Reading the Aurora: A tool for Interconnections

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Thanks to: *Dave Evans, Odile de la Beaujarière, John Samson, Richard Walterscheid, Andy Christensen, Eric Donovan, Mike Ruohoniemi, Vassilis Angelopoulos, Naomi Maruyama, Asti Bhatt, Elizabeth Kendall, Shunrong Zhang, Anthea Coster, BIll Bristow, Yue Deng, Aston Reimer, Roger Varney, Don Hampton, Xueling Shi*

And to my contributing students, post-docs+: *Eftyhia Zesta, Gerard Blanchard, Chih-Ping Wang, Thanasis Boudouridis, Shasha Zou, Xiaoyan Xing, Toshi Nishimura, Yong Shi, Ying Zou, Bea Gallardo, Jiang Liu, Matina Gkioulidou, Chao Yue, Boyi Wang, Victor Pinto, Yuzhang Ma, Christine Gabrielse, Sheng Tian, Sneha Yadav*

- **Basic background.:** Why **"Reading" Aurora can identify flow channels**
- **Reading shows**
  - **Structured flow from dayside to nightside**
    - **Connections to magnetosheath structure** from dayside to nightside through polar cap field lines**.**
  - **Connection to nightside oval flow channels**
    - **Driven, localized reconnection**
  - **Oval flow channel/Streamers**
    - **An Elemental Feature of** Nightside Magnetic **Activity**
    - Application to **different nightside disturbances**
    - Driving of **nightside LSTIDs, neutral winds**
- **Aspects for future**

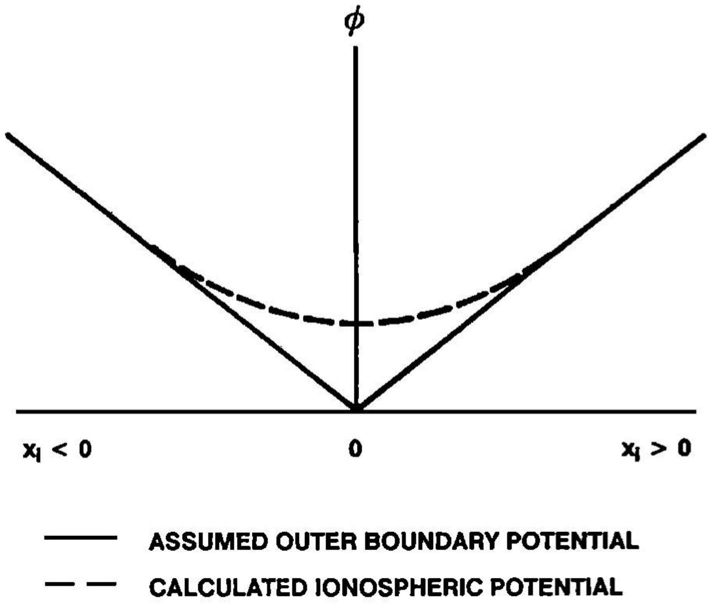
Background 1

- 1970's: High iono. densities, few collisions ⇒ **auroral field-lines "infinitely conducting"**
  - Wave-particle **"Anomalous resistivity" broadly** considered.
- But **max maximum $j_{||}$ from ionospheric** particles:
  - Elec. moving up: downward $J_{||}$ ~10 to 100 $\mu A/m^2$
  - O^+ moving up: upward $J_{||}$ ~0.06 to 0.6 $\mu A/m^2$
  - Auroral $J_{||}$ ~ 1-30 $\mu A/m^2$!: No infinite conductivity for upward $J_{||}$.
- For isotropic plasma sheet elec., **get $J_{||}$ ~1 $\mu A/m^2$**.
  - **Not large enough!**
  - **But $\Delta\phi_{||}$ > 0 enhances electron flux in loss cone, thus enhances $J_{||}$**
- Then **obscure Knight** [1973]: Derived $J_{||}$ vs. $\Delta\phi_{||}$
  - Gives typical auroral $j_{||}$ for typical $\Delta\Phi_{||}$!
  - Assume $1 \ll \dfrac{e\Delta\phi_{||}}{K_{th}} \ll B_i / B_{\phi_{||}}$
    - K_{th} = elec. thermal energy ; B_i = B ionosphere; $B_{\phi_{||}}$ = B at top of $\Delta\phi_{||}$;
    - Knight relation simplifies: $j_{||} = k\Delta\phi_{||}, \ \ where \ \ k = \dfrac{e^2 n_e}{(2\pi m_e K_{th})^{1/2}}$

Knight relation with M-I coupling relates arcs to flows!

