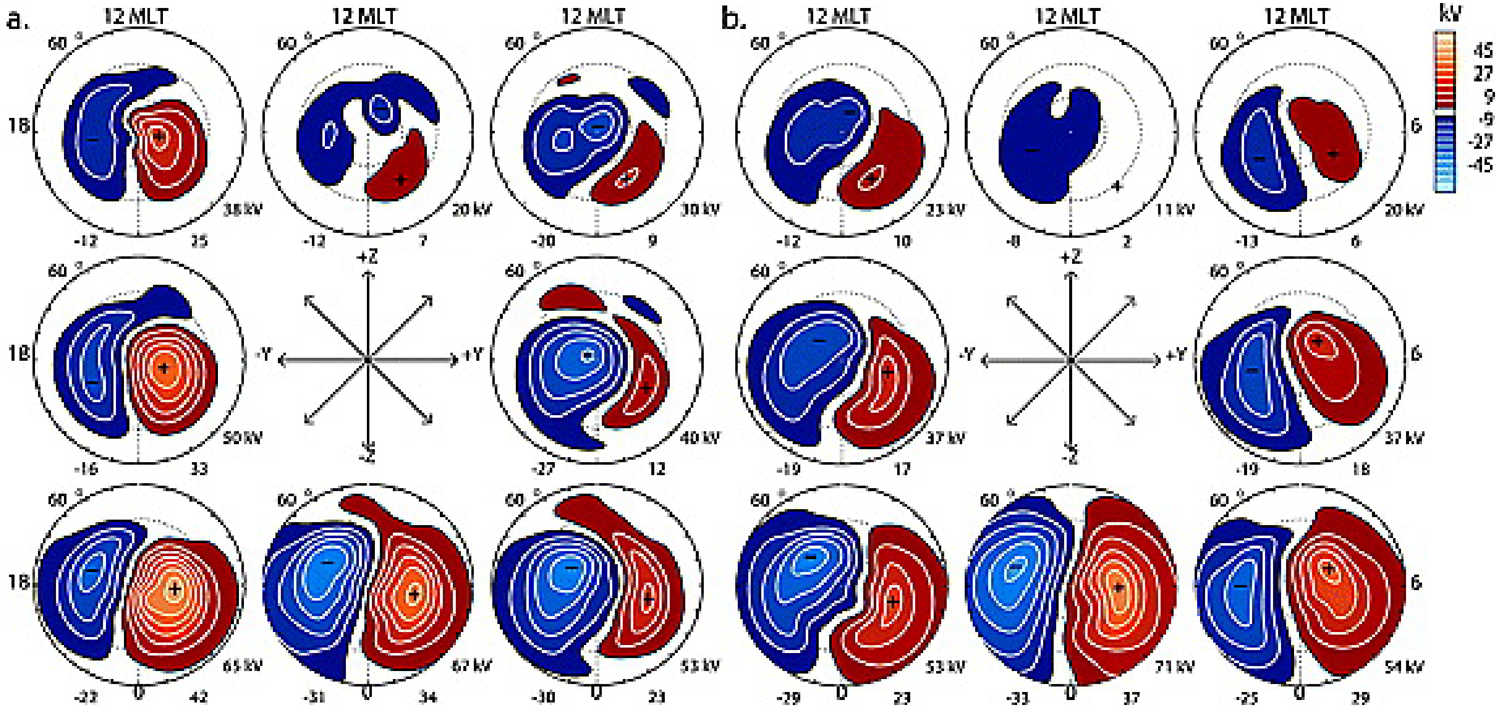


(Not to scale)

See also Figure 9.11 in Kivelson & Russell

Large-Scale Convection: Ionosphere

Contours=Equipotentials=Contours of Motion



Cousins and Shepherd (JGR AGU, 2015)
Data source: SuperDARN HF radar

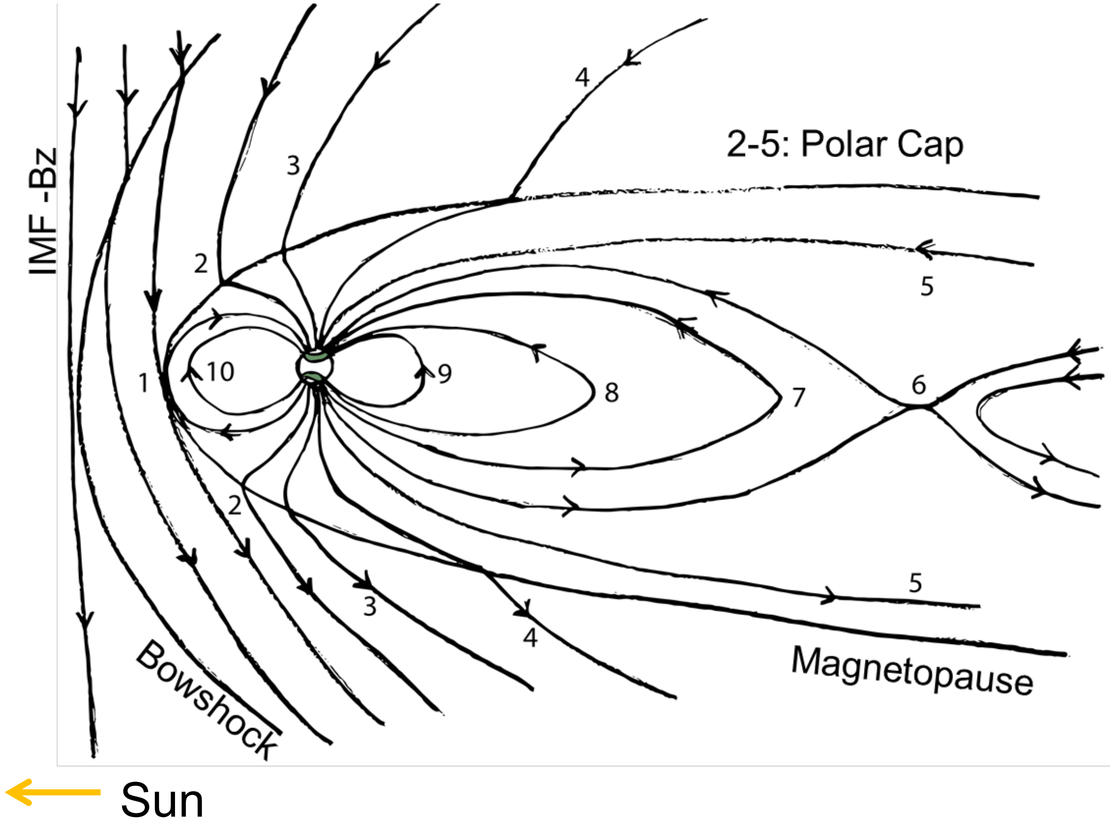
New DRIVE Center, CUSIA: Interhemispheric Asymmetries

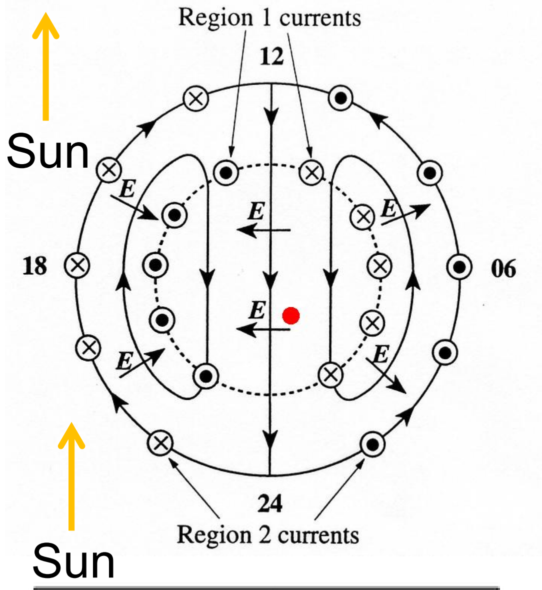
Convection Pattern
Function of:
- IMF clock angle
- Hemisphere
- Solar wind velocity
- Most common: 2-cell
- 3-cell and 4-cell possible for +Bz

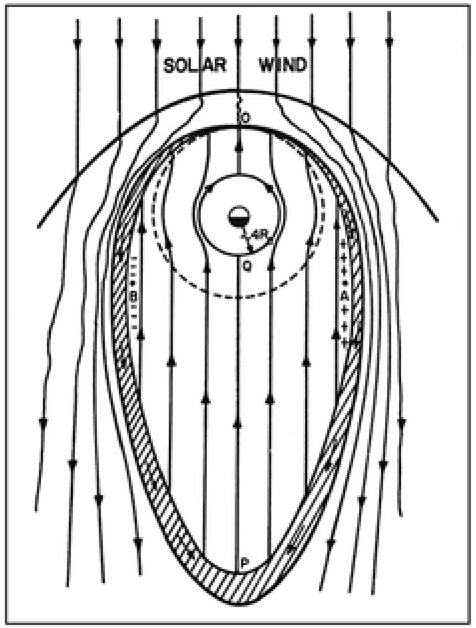
Read More!
- Heppner (1977) using Ogo 6
- Heppner and Maynard (1987) using Dynamics Explorer 2
- Rich and Hairston (1994) using DMSP
- Weimer (1995) using DE satellite data
- Ruohoniemi and Greenwald (1996) using ground-based HF radar data
- Papitashvili and Rich (2002) using DMSP
- Ruohoniemi and Greenwald (2005) and Cousins and Shepherd (2015) using SuperDARN HF radar data
- Haaland et al. (2007) using Cluster data

Large-Scale Convection: Magnetosphere-Ionosphere Coupling

Cowley (AGU Geophys. Monogr. Series, 2000)







$$E = \frac{\phi}{D} \qquad \boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$$

$$E_{PC} = \frac{\phi}{2R_{PC}}$$

$R_{PC} \approx 0.2\, R_E$

$V_{PC} \approx 330\, m/s$

$B_{PC} \approx 62000nT$

$\phi \approx$ 52 kV

Note: 330 m/s is high, background flow closer to ~100 m/s

$E_{Tail} = ?$

$$E_{Tail} = \frac{\phi}{2R_{tail}}$$

$R_{tail} \approx 20\, R_E$

$E_{Tail} \approx 0.2\, mV/m$

See Ramon Lopez's talk in this series about currents

9.4.2 in Kivelson & Russell

Convection: Particle Motion

Particle trajectories, magnetic and electric fields

Contours of motion can be drawn from these relationships.

<u>Guiding-center motion</u>

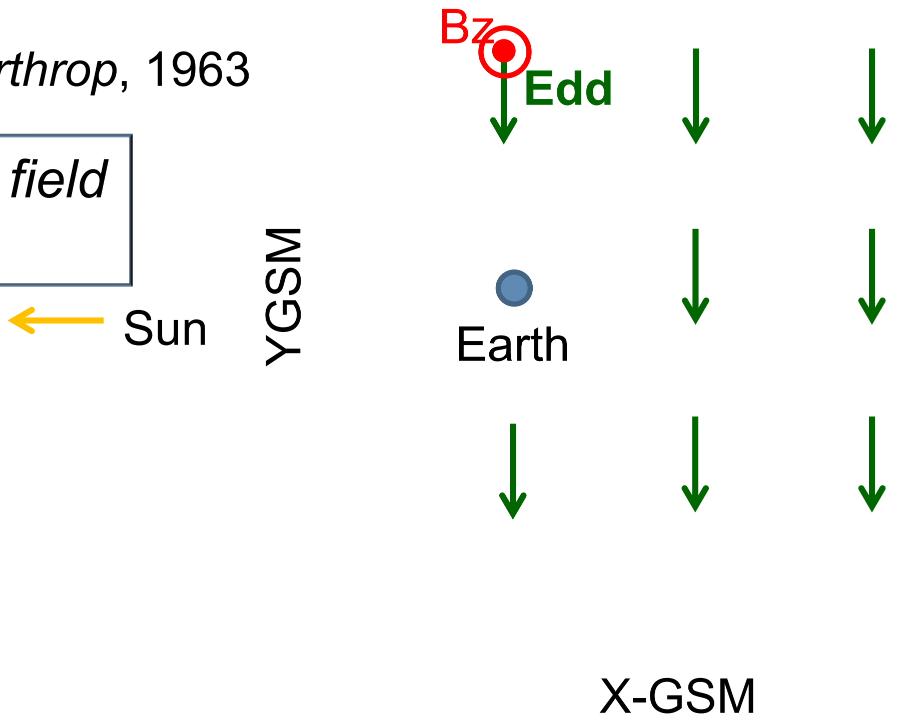
$$\mathbf{V}_{\mathrm{GC}} = \frac{\mathbf{dr}}{\mathbf{dt}} = \mathbf{V}_{\mathbf{E}\times\mathbf{B}}$$

--*Northrop*, 1963

Draw convection E vectors

Edd: *dawn-dusk electric field aka "convection Efield"*

$$\vec{v}_E = \frac{\vec{E}\times\vec{B}}{B^2}$$



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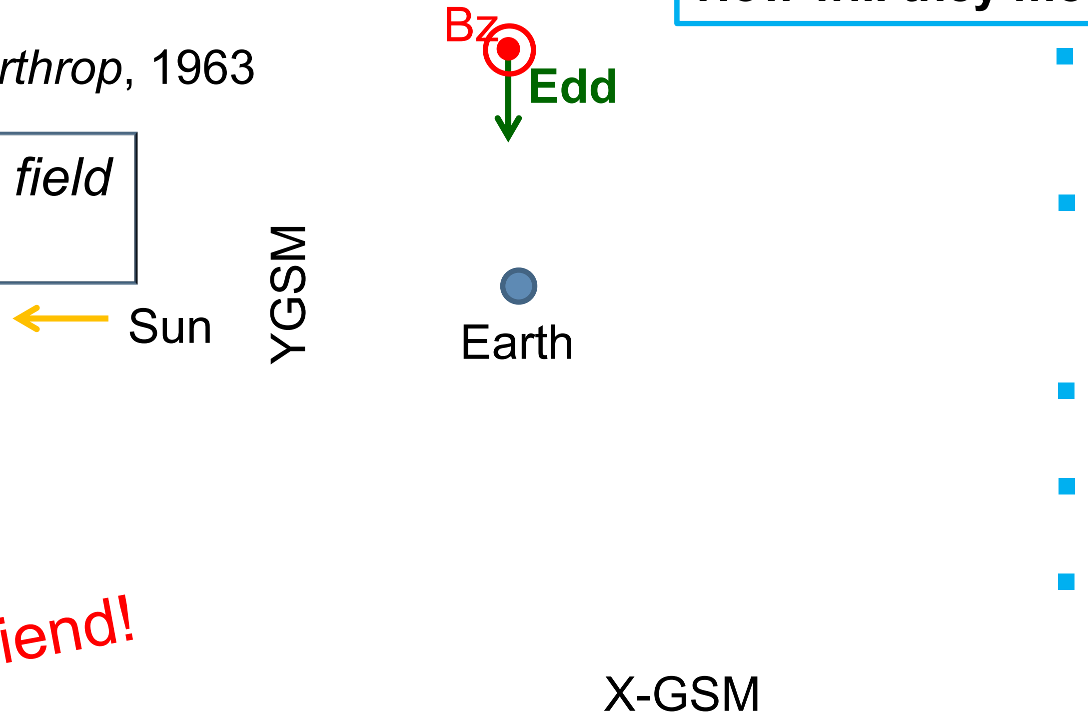
$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2}$$

Right-hand Rule is your friend!

Launch particles from several points downtail. How will they move?



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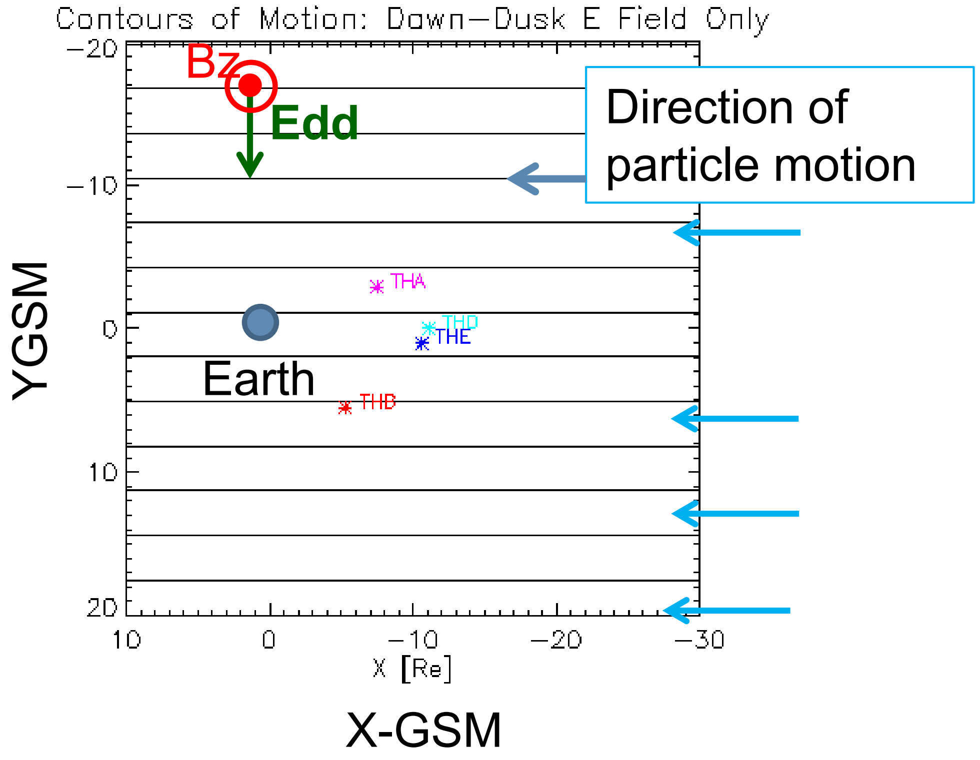
Edd: *dawn-dusk electric field aka "convection Efield"*

Sun

$$\vec{v}_E = \frac{\vec{E}\times\vec{B}}{B^2}$$

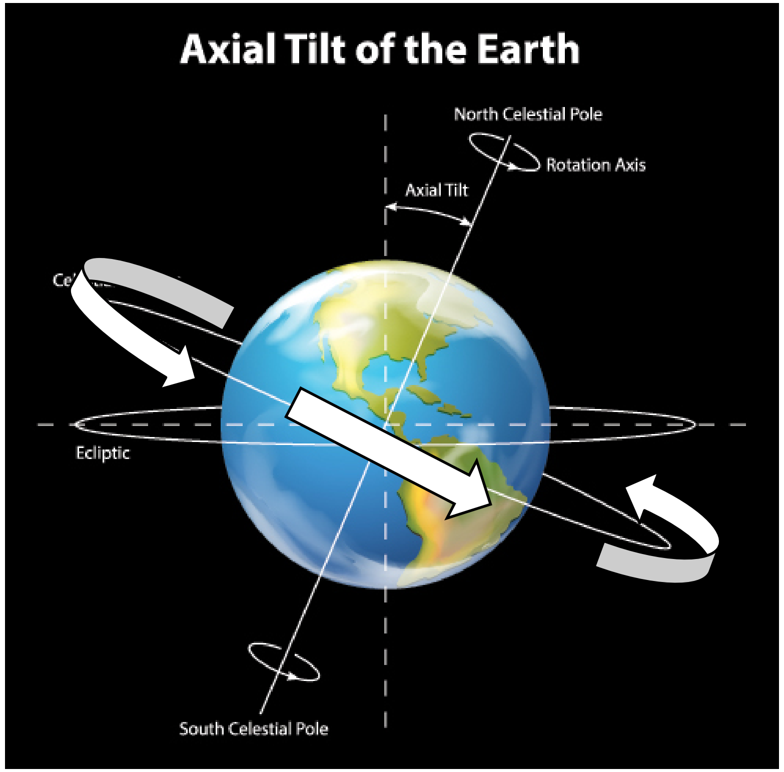


Convection: Particle Motion

Particle trajectories, magnetic and electric fields

What affect might the rotation of the Earth have on our particle trajectories in space?

1. Consider the stationary reference frame outside of the Earth.
2. Consider ionospheric plasma is only partially ionized, and neutral collision frequency is high.



Credit: BlueRingMedia/Shutterstock.com

How do we calculate the co-rotation electric field?

$$\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$$

What is **V**?

$$\boldsymbol{V} = \varpi_{E} \times \mathbf{r}$$

$$\boldsymbol{V} = \frac{2\pi}{24\,h}\, \mathrm{r}\, \boldsymbol{e}_{\boldsymbol{\phi}}$$

What does the co-rotation electric field profile look like on the equatorial plane?

See ch. 5 in Baumjohann &Treumann, 10.5.7 in Kivelson & Russell

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Guiding-center motion

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Draw corotation E vectors

Ecor: *Corotation electric field*

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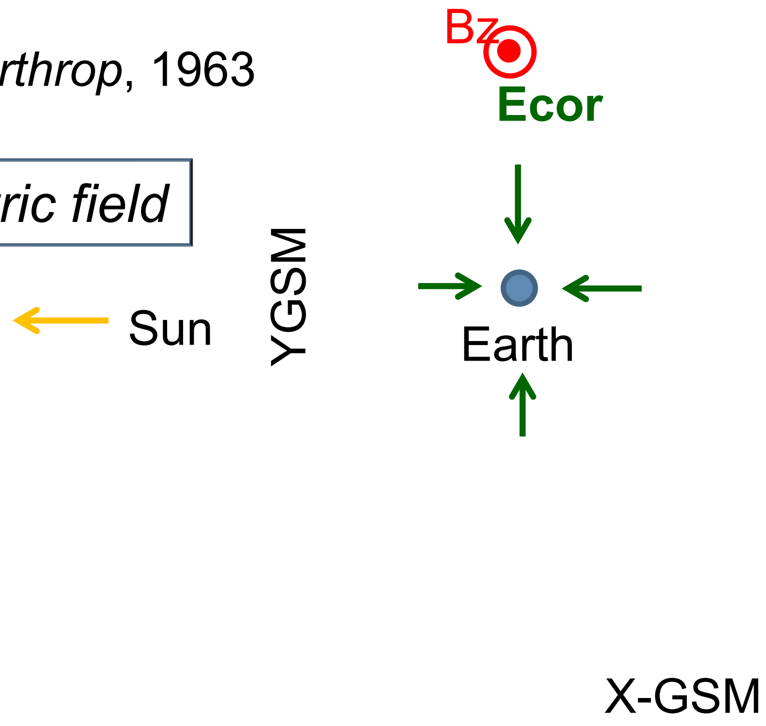

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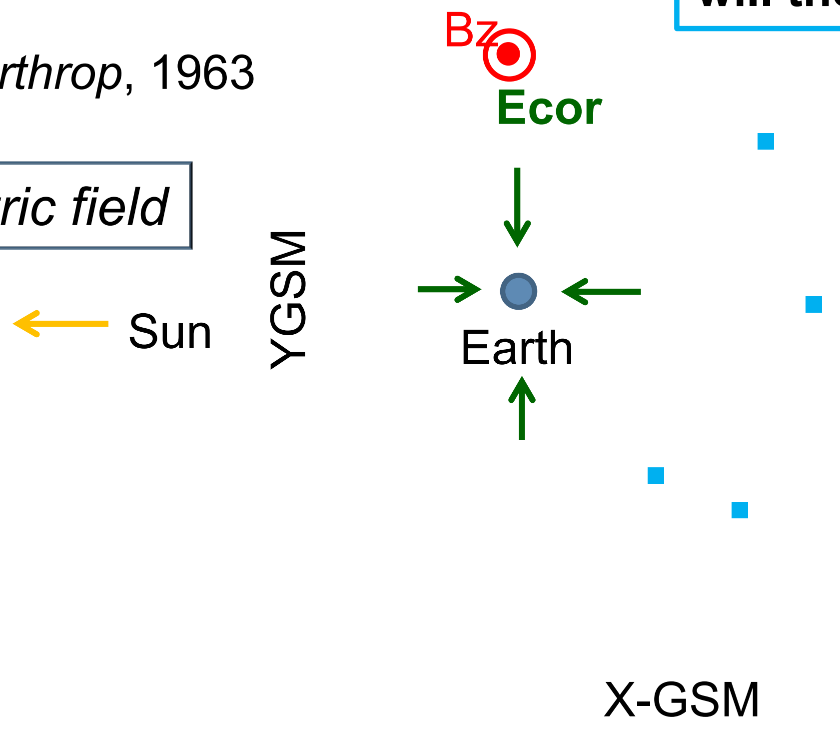
Launch e- from several points. How will the e- move?