- Assume discontinuity in magnetospheric electric field (e.g. at duskside convection reversal):
  - Solid line: **Magnetospheric potential ϕ** (above **$\Delta\phi_{||}$**) vs. distance x_i mapped along **B** to ionosphere.
  - **Solve for ionospheric potential ϕ_i** vs. x_i: dashed line

$$j_{||} = -\frac{\partial}{\partial x_i} I_P = \underline{\frac{\partial}{\partial x_i}\left(\Sigma_P \frac{\partial \phi_i}{\partial x_i}\right)} = k(\Delta\phi_{||}) = \underline{k(\phi_i - \phi)}$$

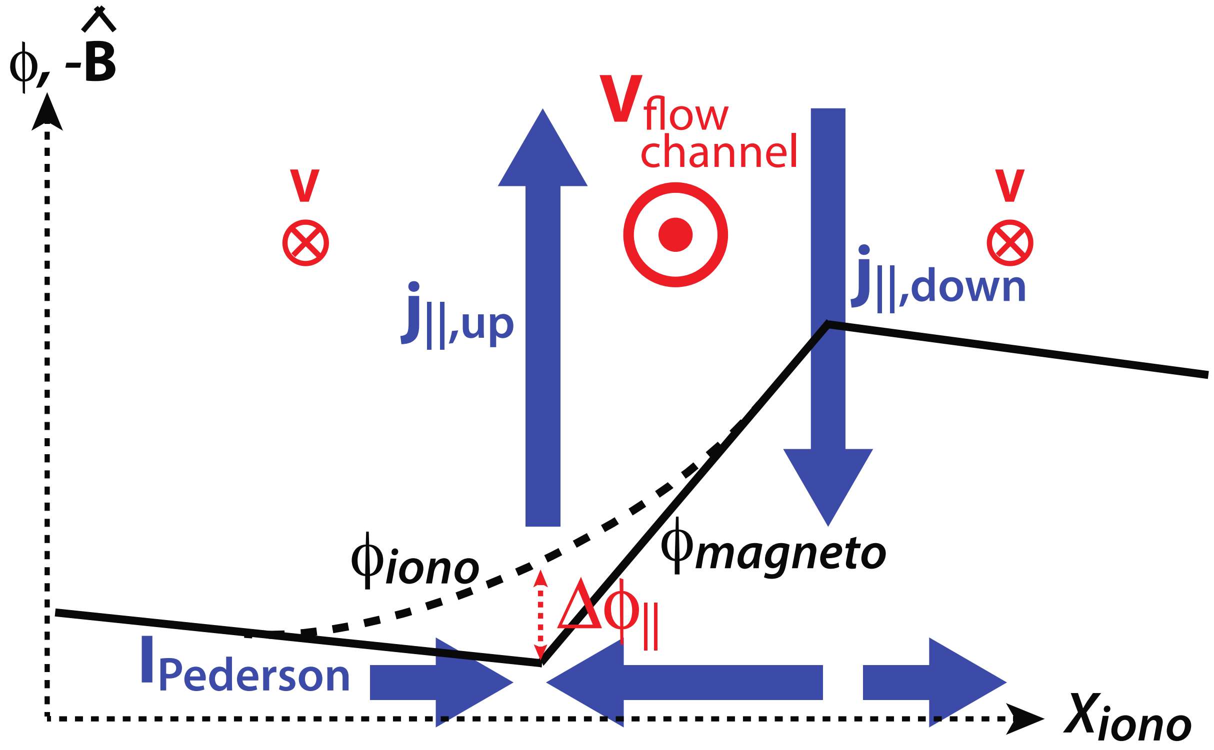


  - Let $\Sigma_P = \text{constant and } \phi(x_i) = \begin{cases} -E_{1,i}x_i, & \text{at } x_i < 0 \\ -E_{2,i}x_i, & \text{at } x_i > 0 \end{cases}$
  - From underlined terms: $\underline{\frac{\partial^2 \phi_i}{\partial x_i^2} = \frac{k}{\Sigma_P}\left[\phi_i + \begin{Bmatrix} E_{1,i} \\ E_{2,i} \end{Bmatrix} x_i\right]}$
  - Solution for $\Delta\phi_{||}$ ($x_i \rightarrow \infty$) = 0: $\Delta\phi_{||} = \Delta\phi_{||,o}\, e^{-\frac{|x_i|}{x_w}}$ where $x_w = (\Sigma_P/k)^{\frac{1}{2}}, \quad \Delta\phi_{||,o} = \frac{x_w}{2}(E_{1,i} - E_{2,i})$