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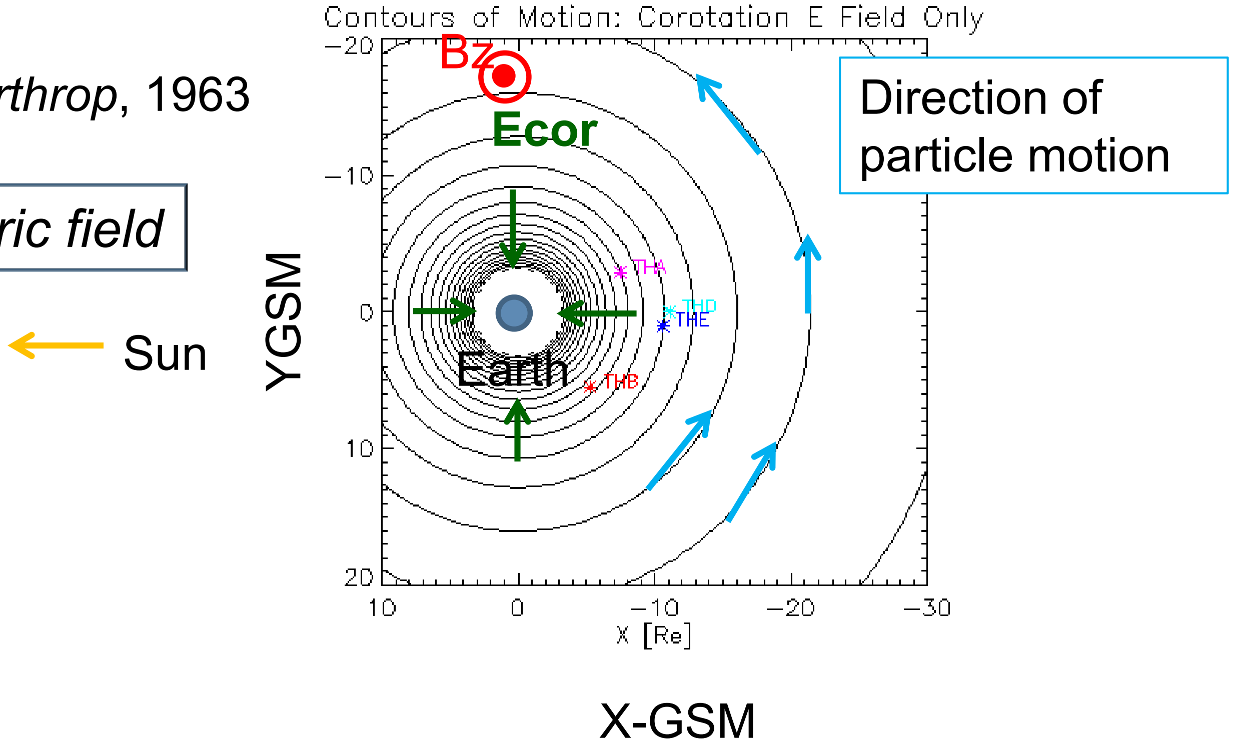

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$$\mathbf{V}_{\mathrm{GC}} = \frac{\mathbf{dr}}{\mathbf{dt}} = \mathbf{V}_{\mathbf{E}\times\mathbf{B}} + \mathbf{V}_{\nabla\mathbf{B}}$$

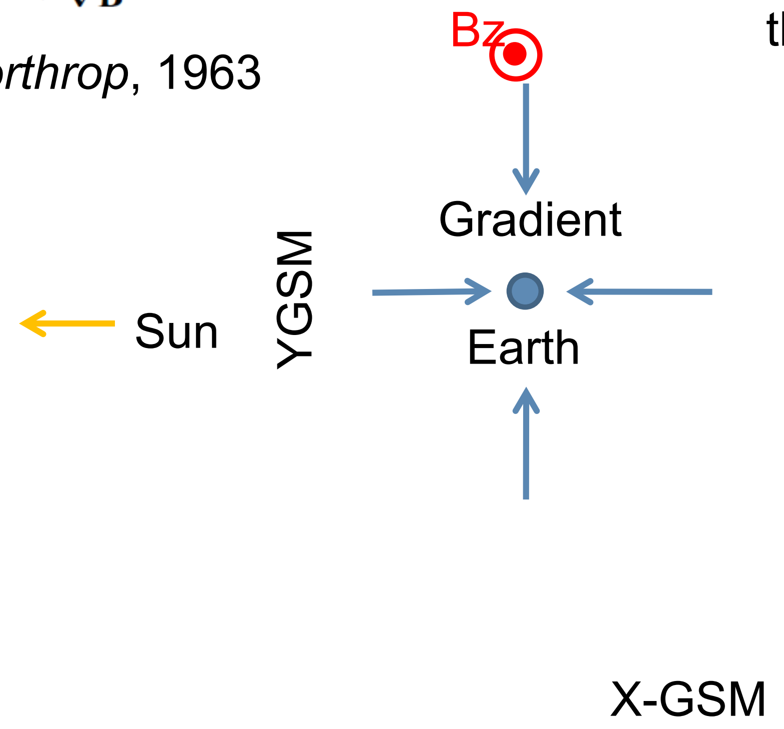
--*Northrop*, 1963

What direction is the gradient?

(The gradient “points” in the direction of increase.)

Grad-B Drift

$$\mathbf{v}_{drift} = \frac{m v_{\perp}^{2}}{2qB}\frac{(-\nabla_{\perp} B)\times \mathbf{B}}{B^{2}}$$



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Convection: Particle Motion

Particle trajectories, magnetic and electric fields

Contours of motion can be drawn from these relationships.

Launch energetic e-. How will they move?

<u>Guiding-center motion</u>

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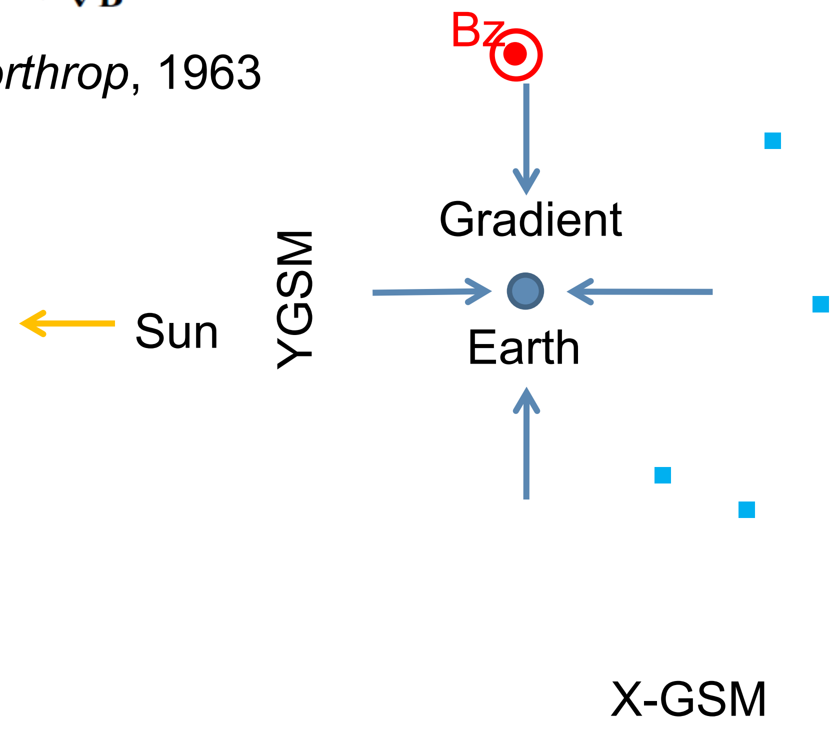

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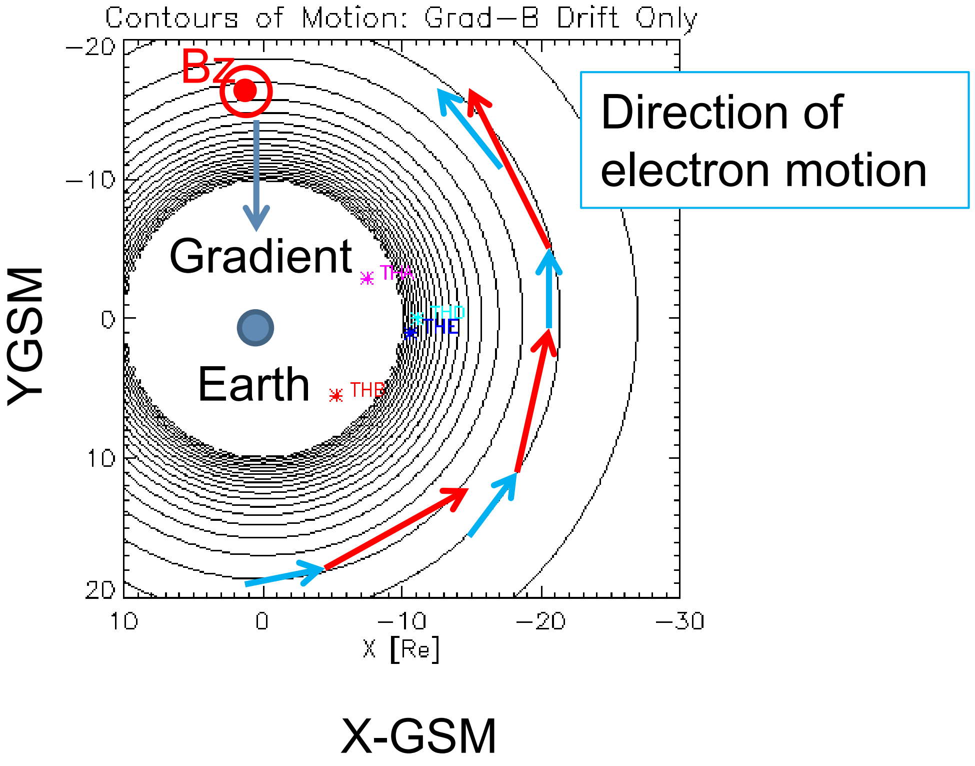
Grad-B Drift

$$\mathbf{v}_{drift} = \frac{mv_{\perp}^{2}}{2qB}\frac{(-\nabla_{\perp}B)\times\mathbf{B}}{B^{2}}$$

Sun

Energy-dependent:
Energetic e- drift faster



Convection: Particle Motion

Particle trajectories, magnetic and electric fields

Contours of motion can be drawn from these relationships.

Launch energetic i+. How will they move?

Guiding-center motion

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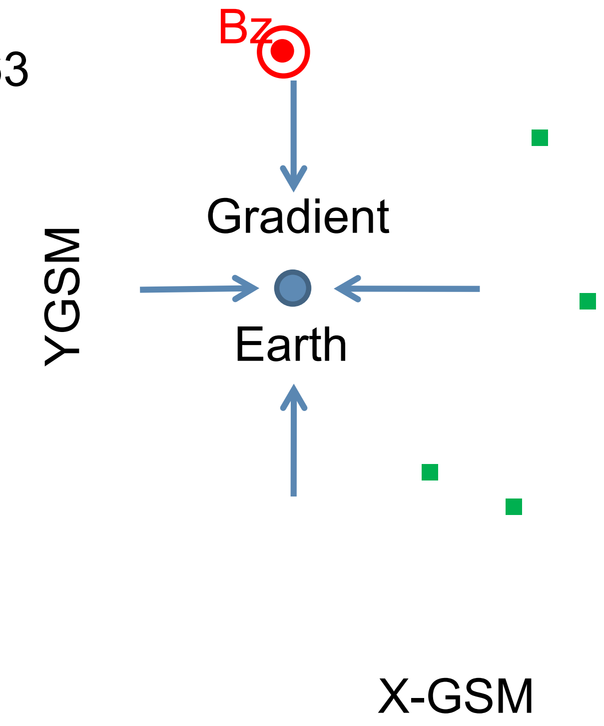
Grad-B Drift

$$\mathbf{v}_{drift} = \frac{mv_{\perp}^{2}}{2qB}\frac{(-\nabla_{\perp}B)\times\mathbf{B}}{B^{2}}$$

Sun



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--*Northrop*, 1963

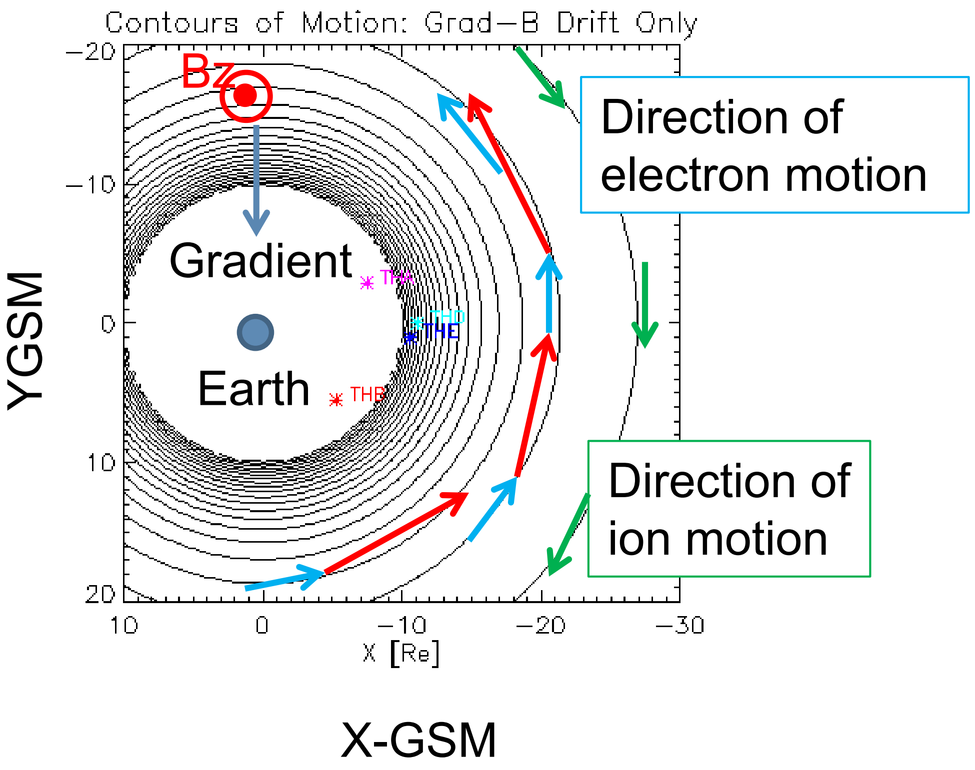
Grad-B Drift

$$\mathbf{v}_{drift} = \frac{mv_\perp^2}{2qB}\frac{(-\nabla_\perp B)\times\mathbf{B}}{B^2}$$

Sun

Energy-dependent:
Energetic e- drift faster

Energetic i+ drift opposite direction (clockwise)



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$$\mathbf{V}_{\mathrm{GC}} = \frac{\mathbf{dr}}{\mathbf{dt}} = \mathbf{V}_{\mathbf{E}\times\mathbf{B}} + \mathbf{V}_{\nabla\mathbf{B}} + \mathbf{V}_{\mathbf{R}}$$

--*Northrop*, 1963

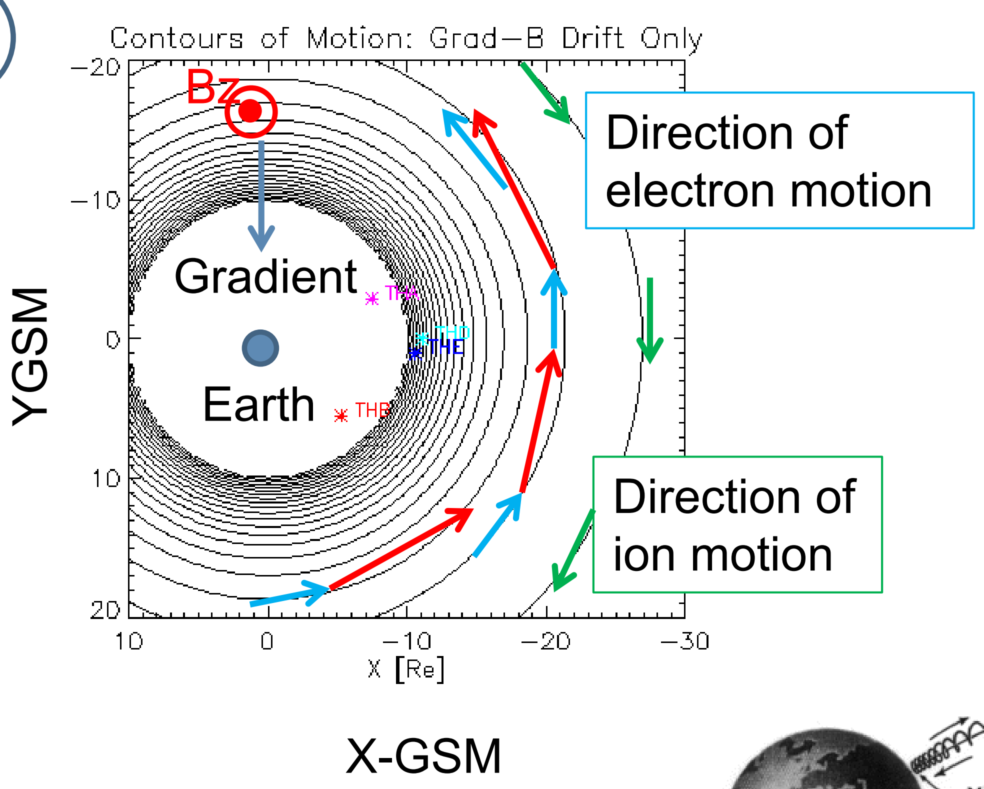
Curvature Drift

$$\vec{v}_R = \frac{2K_{\parallel}}{qB}\,\frac{\vec{R}_c \times \vec{B}}{R_c^2 B}$$

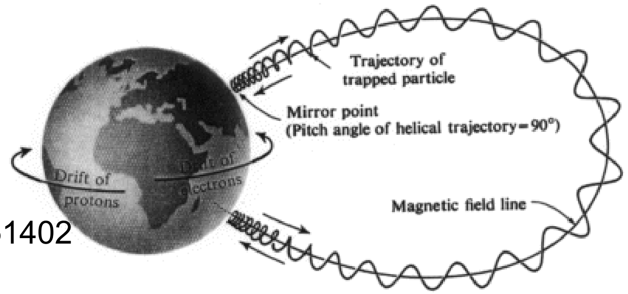
Sun

Energy-dependent:
Energetic e- drift faster

Energetic i+ drift
opposite direction
(clockwise)



R.E. Mars, 2002, Lawrence Livermore
National Laboratory Report UCRL-ID-151402



Convection: Particle Motion

Particle trajectories, magnetic and electric fields

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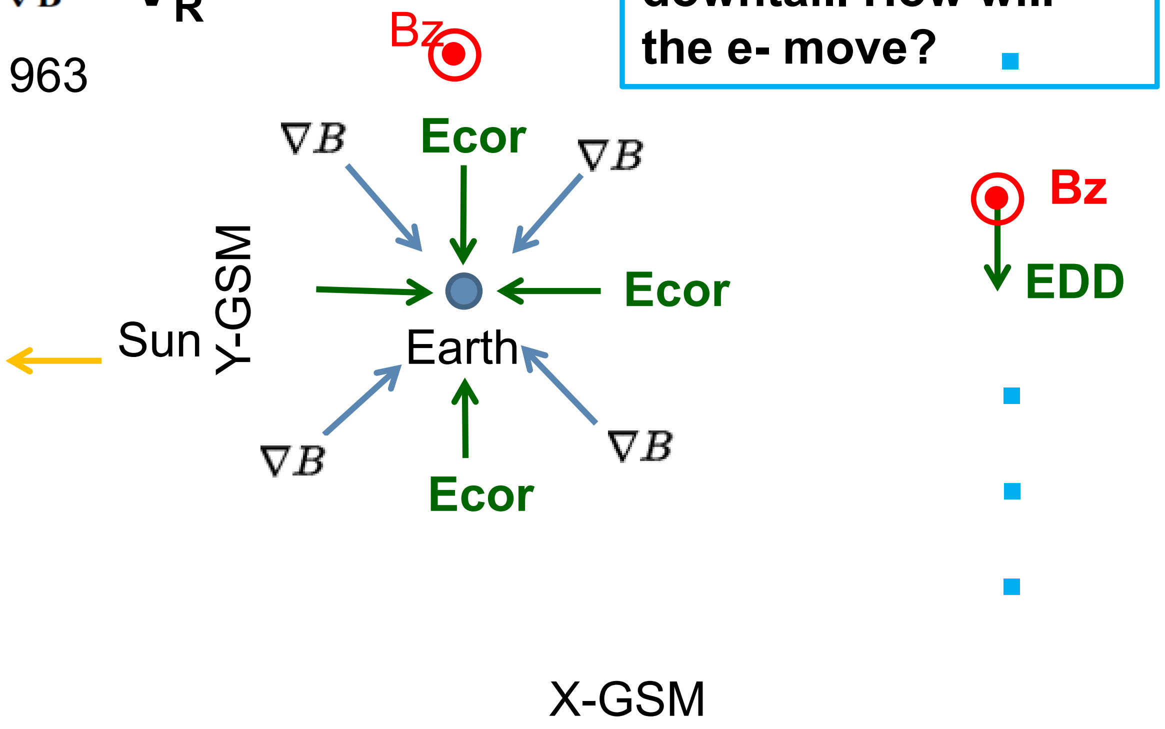
<u>Guiding-center motion</u>

$$V_{GC} = \frac{dr}{dt} = V_{E\times B} + V_{\nabla B} + V_R$$

--*Northrop*, 1963

Launch e- from several points downtail. How will the e- move?



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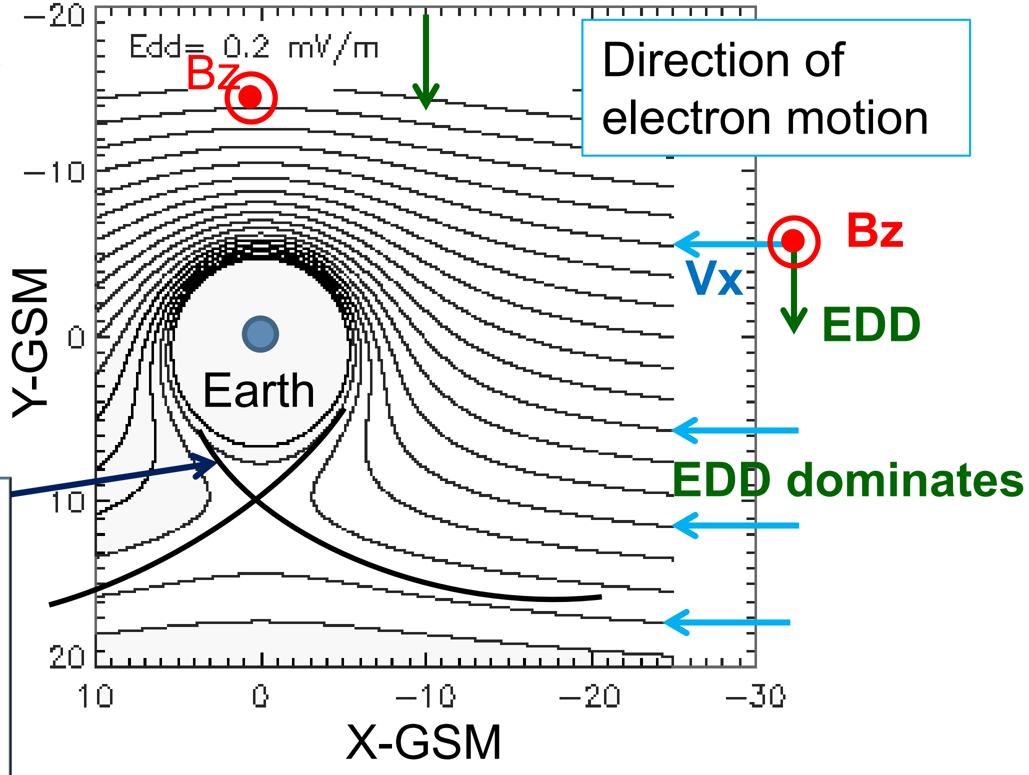
--*Northrop*, 1963

Sun



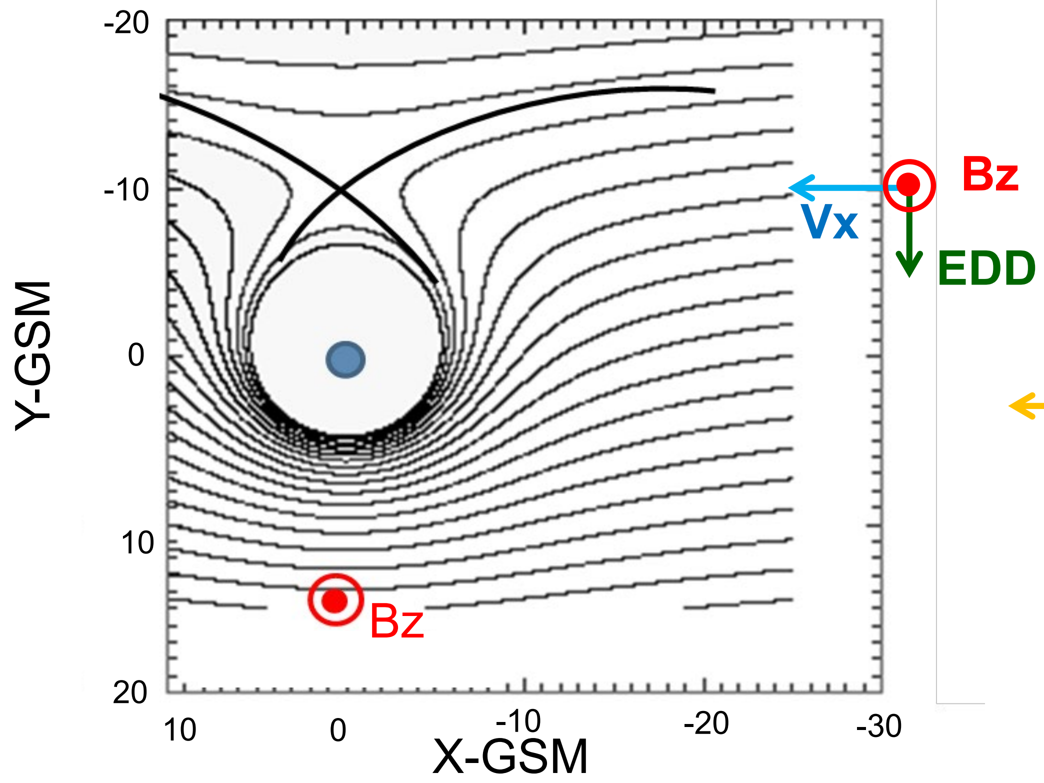
Alfvén Layer ("separatrix"): Boundary separating "trapped" and "convecting" particles. Inside, Ecor, gradB, and curvature drift dominate.

Convection: Particle Motion

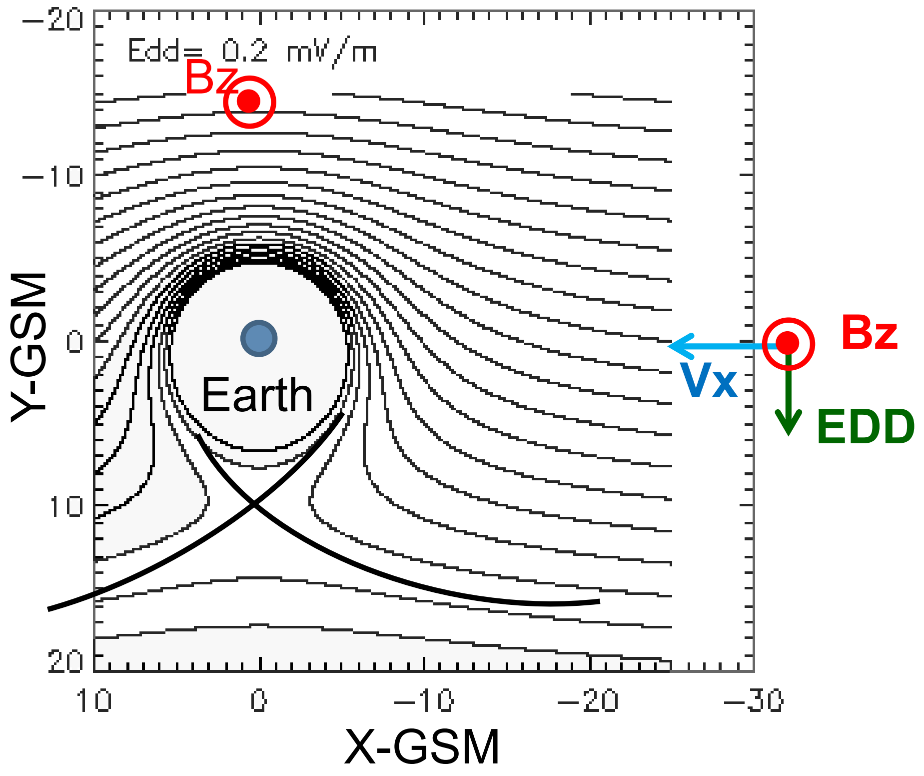
Particle trajectories, magnetic and electric fields

$$\mathbf{v}_{drift} = \frac{mv_\perp^2}{2qB}\frac{(-\nabla_\perp B)\times\mathbf{B}}{B^2}$$

Which plot below represents ion motion and the ion Alfven Layer?



Sun



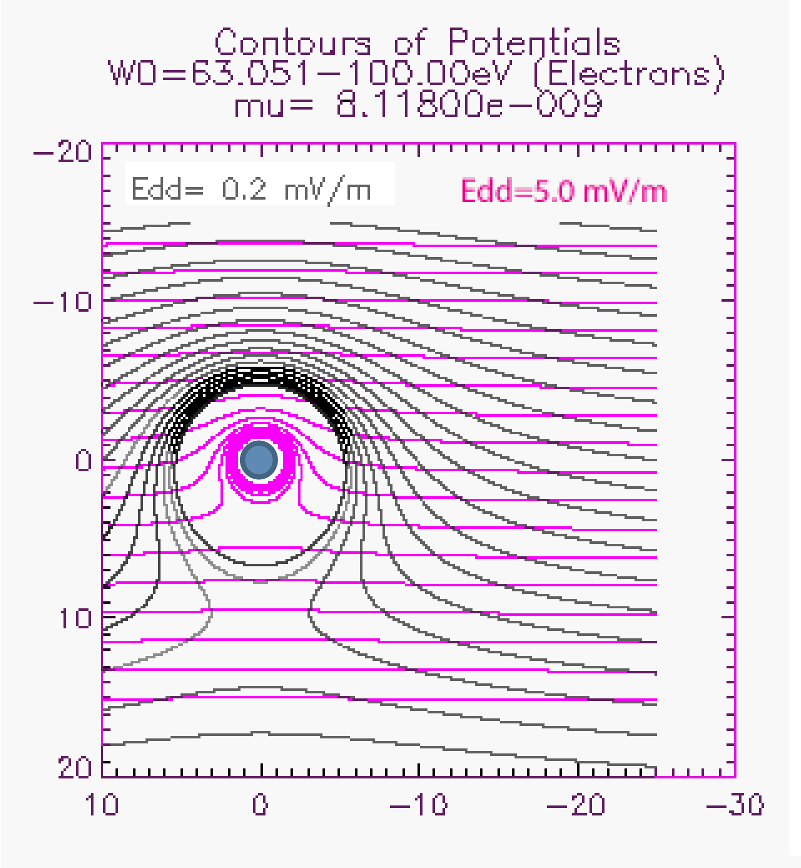
Both are correct! The left is for energetic (hot) ions, while the right is for cold ions that do not gradB drift.

But how do particles get past the Alfvén Layer?

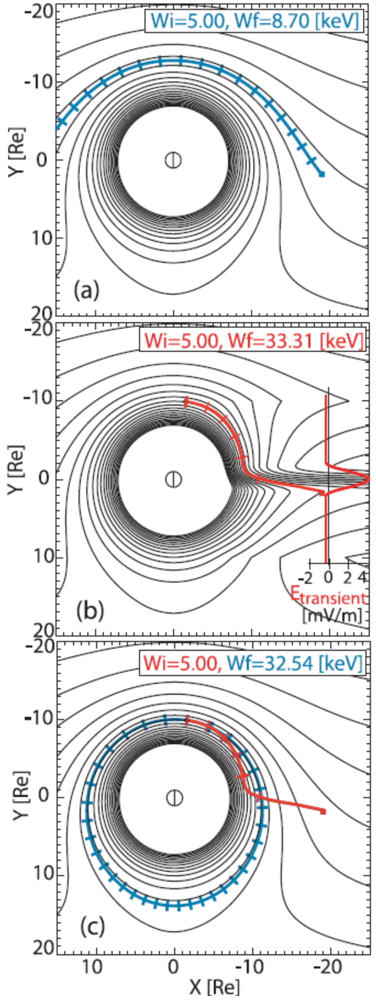
In terms of convection…(I let others in this series discuss diffusion and i+ outflow…)

Enhanced solar wind driving: Faster **V**→Larger **Edd**
Walker and Kivelson, 1975

Sun



Localized fast flows:
Faster **V**→Larger **E**
Gabrielse et al. (AGU JGR, 2012)



e.g., Pfitzer and Winckler, 1969; Baker et al., 1979; Moore et al., 1981; Aggson et al., 1983; Mauk and Meng, 1987; Reeves et al., 1990

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Convection on Mesoscales

Embedded in the background convection pattern, mesoscale phenomena carry the bulk of the load.

Angelopoulos et al. (1992; 1994) showed bursty bulk flows transport >60% of the magnetic flux earthward on the nightside: >10 min of enhanced flow with bursts exceeding 400 m/s.

And mesoscale phenomena start at the beginning with dayside reconnection…

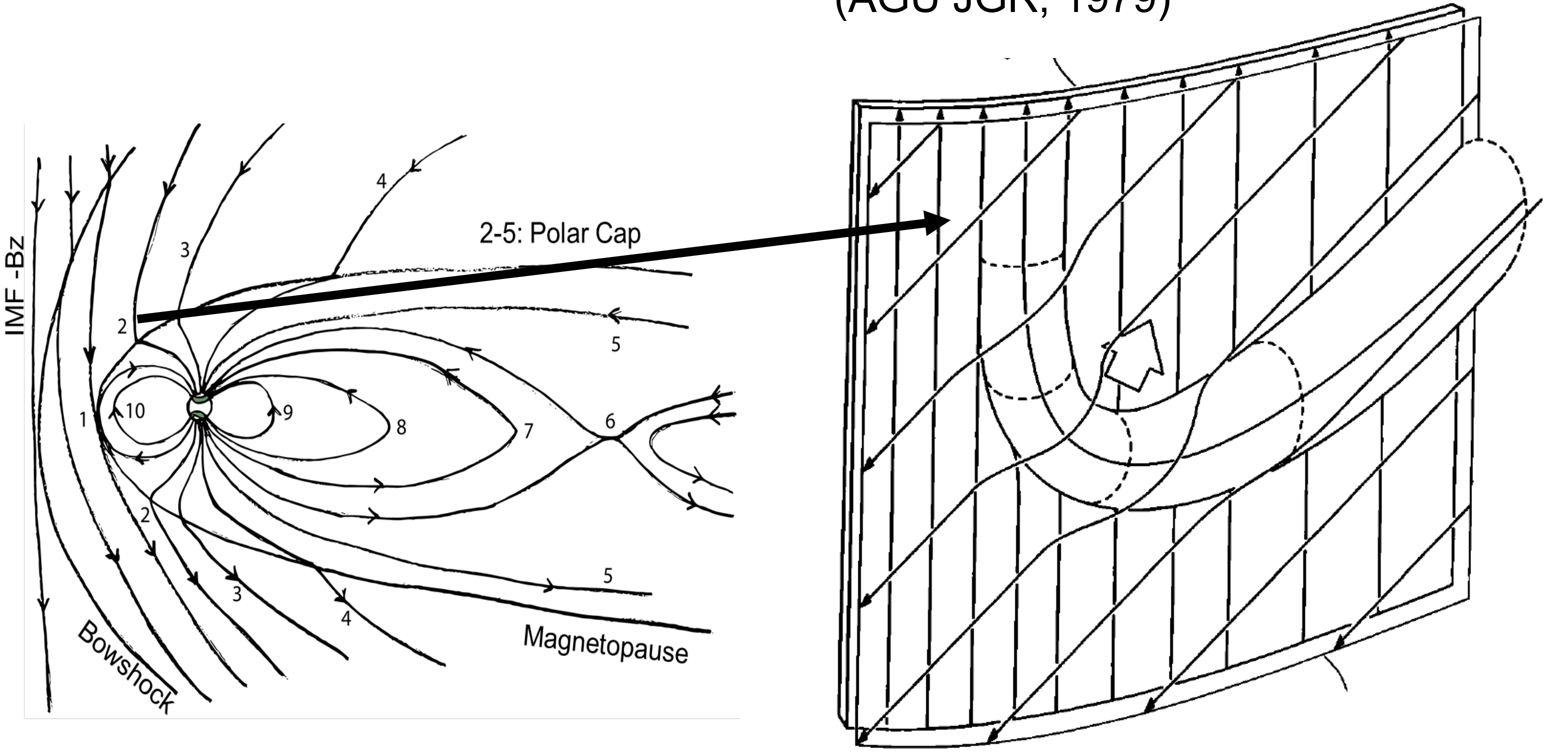
Mesoscale in the magnetosphere: ~1 to several R_E wide
Mesoscale in the ionosphere: ~50-500 km wide

Convection on Mesoscales

Dayside and Polar Cap Convection

- See Ying Zou's Presentation in this Series on Dayside Reconnection

Modified from Russell and Elphic (AGU JGR, 1979)



SuperDARN observed fast flow

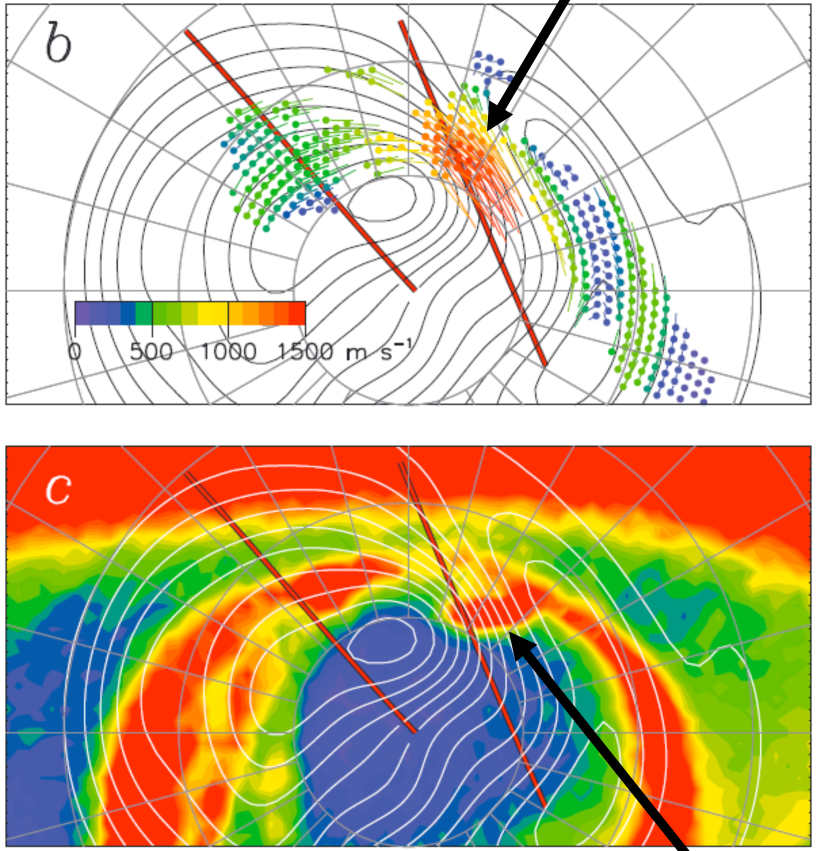


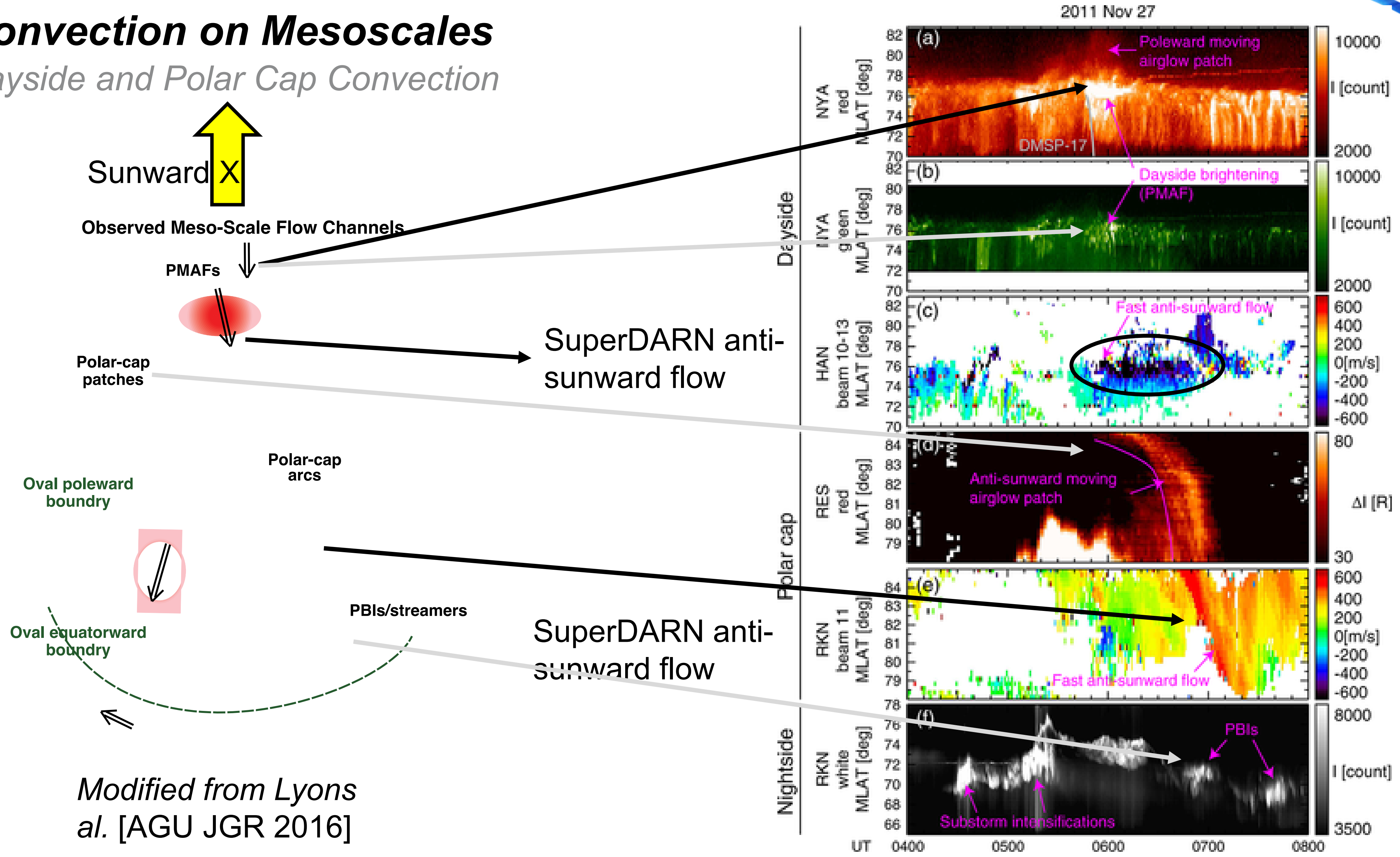
IMAGE FUV/WIC observed PMAF

Milan et al. (AGU JGR, 2016)

Transient magnetopause reconnection has been related to polar cap patches (Carson et al., 2006; Lockwood and Carlson, 1992), which have been related to poleward moving auroral forms (PMAFs) (Wang et al., 2016)

Convection on Mesoscales

Dayside and Polar Cap Convection

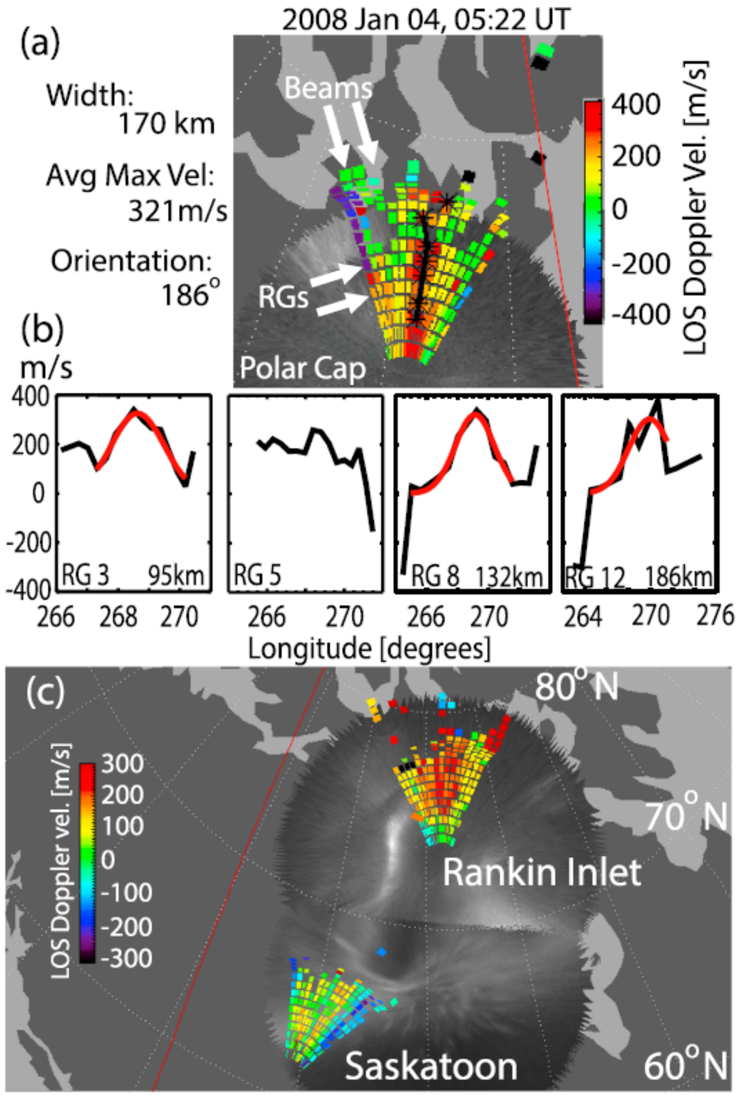


Modified from Lyons al. [AGU JGR 2016]

Nishimura et al. (AGU JGR, 2014)

Convection on Mesoscales

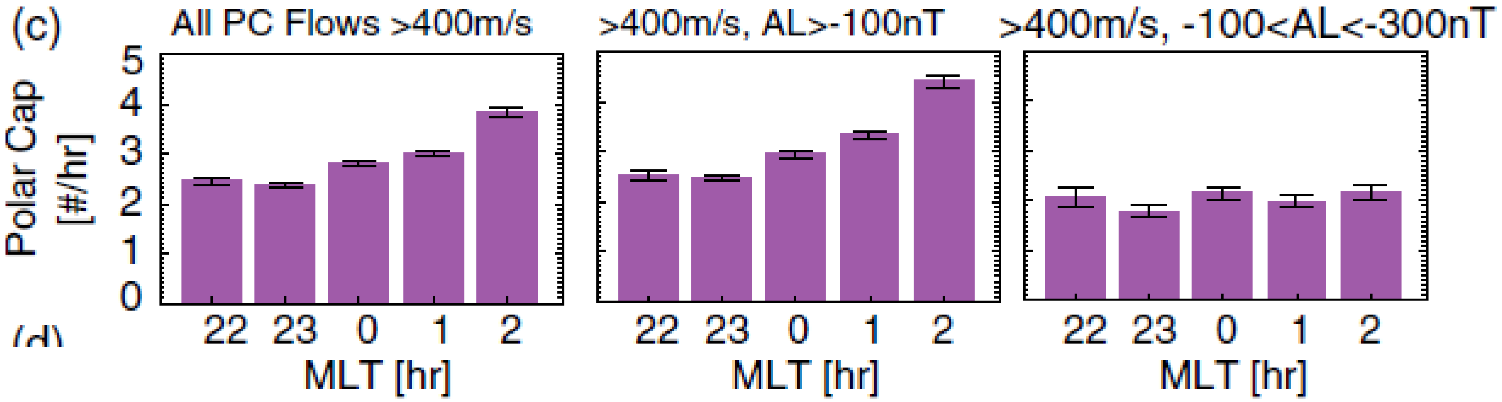
Polar Cap Convection

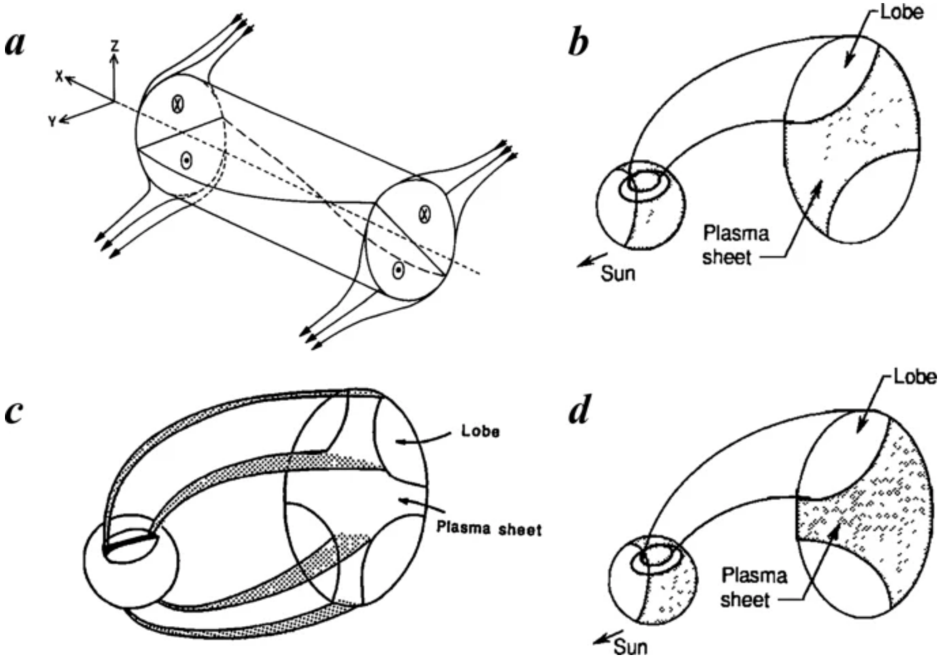


Gabrielse et al. (AGU JGR, 2018)

Fewer polar cap mesoscale flows during substorm.