- Taking ionospheric Σ_P = 5 mhos, magnetospheric n = 1 cm-3, Kth = 0.25 keV gives:
  - A natural width: X_w = 54 km
  - A peak field-aligned potential drop: $\Delta\phi_{||,0}$ = 2.5 kV for **ΔE_i** = 100 mV/m
  - Get an auroral arc!

See *Lyons* (1980;1981)

For Flow Channel: Knight relation with current continuity relates arcs to flows!

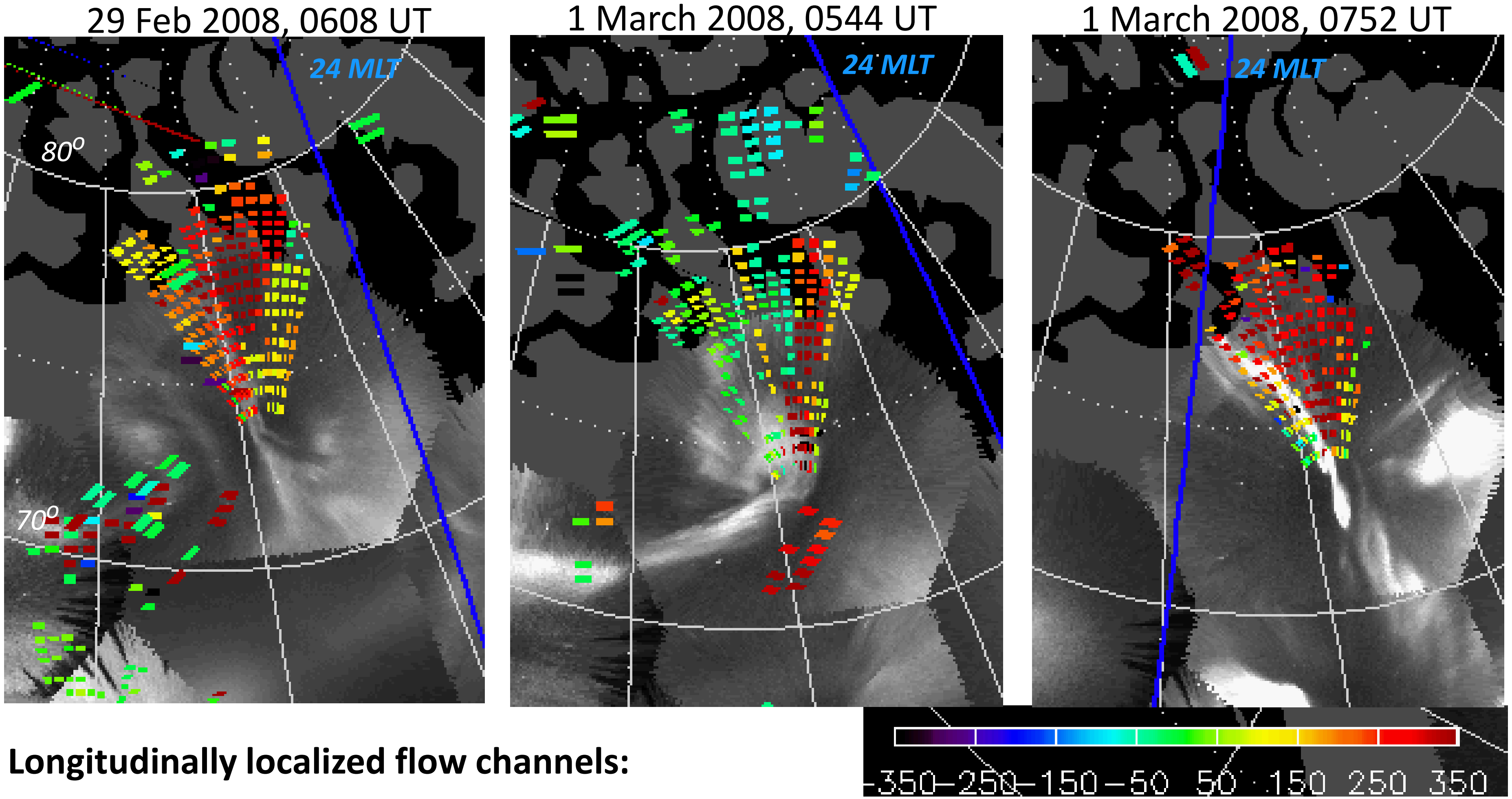


Arc to right of flow channel center, **downward $J_{||}$ to left**

Can see arcs, and thus imply the flow channels: ***Reading the aurora***

Verfication: THEMIS ASI image and SuperDARN l-o-s flows

[Bea Gallardo-Lacourt+, 2013]