Similar trend as polar cap arcs: sun-aligned auroral arcs in polar cap (Berkey et al., 1976; Hosokawa et al., 2011; Valladares et al., 1994; Hosokawa et al., 2020)





Polar Cap Arcs

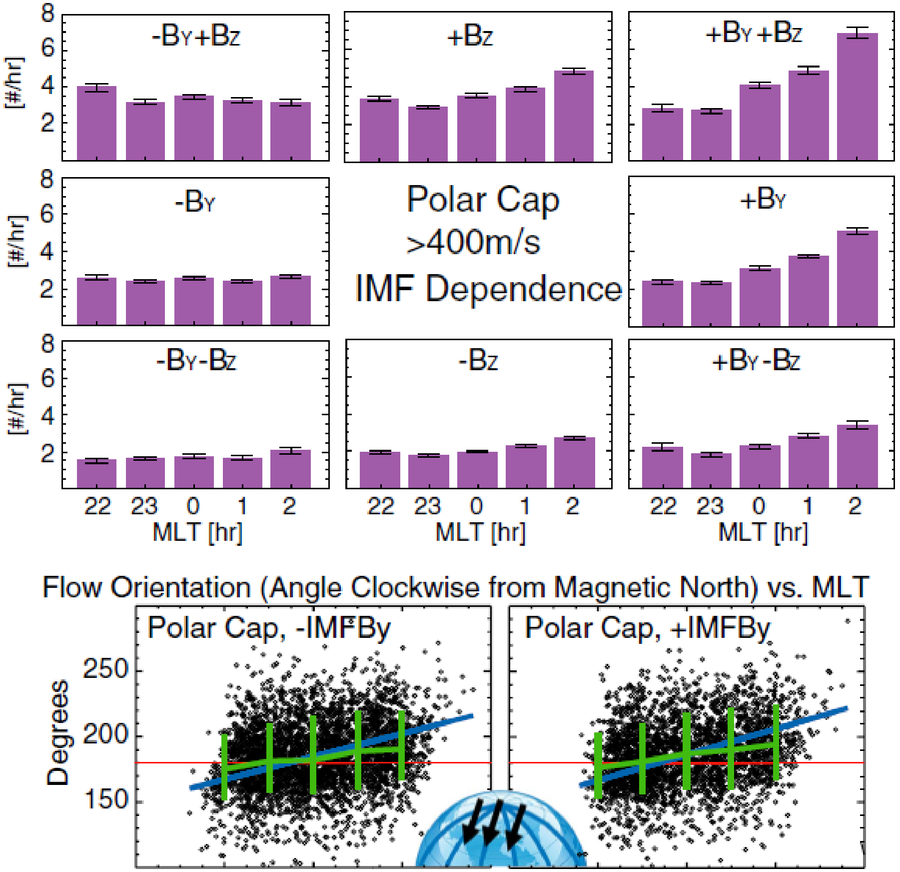
From Hosokawa et al., 2020: (**a**) Tail twist for duskward IMF (Cowley 1981) (**b**) oval-aligned TPA at dusk due to twist of tail plasma sheet for duskward IMF (Makita et al. 1991), (**c**) bifurcated tail plasma sheet mapping to a TPA in the center of the polar cap, and a conjugate TPA in the other hemisphere (Obara et al. 1988), (**d**) possible relations of polar cap arc formation with plasma sheet configuration (taken from Makita et al. 1991)

Convection on Mesoscales

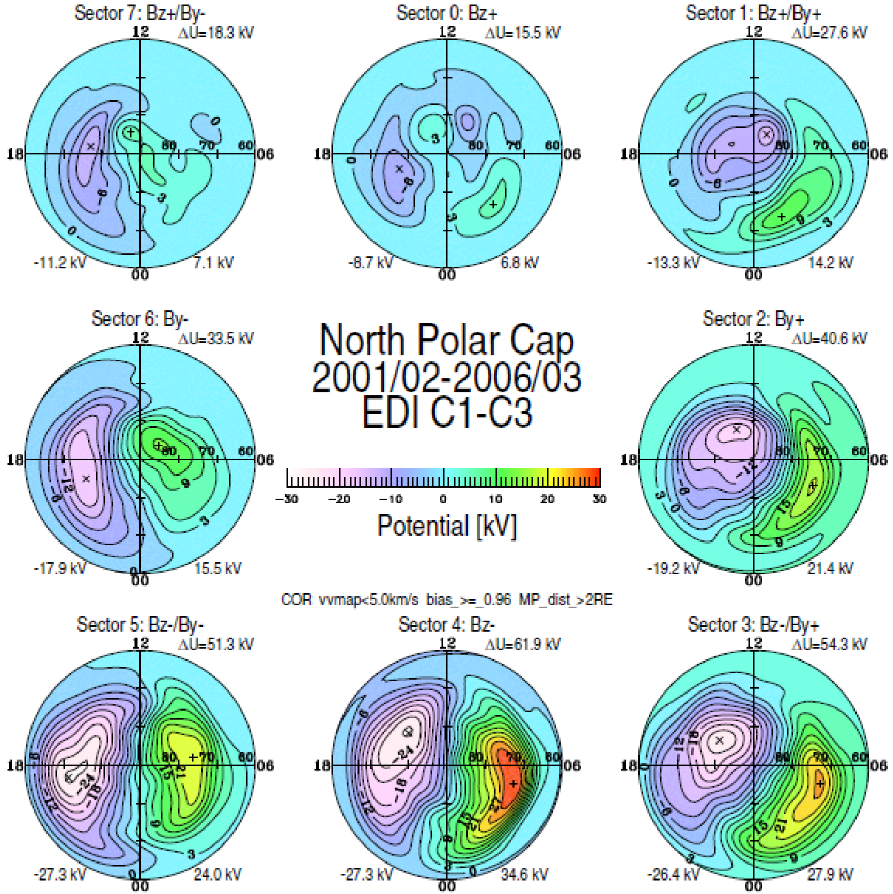
Polar Cap Convection

Mesoscale equatorward flows tend to be embedded in the background flow

- More post-midnight during +BY like polar cap arcs (Hosokawa et al., 2011) and majority of background convection.
- Tilted east-to-west



Gabrielse et al. (AGU JGR, 2018)



Haaland et al. (AGU JGR, 2007)

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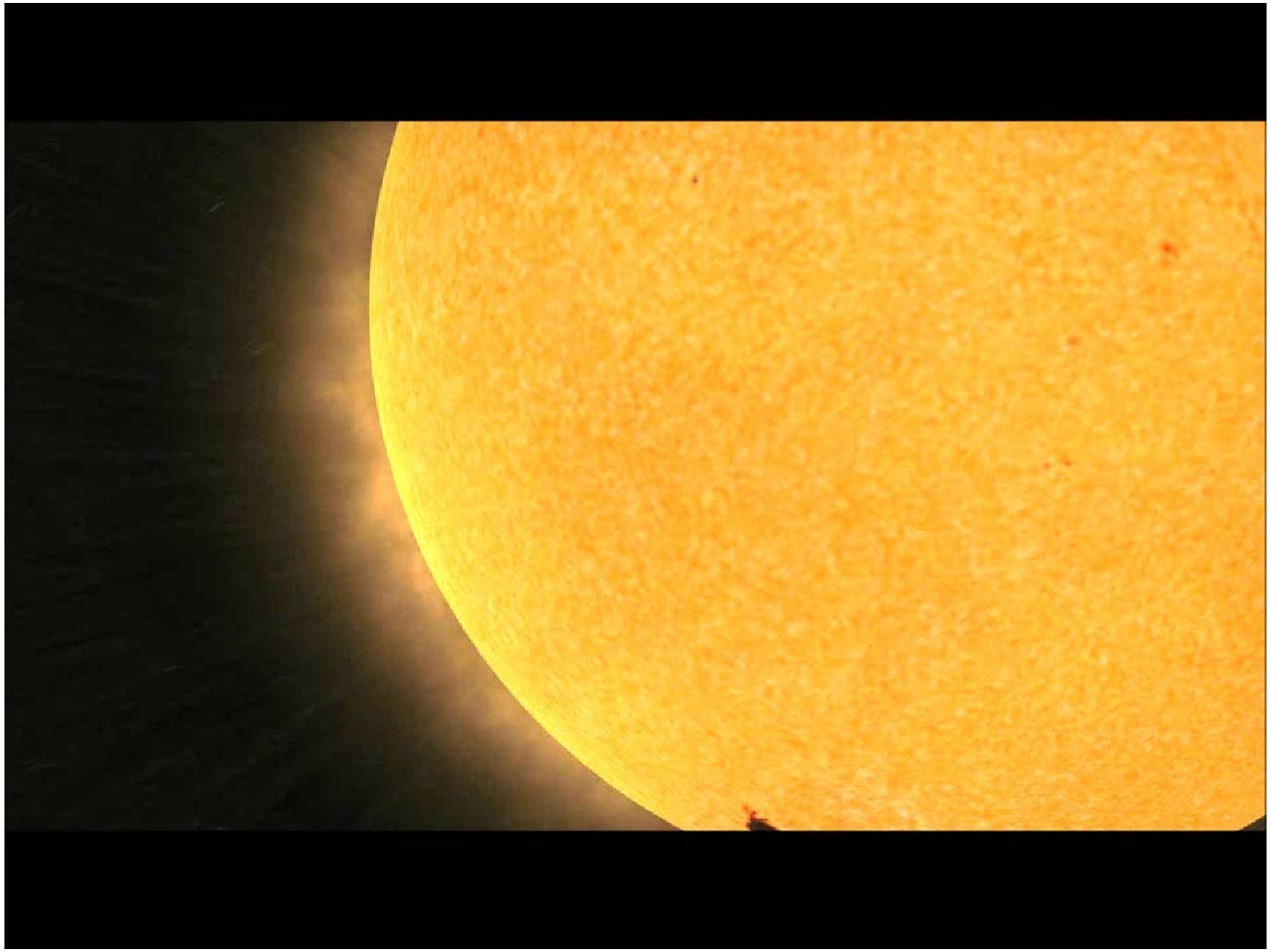
Convection: Substorm

Not steady-state: Increase load in the tail requires explosive response

1. **Growth Phase**
   a) Tail stretching
   b) Flux loading in the tail
   c) Solar wind energy stored in magnetosphere
2. **Expansion Phase**
   a) Initiated by substorm onset
   b) Release of "pent-up energy"
3. **Recovery Phase**
   a. Magnetosphere returns to "ground state"

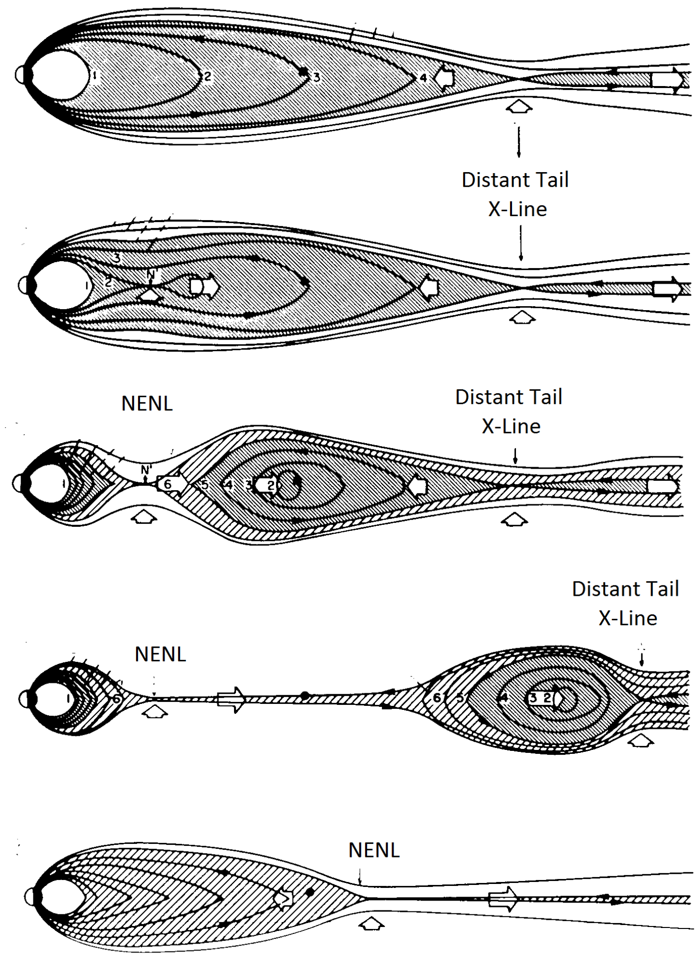
Duration: ~90 minutes



Video: Courtesy of NASA

Substorm Overview

Phenomenology



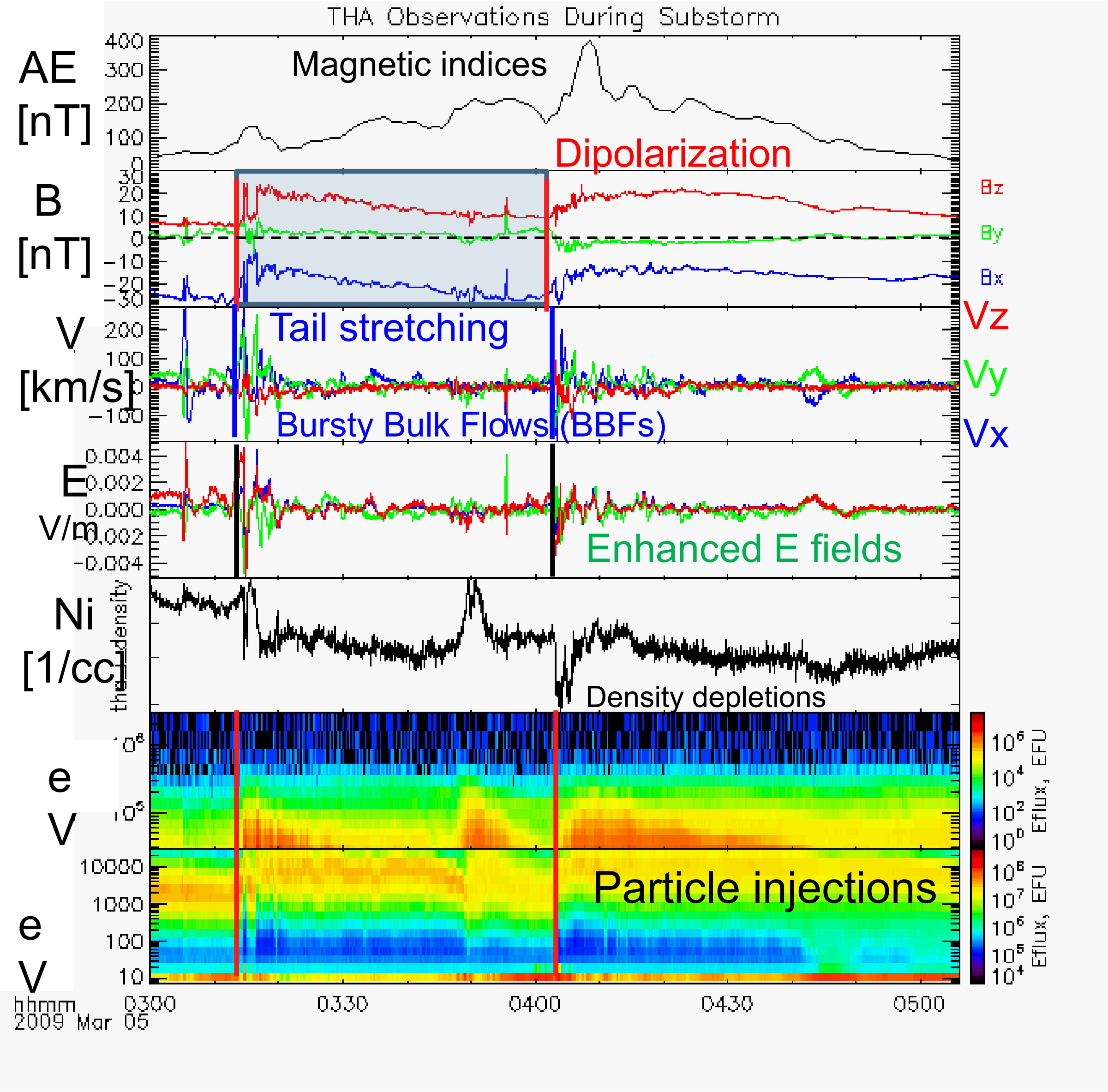
Modified from Hones (AGU JGR, 1977)

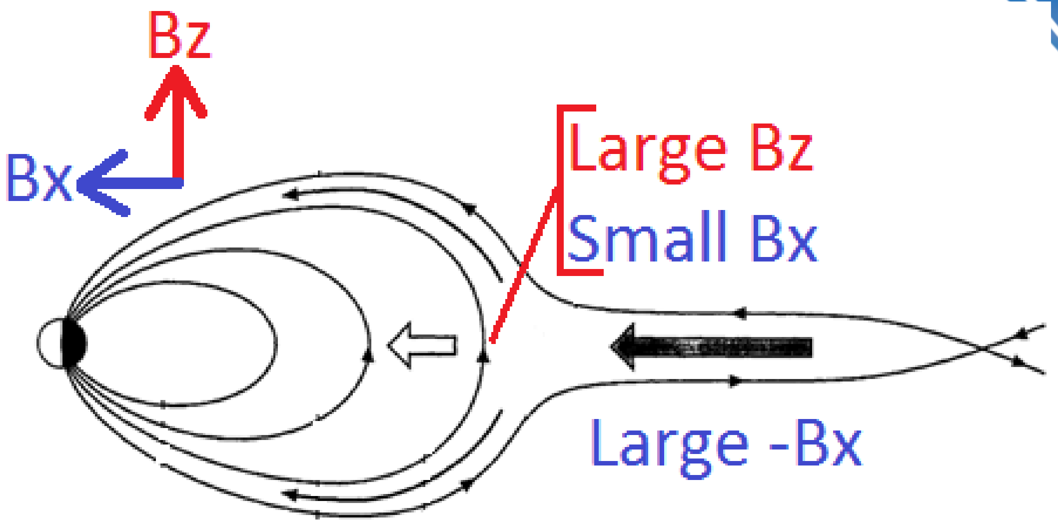
Three Timing Sequences Proposed:

1. Near-Earth Neutral Line (NENL)
    1. Tail stretching & additional load→reconnection ~20-30RE
    2. Earthward flows transport magnetic flux
    3. Large-scale dipolarization and substorm current wedge form ~6.6-12 RE
    4. Hones et al., 1973; 1977; Nice review: McPherron et al. 2020
2. Current Disruption (CD)
    1. Tail stretching thins current sheet to such extent that instability forms ~9-12 RE
    2. Current is diverted along field lines into ionosphere (substorm current wedge), dipolarization forms
    3. Triggers reconnection and/or earthward flows
    4. Lopez et al., 1990; Lui et al., 1991; Lui et al., 2011
3. Streamer-triggered substorm
    1. Flow forming at distant X-line travels earthward (observed optically as a streamer)
    2. Reaches thin, unstable current sheet near 9-12 RE
    3. Causes instability resulting in substorm
    4. Nishimura et al., 2011; 2013; Nice review: McPherron et al. 2020

Substorm Overview

Magnetic field reconfiguration: In situ observations





Often corresponds to:

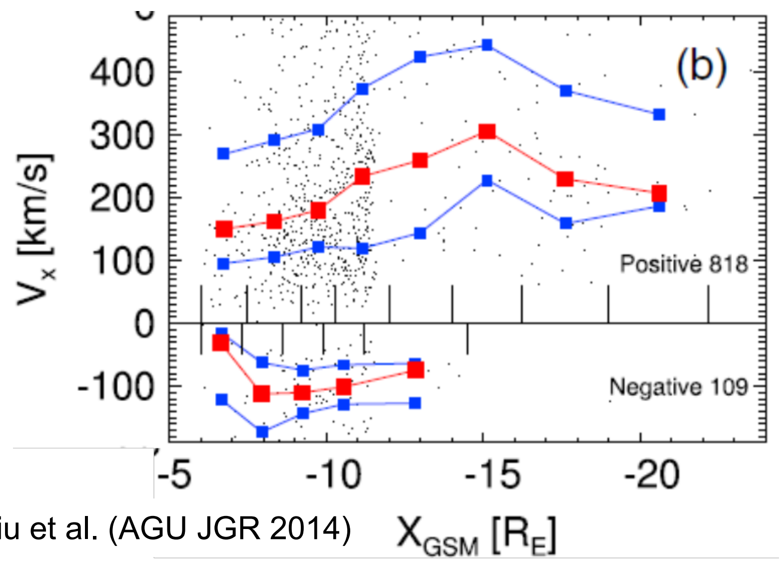
- Substorm (AE index)
- Fast flows (>400 km/s)
- Strong electric fields (2-10s mV/m)
- Plasma density depletions
- Particle injection (flux increase)

https://gem.epss.ucla.edu/mediawiki/index.php/GEM_Tutorials#2017_Summer_Workshop

Substorm: Convection on Mesoscales

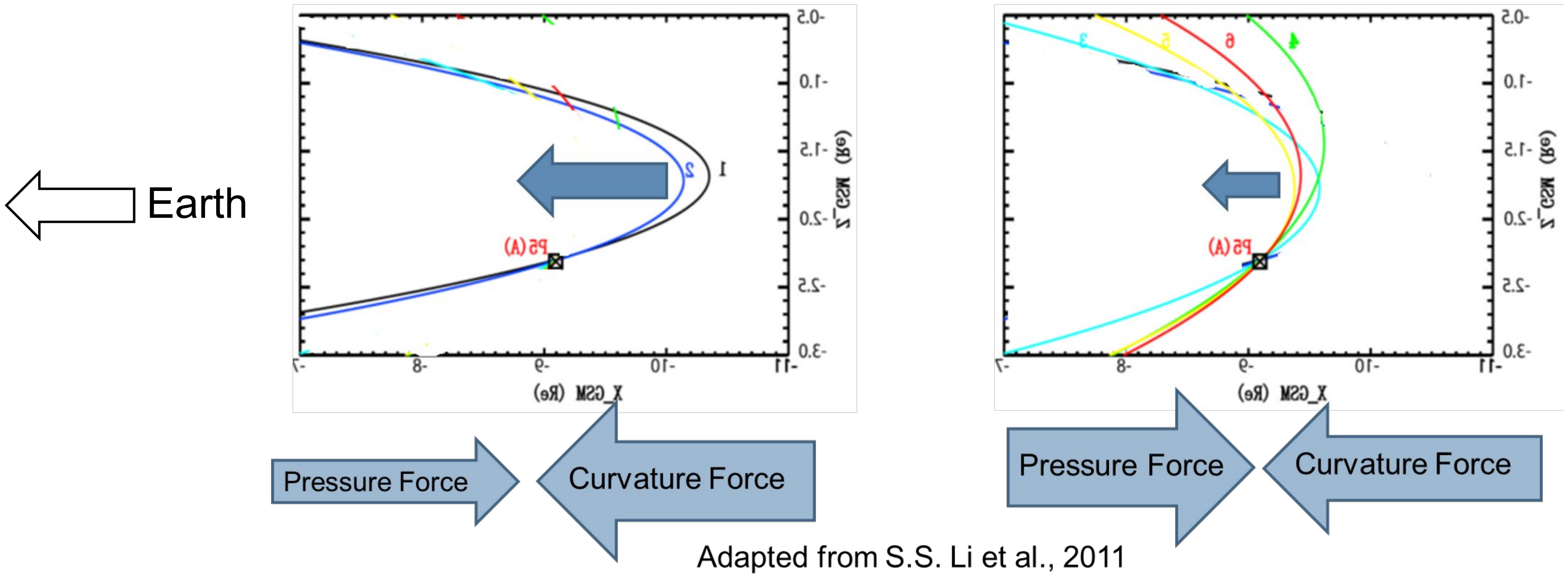
Magnetotail Transients: In terms of local forces

1. Reconnection (*Jim Drake 10/29/2020*)
2. Curvature force of field line > Pressure force from dipole
3. Flux tube accelerates earthward
4. Pressure force increases, flux tube brakes



Liu et al. (AGU JGR 2014)

Curvature gradient force vs. Pressure gradient force



Adapted from S.S. Li et al., 2011

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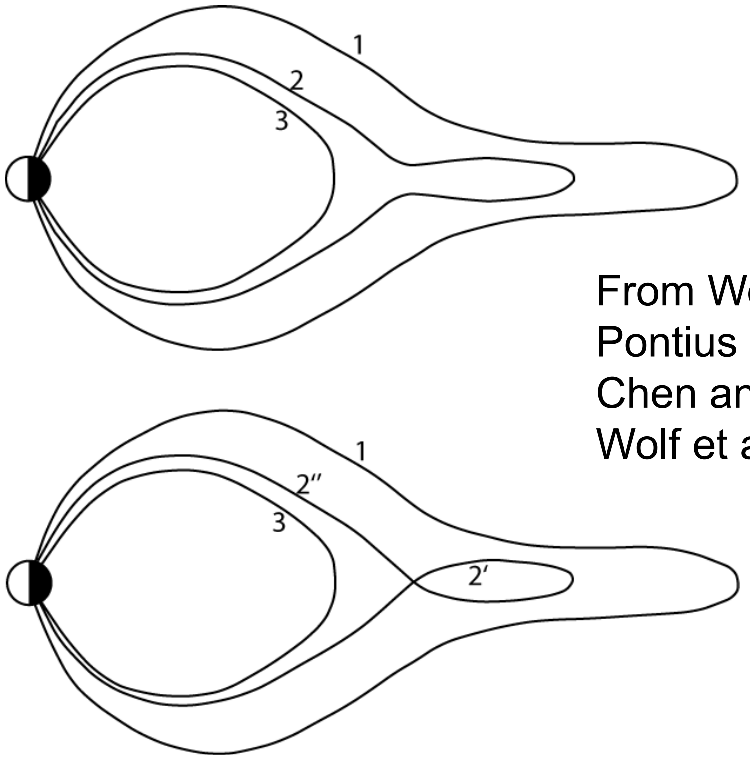
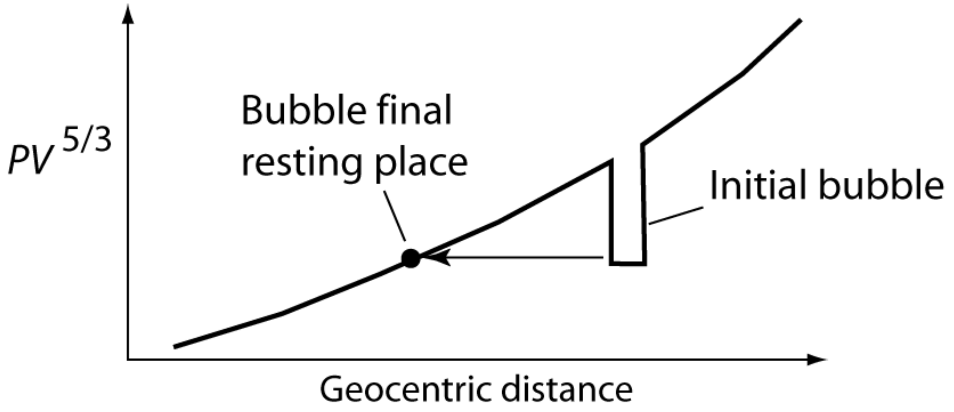
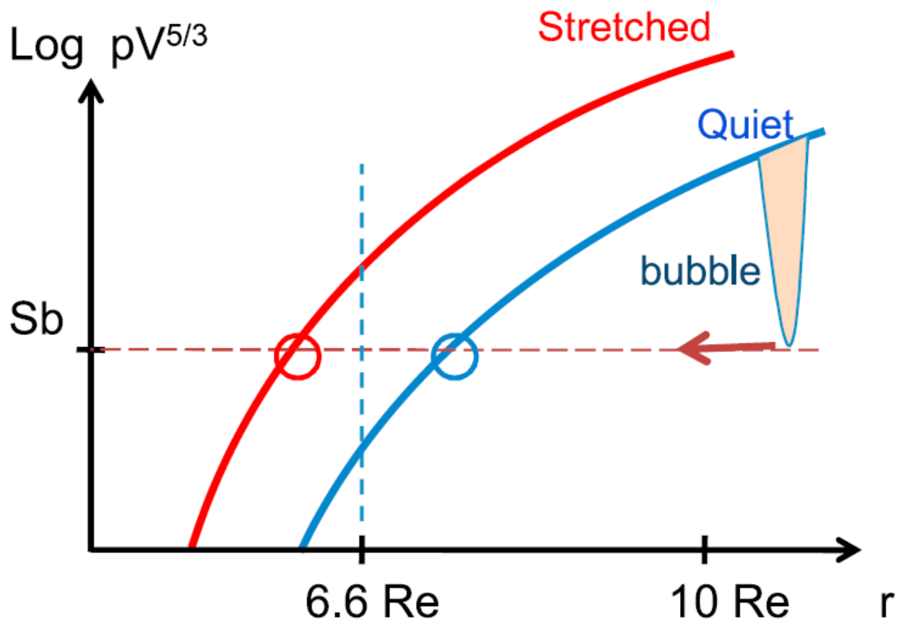
Substorm: Convection on Mesoscales

Magnetotail Transients: In terms of entropy



From Wolf GEM Tutorial 2012
Pontius and Wolf, 1990
Chen and Wolf, 1993; 1999
Wolf et al., 2009





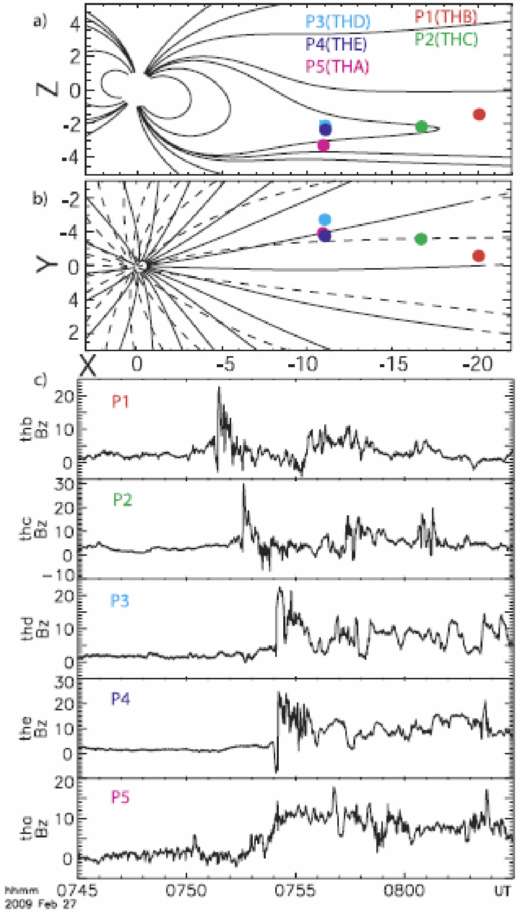
Sergeev et al. (AGU JGR 2012)

Low entropy plasma bubbles

- Global description
- Formulated in terms of Rayleigh-Taylor Instability
- GEO penetration depends on tail preconditioning (Sergeev et al., 2012)

Magnetic Flux Transport

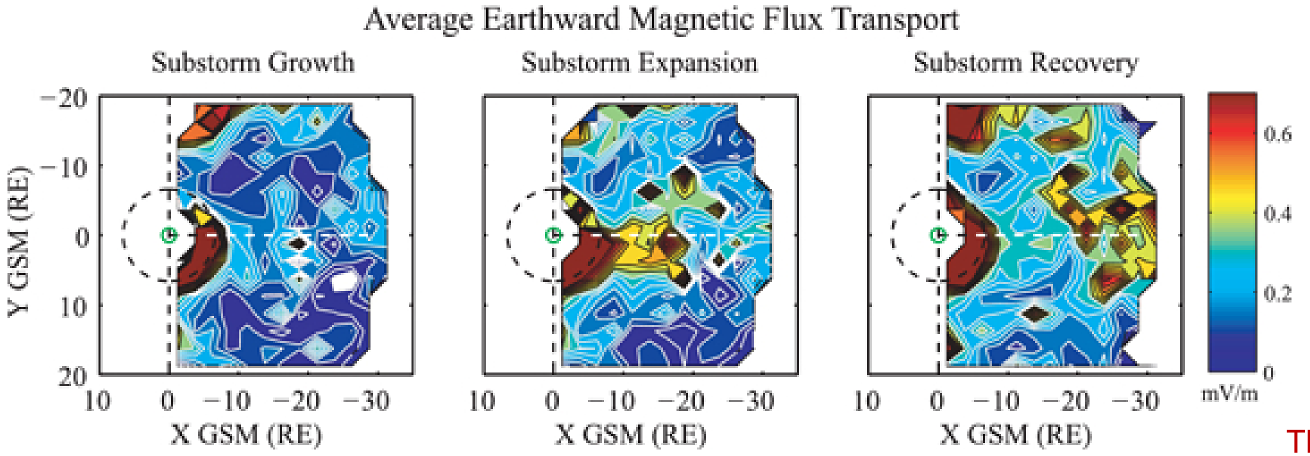
Most during substorm expansion phase



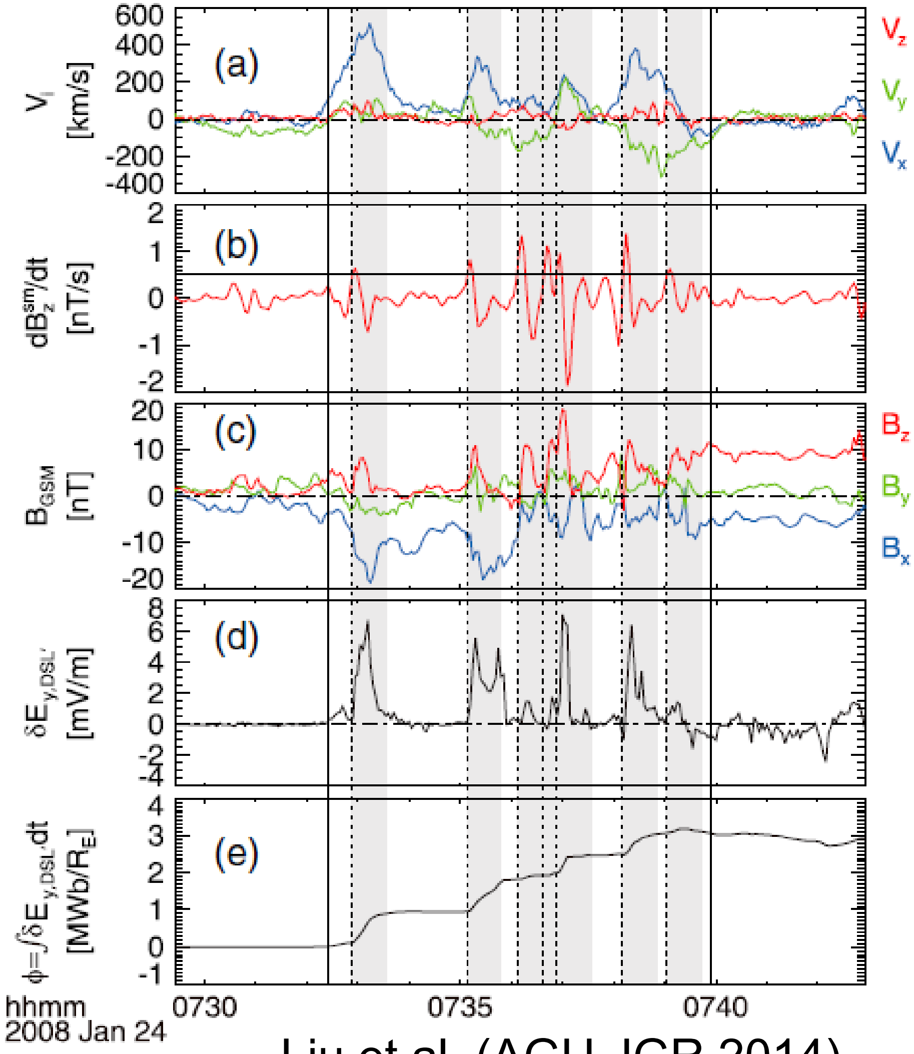
Runov et al. (AGU GRL 2009)

- **>60% magnetic flux carried in BBFs** (Angelopoulos et al., 1992; 1994)
- **~70% of BBF flux transport within dipolarizing flux bundles (DFBs)** (Liu et al., 2014)
- **Most magnetic flux transport occurs during substorm expansion phase** (e.g., Kissinger et al., 2012; Lyons et al., 2012; Merkin et al., 2020)

Kissinger et al. (AGU JGR 2012)

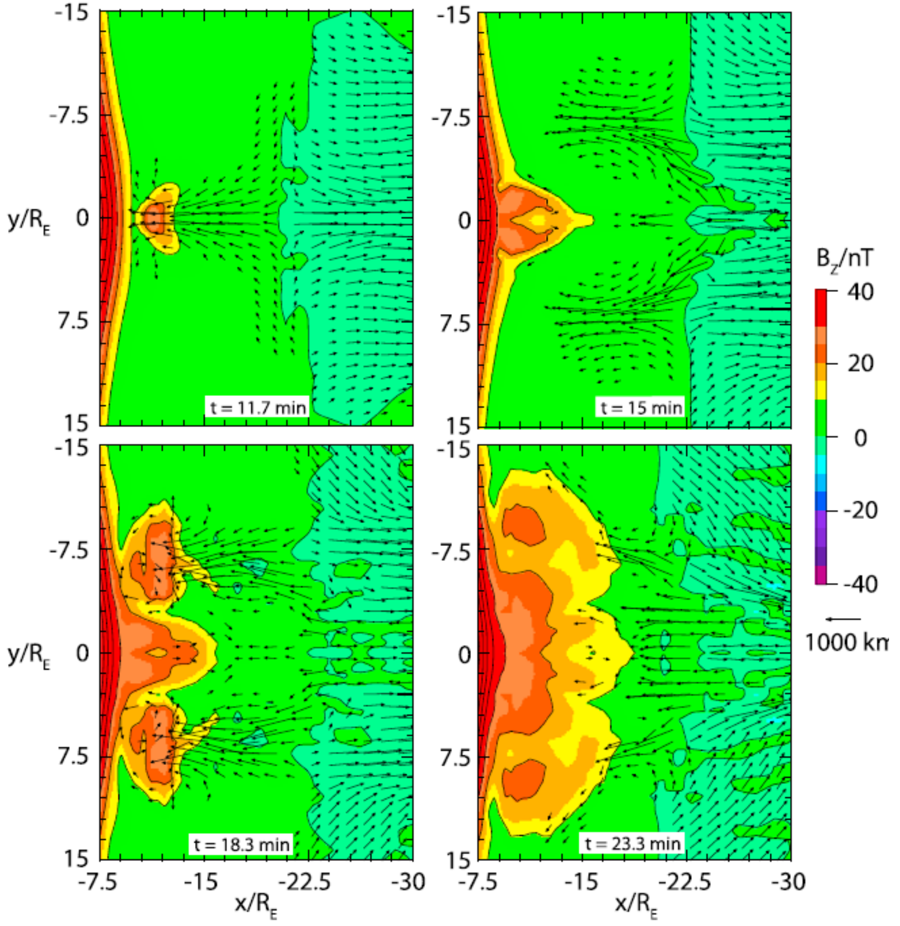


Multiple DFBs in a Bursty Bulk Flow (BBF)

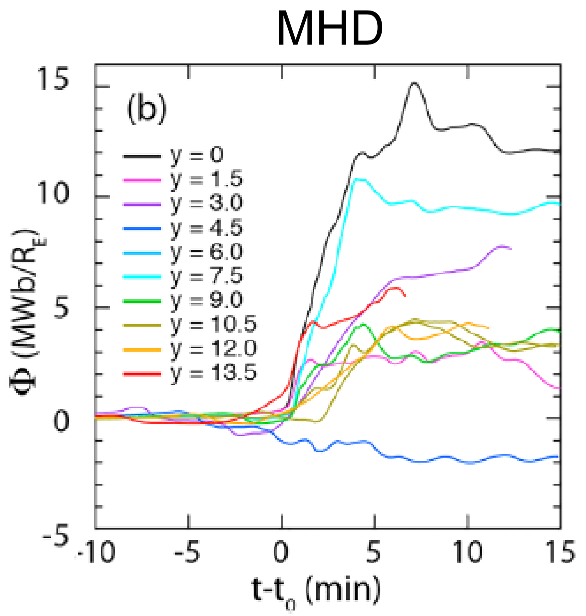


Liu et al. (AGU JGR 2014)

Substorm: Magnetic Flux Transport

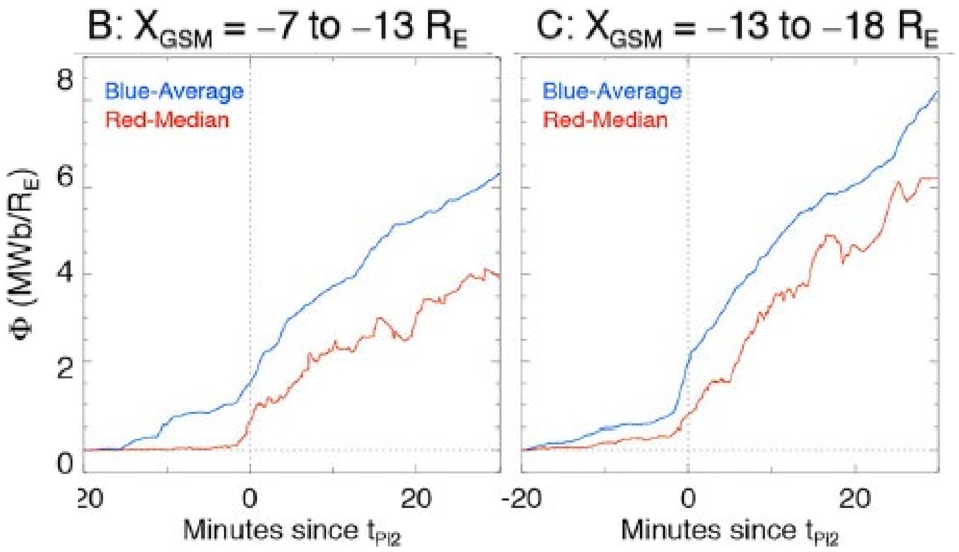


Figures modified from Birn et al. (AGU JGR 2019)



The total flux transported earthward from the reconnection site was ~ 2.3×10^8 Wb, commensurate with estimates of 1–3.6×10^8 Wb by Angelopoulos et al. (1994).

This flux was associated with up to seven dipolarization front events localized across the tail.

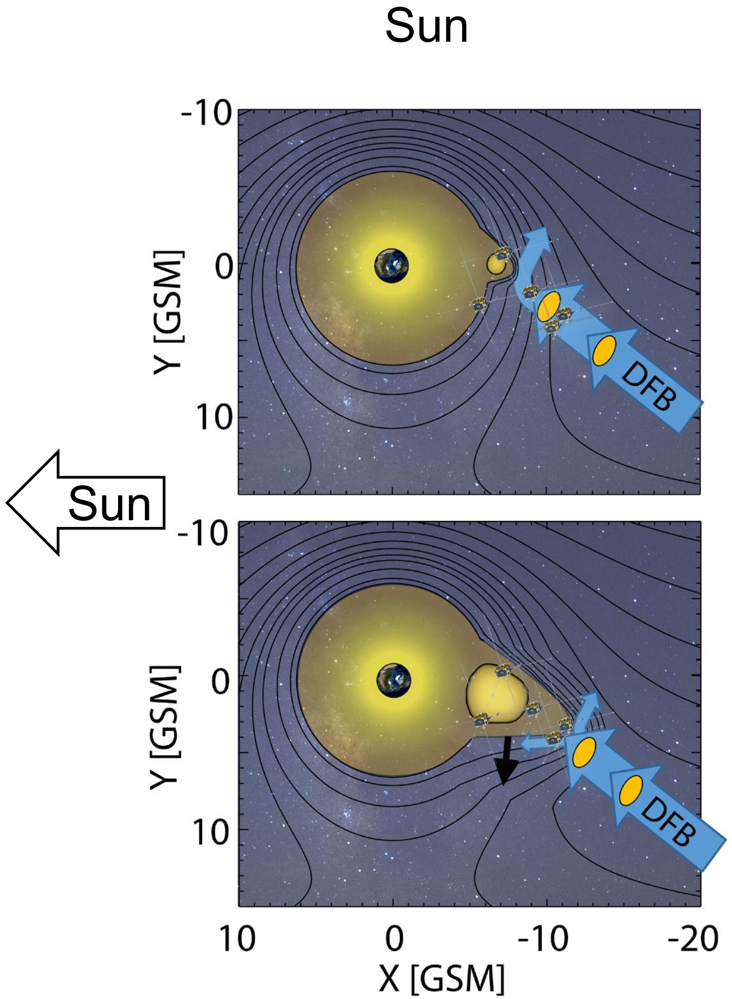


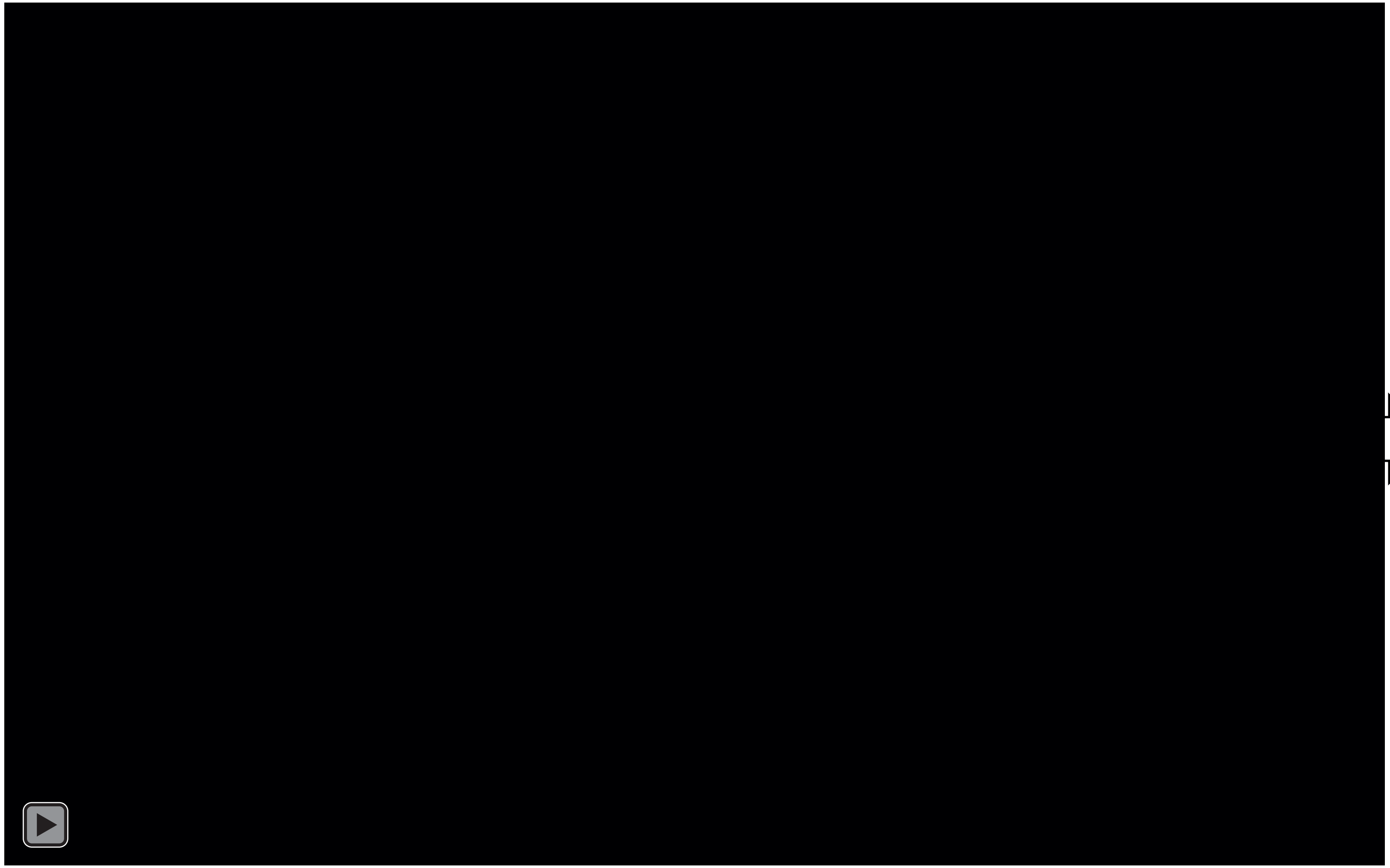
THEMIS statistics

Substorm Dipolarization

Magnetic Flux Pileup

Shiokawa et al., 1997; Baumjohann et al., 1999; Baumjohann, 2002; Nakamura et al., 2009; 2013

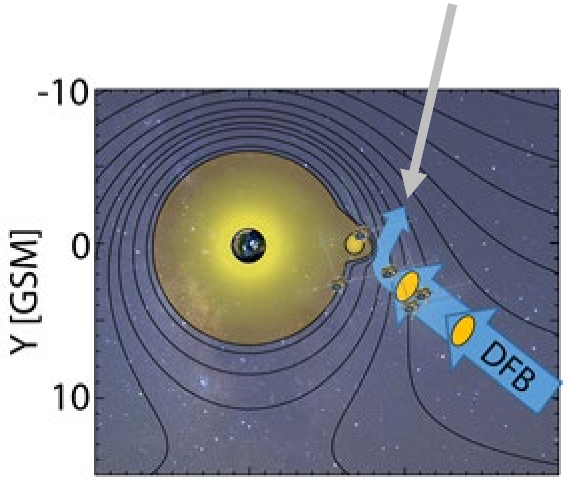


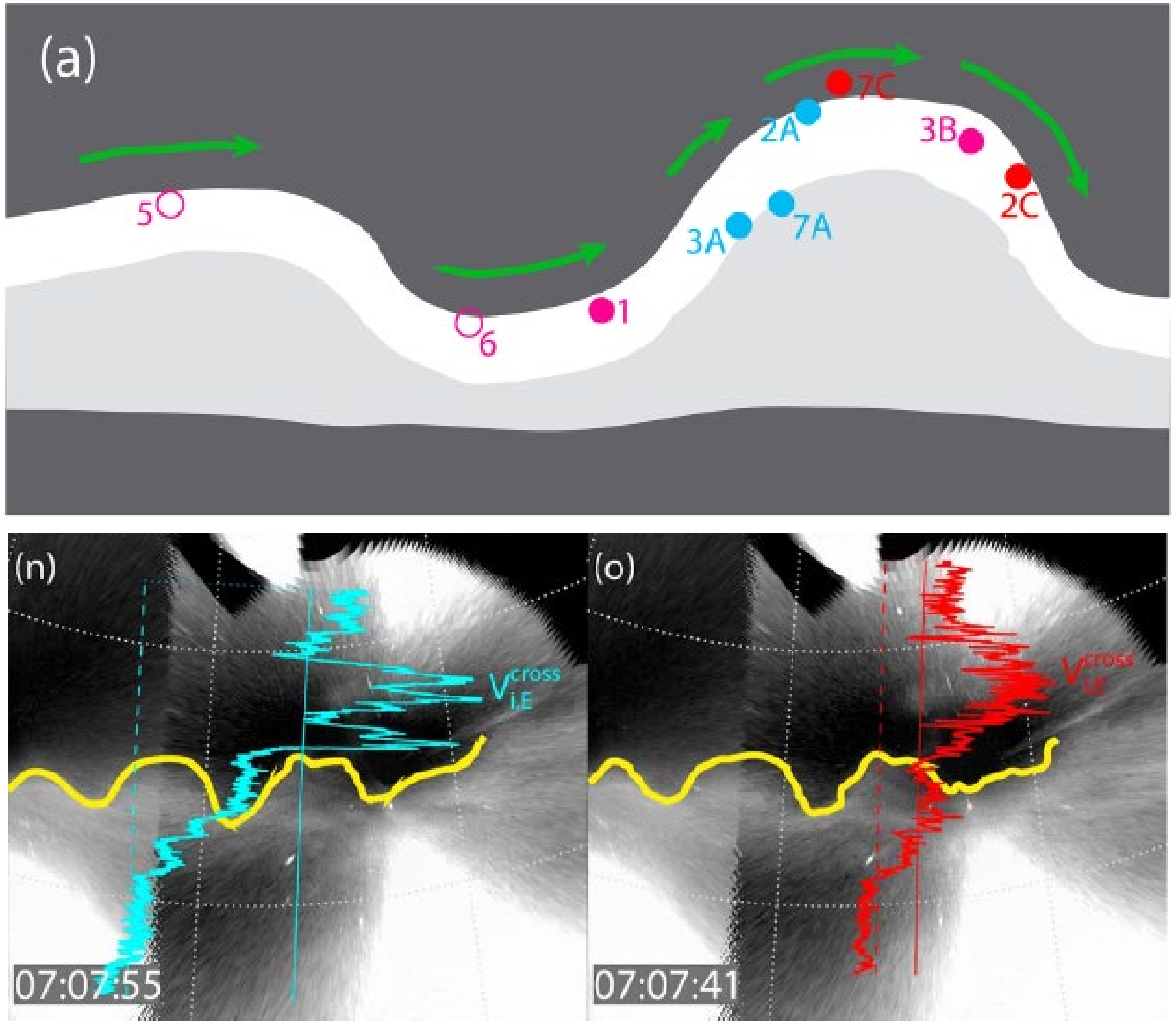


Modified from Gabrielse et al. (AGU JGR 2019)
Observations: Bz, Vx, and Injections

Merkin et al. (AGU JGR 2019)
Modeling: Bz and Vx

Diverted Flows



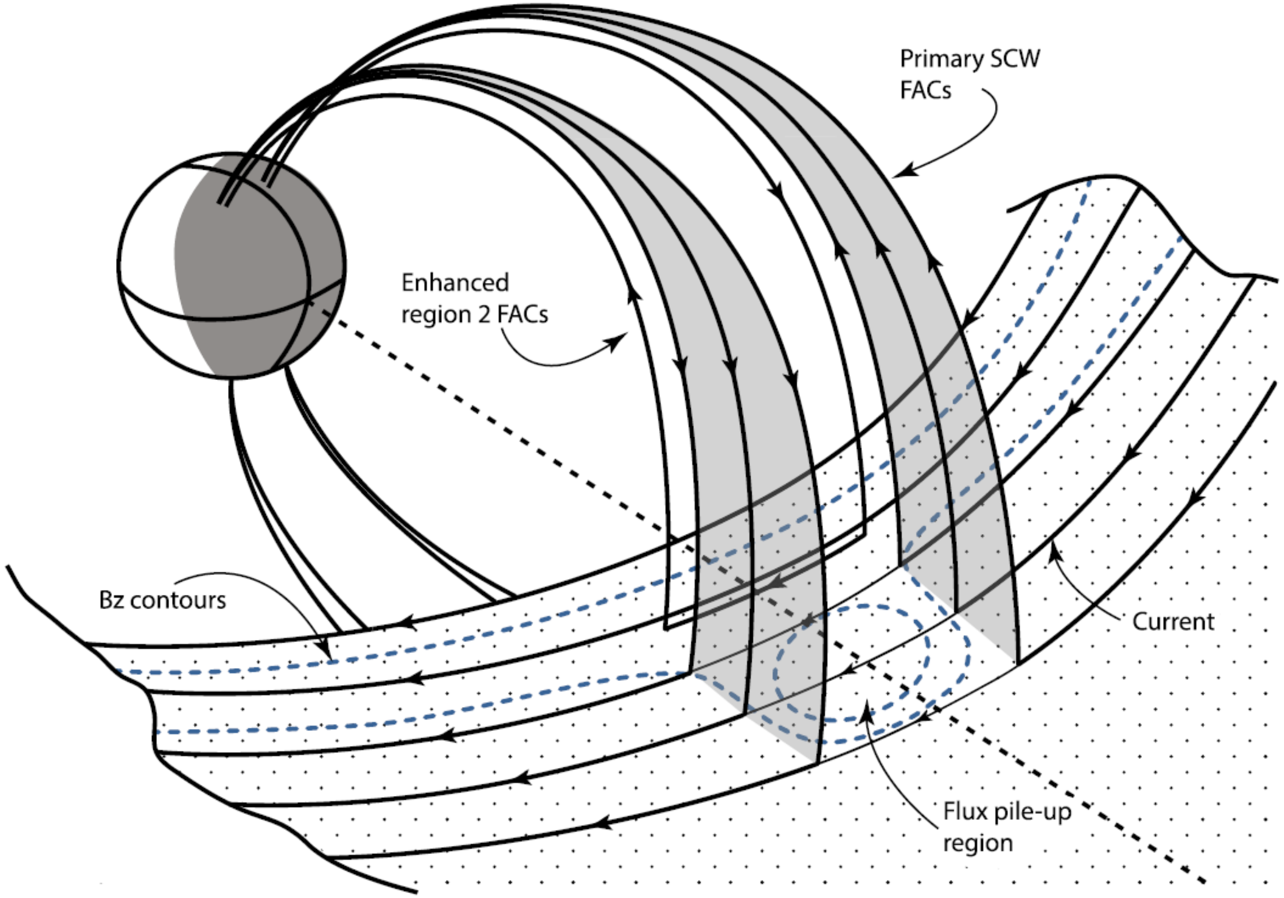


SWARM and THEMIS ASIs used to correlate diverted, fast flows to omega bands post-midnight: Kelvin-Helmholtz

Modified from Liu et al. (AGU GRL 2018)

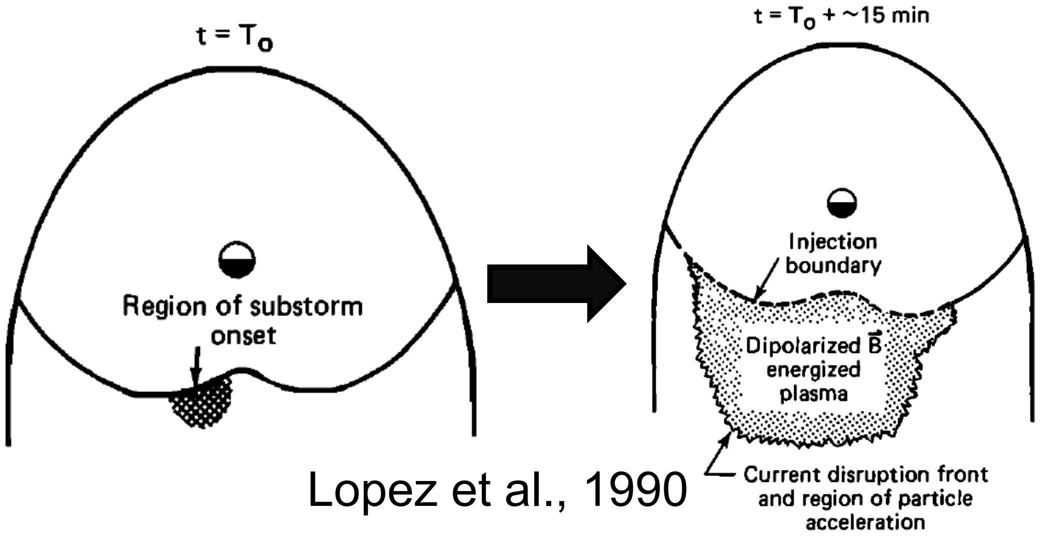
Substorm Current Wedge

A result –or cause— of large-scale dipolarization



Dipolarization diverts current: Kepko et al. (Space Science Reviews, 2014)

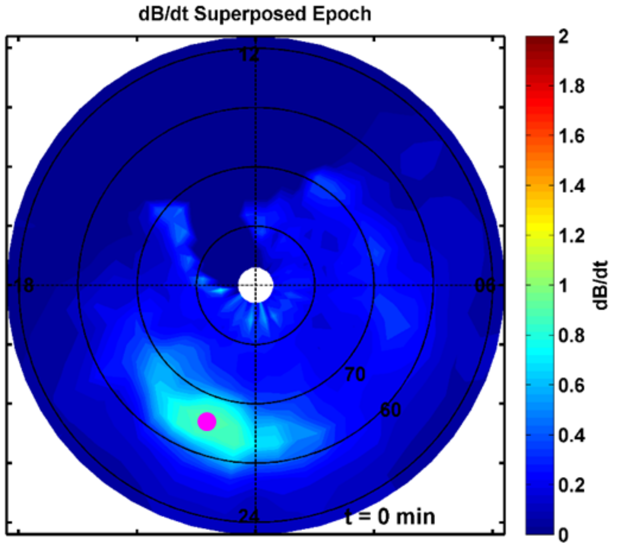
Current disruption: Instabilities form when current sheet becomes too thin.



Lopez et al., 1990

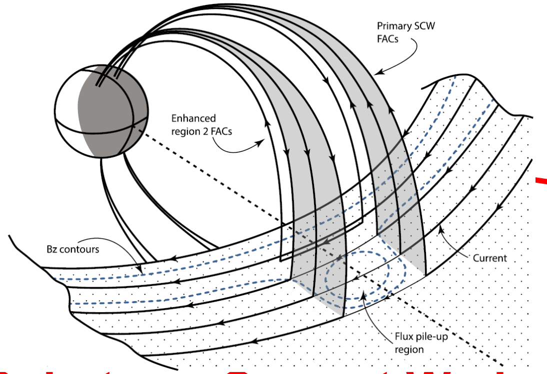
Substorm Current Wedge

Magnetic Indices

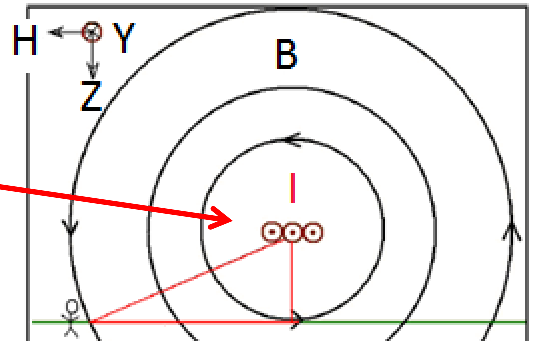


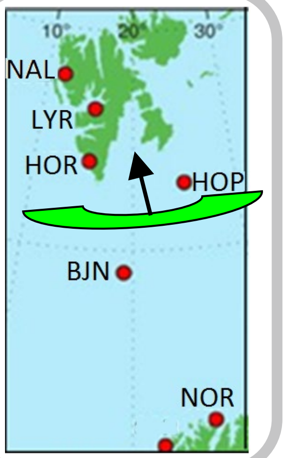
From James Weygand

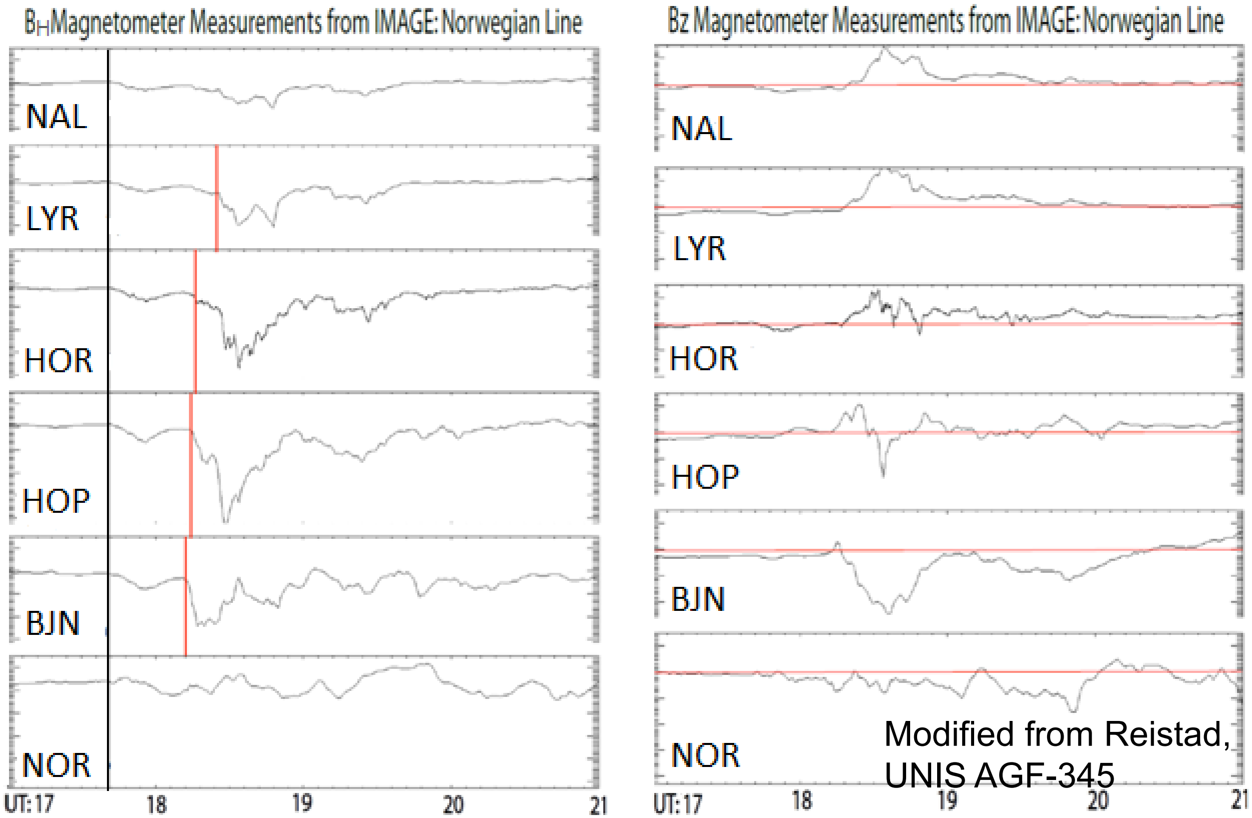
Kepko et al. (Space Science Reviews, 2014)



Substorm Current Wedge





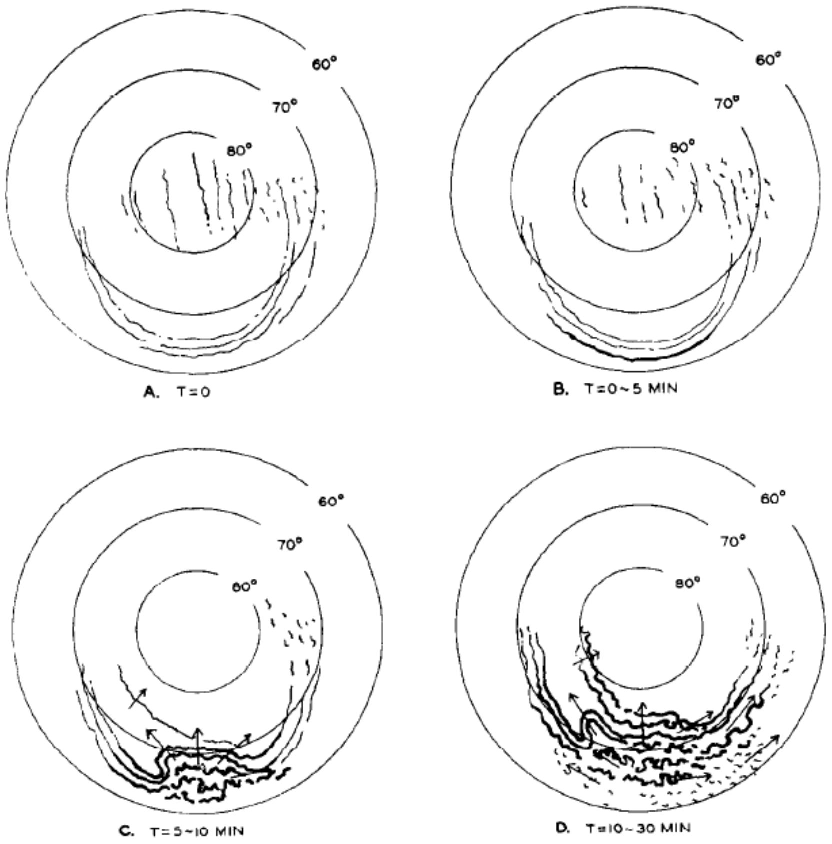


Modified from Reistad, UNIS AGF-345

Substorm Overview

Auroral Onset: The OG Substorm Onset Definition

Auroral Onset

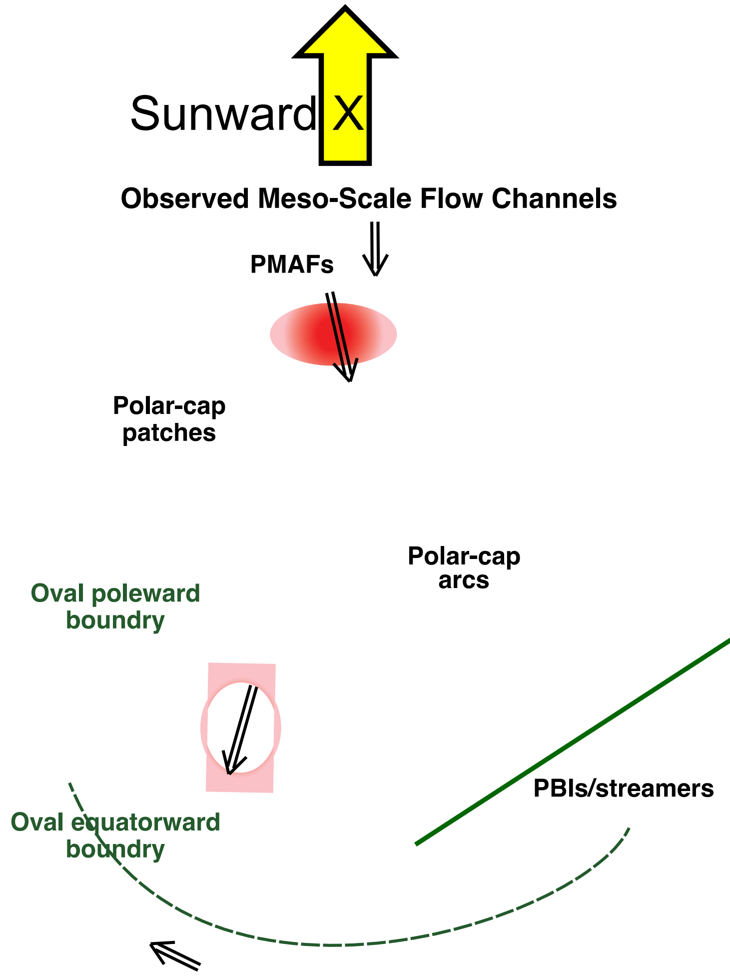


Adapted from Akasofu
(Planetary and Space Sciences, 1964)
886—1578 citations

THEMIS white light All-Sky-Imagers (false color)

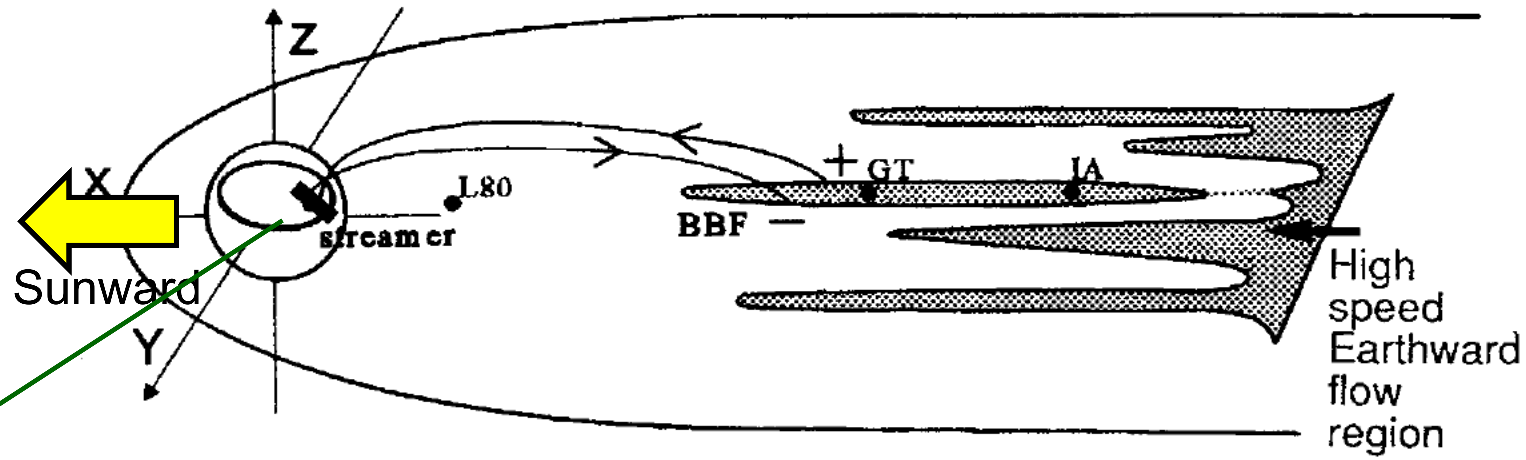
Convection on Mesoscales

Magnetotail Flows and the Ionosphere



Modified from Lyons al. [AGU JGR 2016]

Sergeev et al. [AGU GRL 2000]



Convection on mesoscales can be studied in the magnetosphere by satellites or in the ionosphere by low-earth orbiting satellites or ground-based radar.

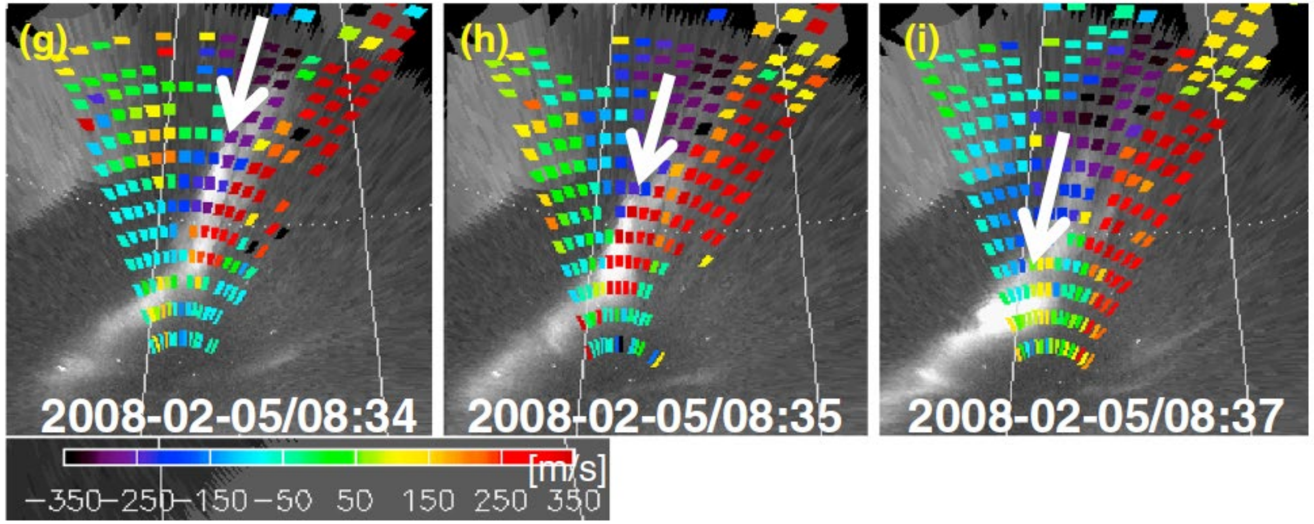
Although, McPherron et al. (2020) found not every flow burst had an associated streamer.

Convection on Mesoscales

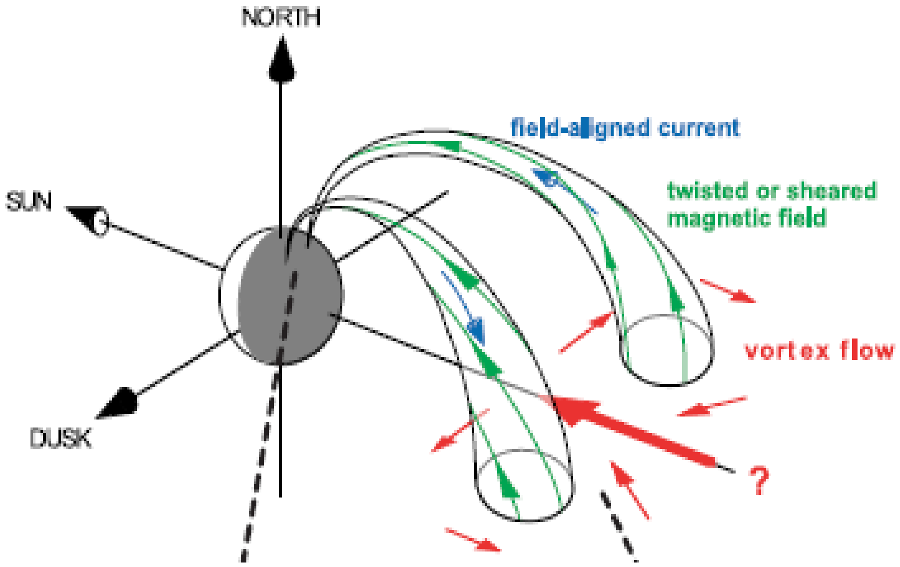
Magnetotail Flows and the Ionosphere

Flow shear from vortex creates field-aligned current, accelerates electrons and creates equatorward-traveling auroral streamers.

Blue=poleward/tailward flow, red=equatorward/earthward flow



Gallardo-Lacourt et al. (AGU JGR, 2014)



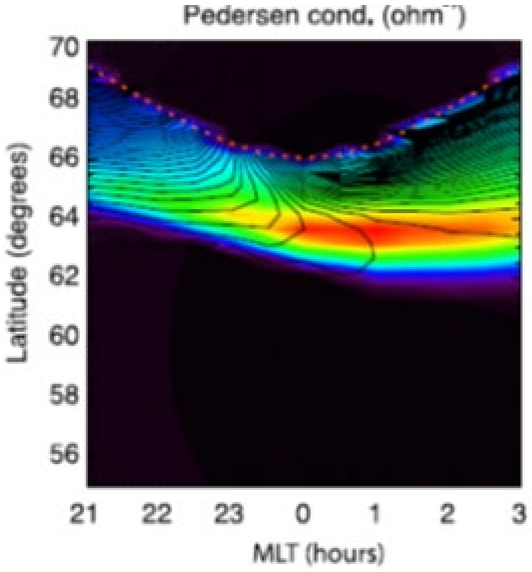
Birn et al. (AGU JGR, 2004)

Note: The optical signature (streamer) lies west of the equatorward/earthward flow and east of the poleward/tailward flow, right at the flow shear region.

Read more!
Henderson et al., 1998; Sergeev et al., 1999, 2000; Lyons et al., 1999, 2002; Kauristie et al., 2000; Zesta et al., 2000; Zou et al., 2010, 2013.

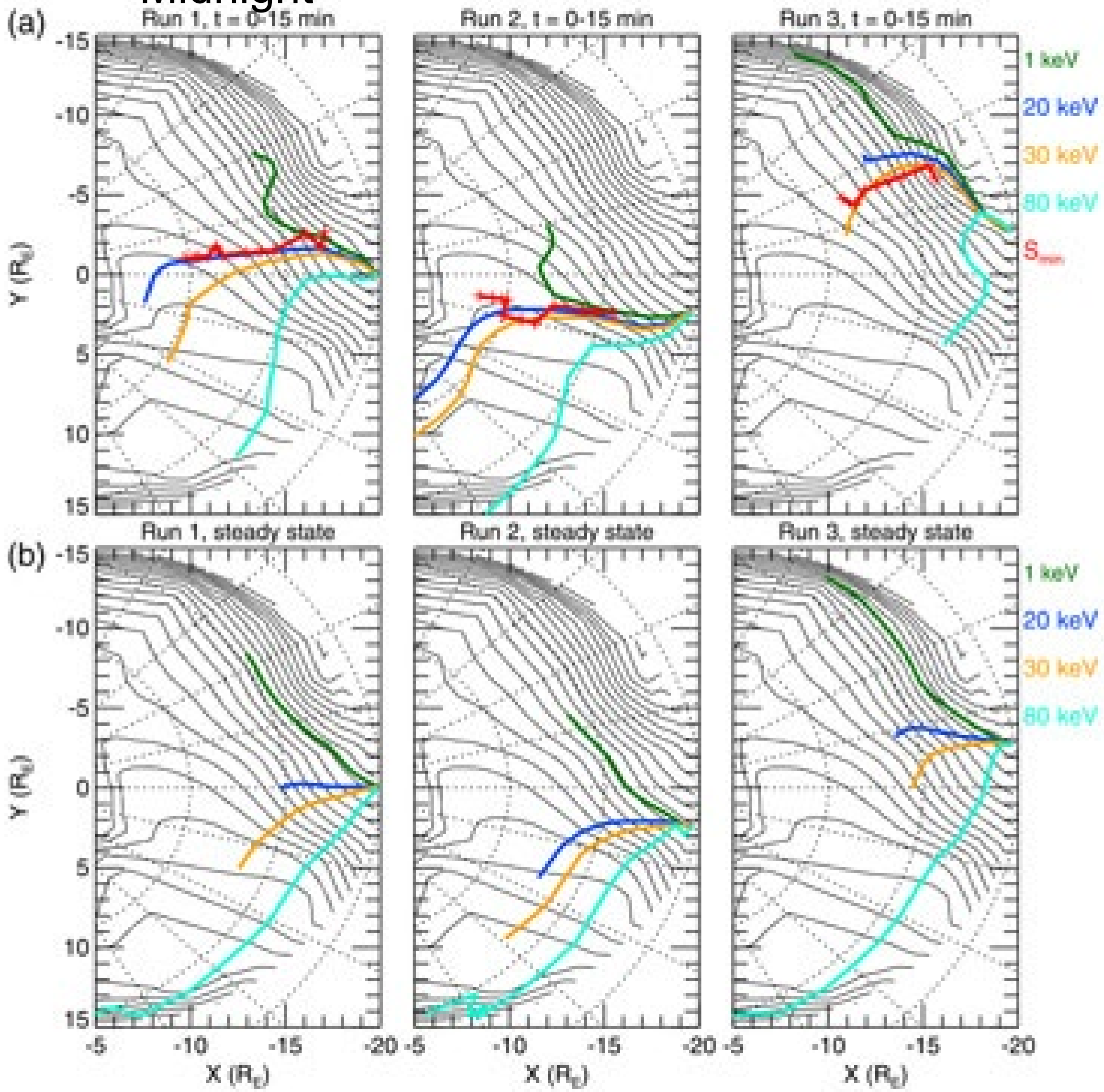
Convection and Ionospheric Feedback

Gkioulidou et al. (AGU JGR 2009)



- Increased conductance gradients from precipitation post-midnight (Gkioulidou et al., 2009)
  - →Shielding Efield increases where conductance is lower (pre-midnight)
  - →Slowed large-scale convection pre-midnight
  - →Ions gradB drift duskward cancels out dawnward ExB
  - →Pre-midnight bubble can penetrate more deeply

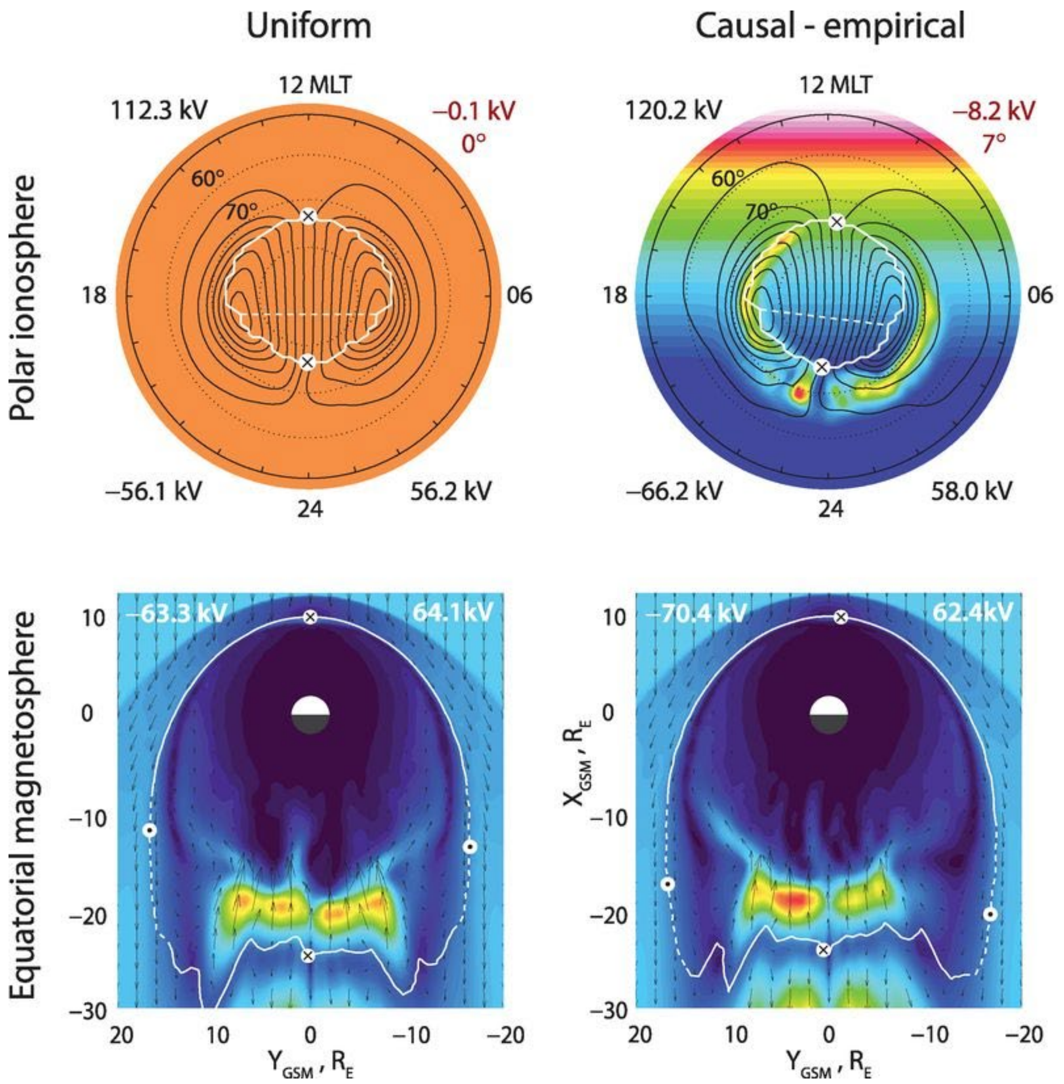
Midnight Pre- Post-



Wang et al. (AGU JGR 2018)

Convection and Ionosphere Feedback:

Meridional gradient in Hall conductance results in enhanced reconnection/flows pre-midnight



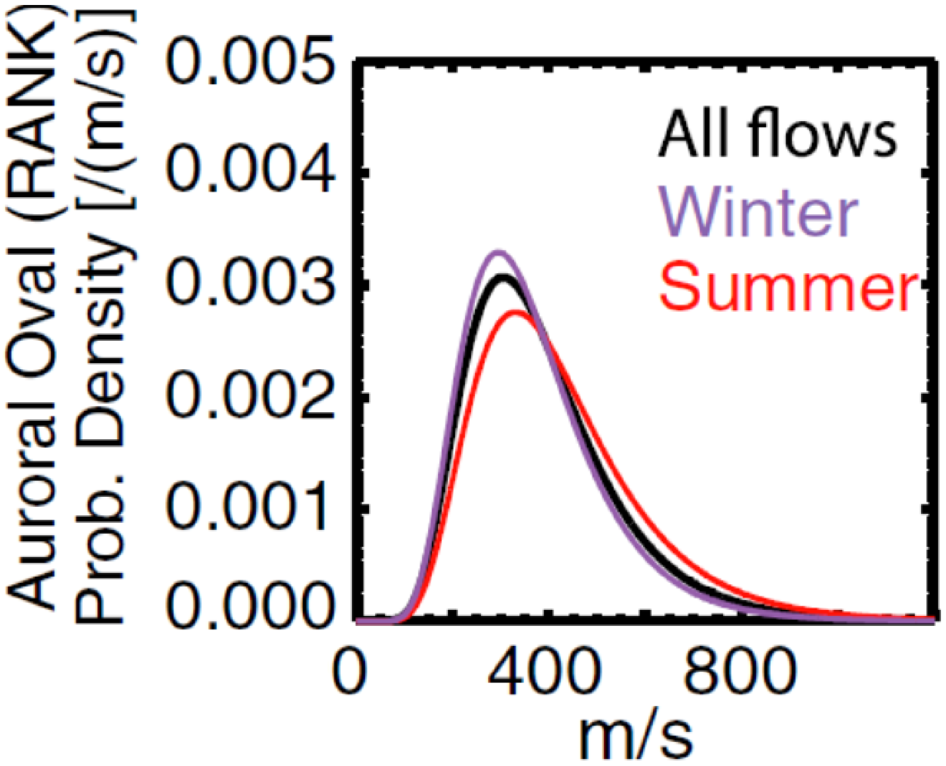
Modified from Lotko et al. (Science, 2014)

Convection and Ionospheric Feedback

Magnetotail Flows and the Ionosphere

- Higher conductivity → Slower flows
  - *More nightside precipitation during the winter → higher conductivity (Ohtani et al., 2009; 2014) → Slower mesoscale flows in the winter*

$$\boldsymbol{J} = \sigma_0 \boldsymbol{E}$$

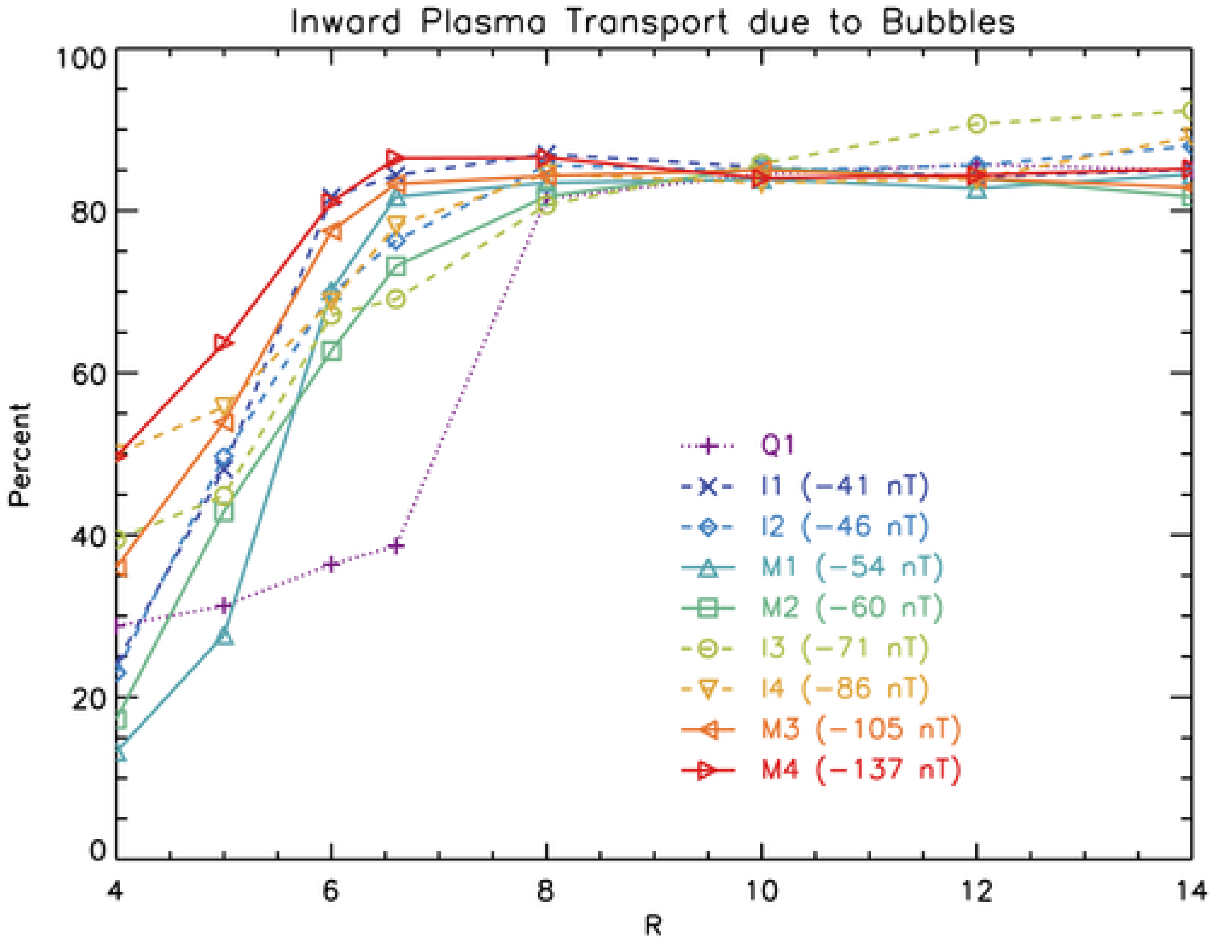


Gabrielse et al. (AGU JGR, 2018)

Plasma Transport

Majority due to Bubbles/Mesoscale flows

MHD (OpenGGCM) +RCM



Cramer et al. (AGU JGR 2017)

Plasma Transport

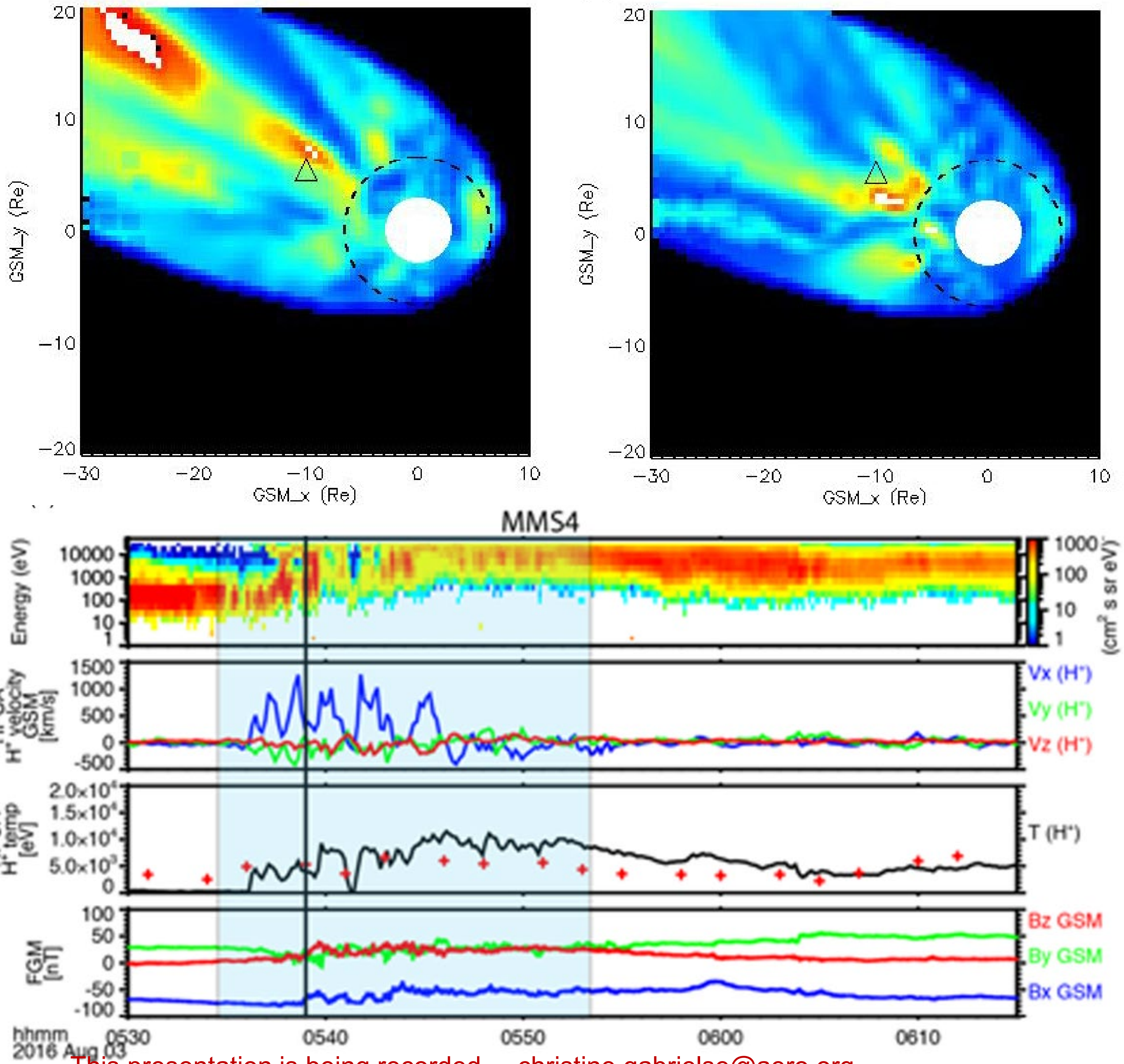
Keesee, GEM 2020 Presentation (see also Keesee et al., 2014)

TWINS: 2D map of ion temperature

Compare with in situ data (MMS)

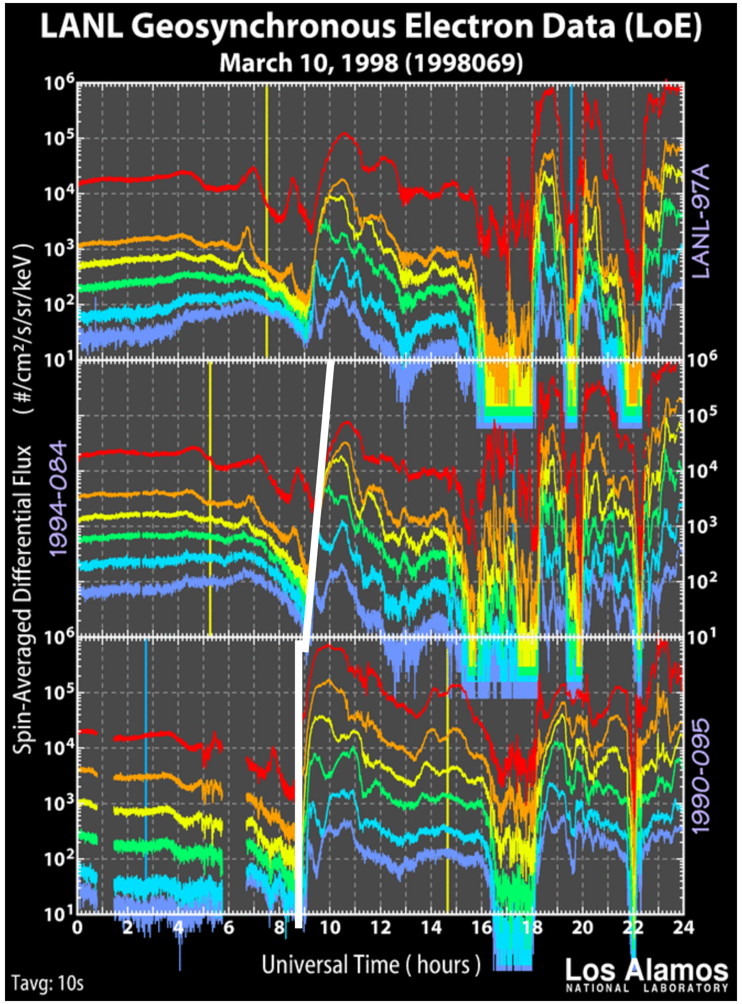
Are particles transported all the way earthward from X-line?

How much energy transferred from X-line to inner magnetosphere?



Particle Transport

Particle Injections



http://hpde.gsfc.nasa.gov/LWS_Space_Weather/LANL_descrip.html

Reeves et al. (Proceedings of the 3rd International Conference for Substorms,1996)

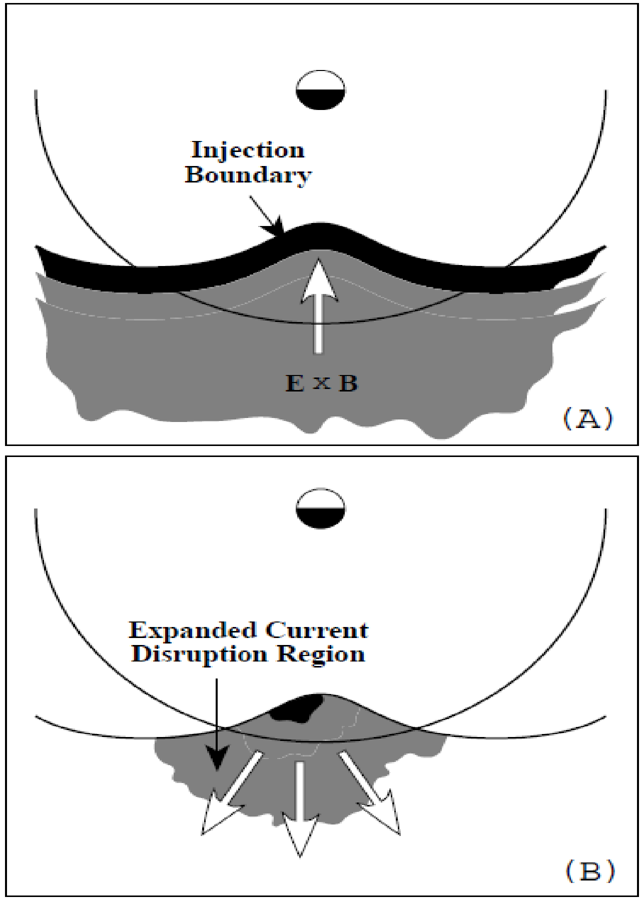


Figure 1: Propagation of the substorm injection region predicted by (A) the Convection Surge model and (B) the Current Disruption model.

Earthward motion of a boundary between hot and cold plasma

(e.g., Mauk and McIlwain, 1974; Konradi et al., 1975; Mauk and Meng, 1983; Reeves et al., 1990; Birn et al., 1997)

Tailward propagation also observed

(e.g., Lopez et al., 1990; Spanswick et al., 2010; Gabrielse et al., 2019)

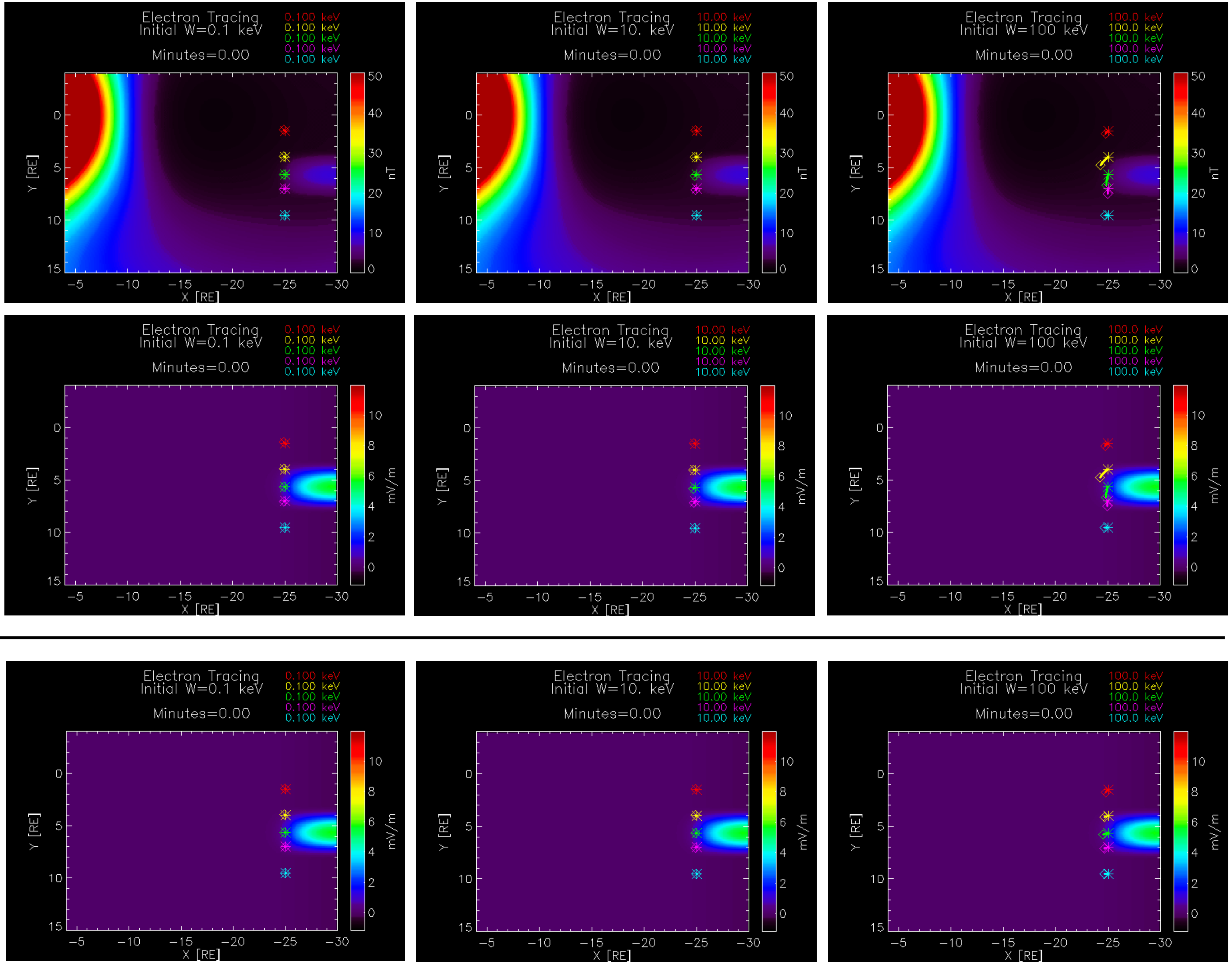
Particle Transport

Initial energy: 0.1 keV 10 keV 100 keV

E and B
B plotted

E and B
E plotted

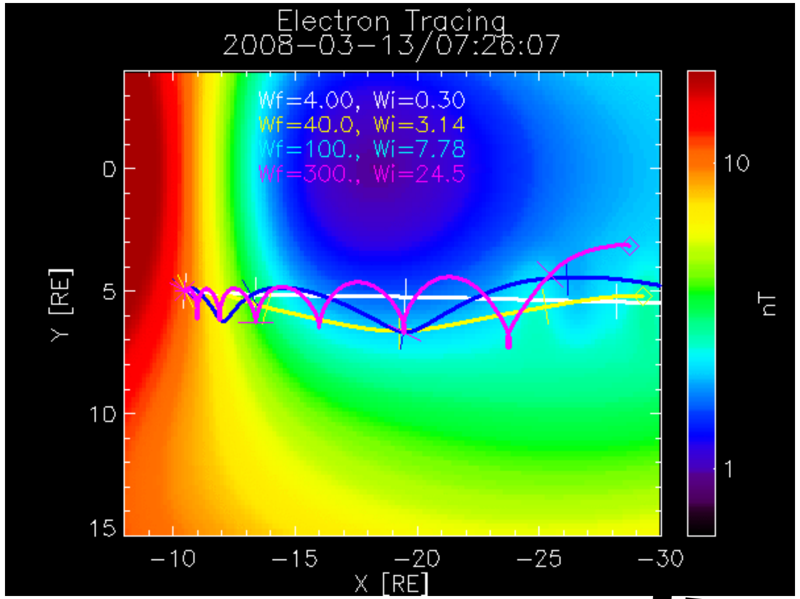
No B
E plotted

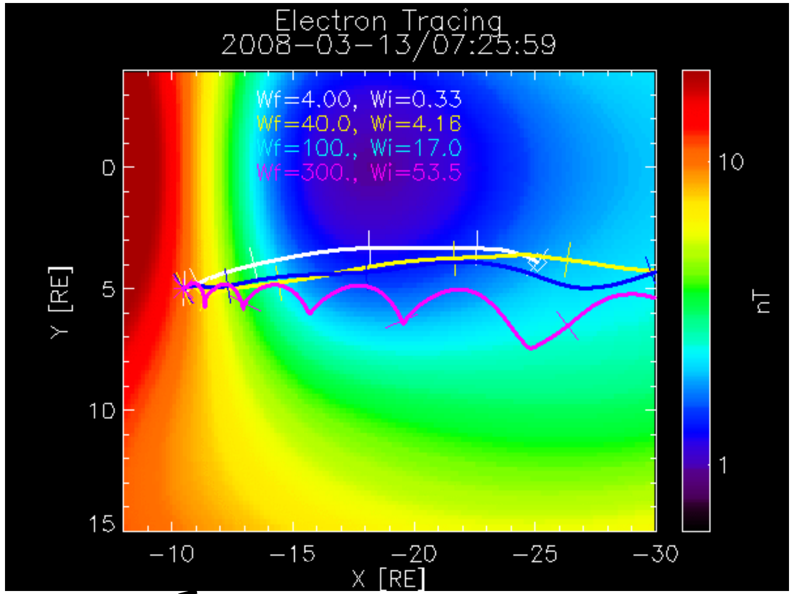


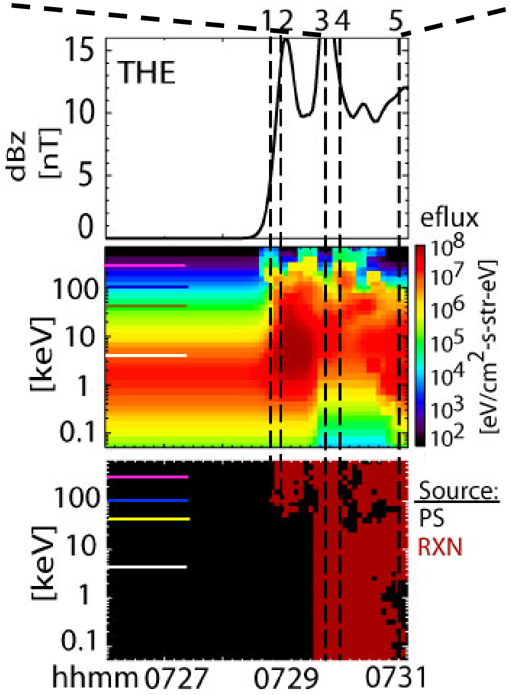
Gabrielse et al.
(AGU JGR, 2016)

This presentation is being recorded. – christine.gabrielse@aero.org

Particle Transport

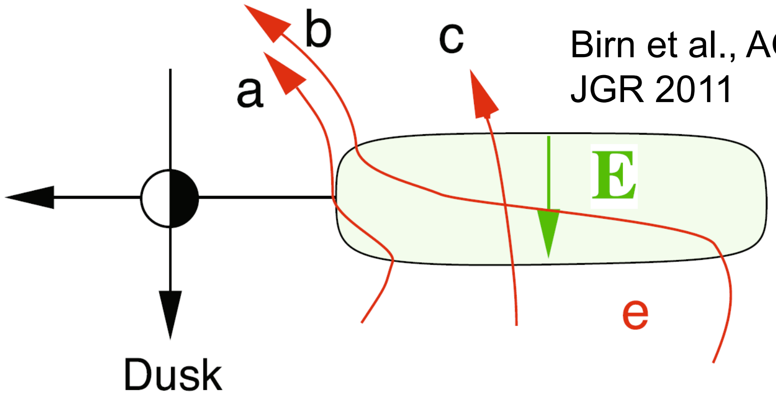






Gabrielse et al. (AGU JGR 2017) for electrons

Explains how very localized DFB can energize particles more than what can be gained by drifting across a narrow potential drop.



Birn et al., AGU JGR 2011

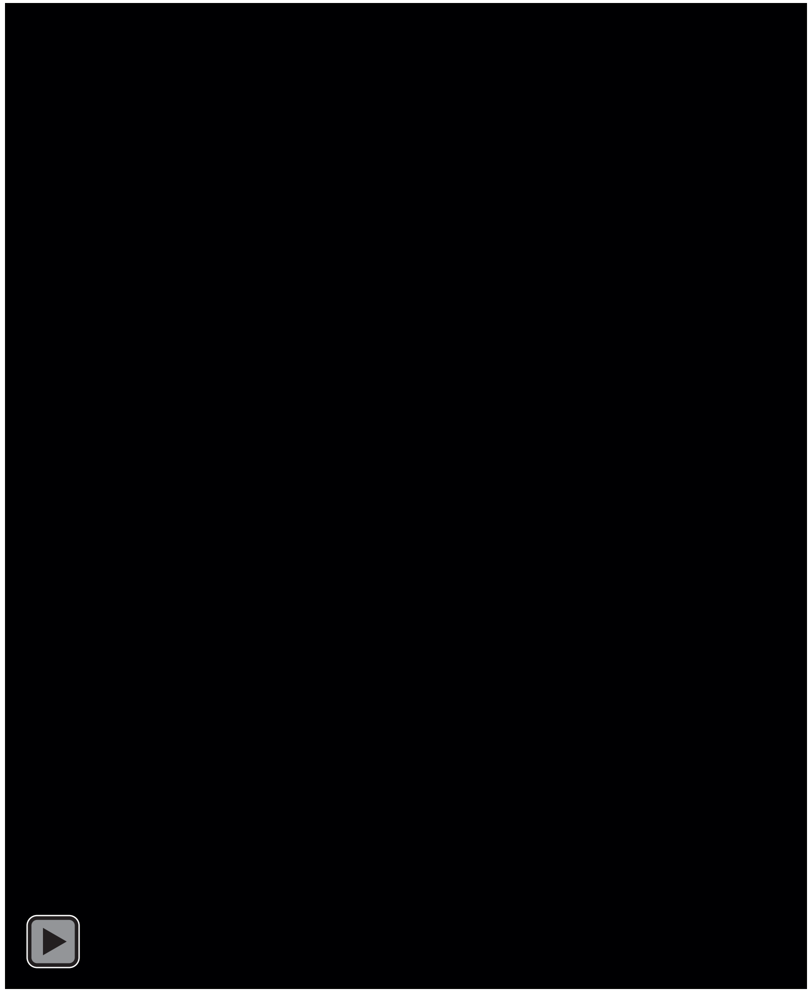
Typical picture without localization in X

Only considering adiabatic energization, largest source is from dB/dt of the dipolarization front a trapped electron finds itself gradB drifting about.

Particle Transport

Both studies below suggest energization can be non-adiabatic

Eshetu et al. (AGU JGR 2019): Electrons in LFM MHD
See also: Kim et al. (2000) and Sorathia et al. (2018) for electron trapping in MHD fields



Ukhorskiy et al. (AGU JGR 2019): Ions in MHD

Recent Work and Looking Forward

Convection and Substorms

- **This talk focused more on IMF -Bz, but IMF +Bz and IMF BY→interhemispheric asymmetries many open questions**
- **Mesoscale convection is important! Especially when discussing substorms.**
  - *Joachim Birn will talk more next week about the magnetotail and substorms!*
- **Working on quantifying their contribution**
  - *Newest papers hot off the press:*
    - GEM Focus Group on Magnetotail Dipolarization and its Effects in the Inner Magnetosphere: bit.ly/DIPFG
- **Quantify contributions to radiation belts and ring current**
  - *Check out Drew Turner's seminar in this series on radiation belts in two weeks!*
- **Vast implications on the ionosphere-thermosphere-mesosphere**
  - *GEM FG 3D Ionospheric Electrodynamics and Its Impact on the Magnetosphere-Ionosphere-Thermosphere Coupled System:* bit.ly/IEMIT
  - *Global models (e.g., GITM) now computationally capable of including mesoscales (flows, Efields, precipitation, etc.)*
  - *Models need data inputs to inform how to run!*
  - *Feedback has implications on magnetosphere*
- **I repeat other speakers' call for multi-point observations**
  - *Spread in azimuth (MLT) and radial distance*
  - *Observe aurora/precipitation simultaneously to in situ particle data*
  - *Coordinate with improving modeling efforts that include smaller scales*
  - *GEM FG System Understanding of Radiation Belt Particle Dynamics through Multi-spacecraft and Ground-based Observations and Modeling:* bit.ly/RBMulti