Longitudinally localized flow channels:

- Extend from Λ = 80^o to east side of 2 streamers, 1 Harang aurora
- Along streamer edge as far equatorward as echoes
- Enter oval from polar cap

Polar Cap Convection:

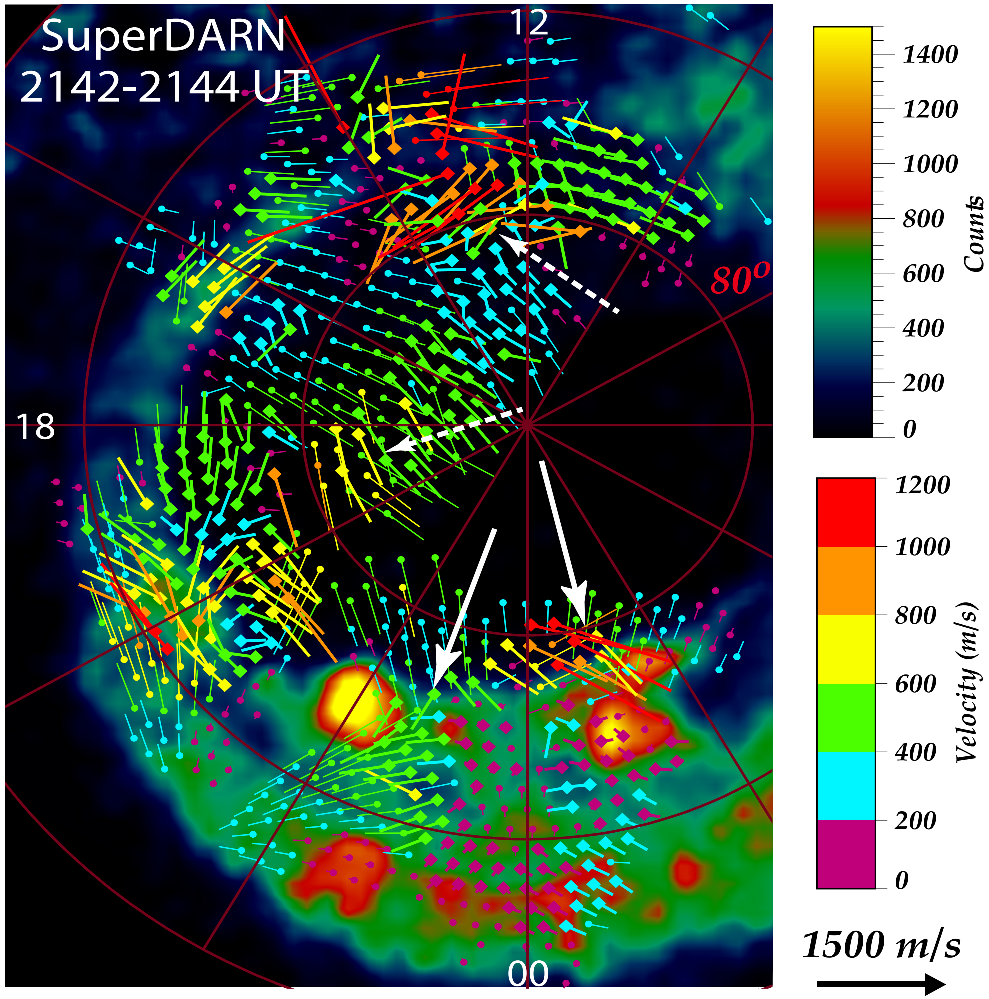
- Do **not** have good global coverage
- Thus, traditionally **use statistical patterns**
  - Smooth, 2-4 cells, varying $\Delta\phi_{pc}$

Best global coverage SuperDARN example *(that I have seen)*

- Much localized flow structure
- **Related to observable aurora** on nightside: PBIs

Much about structure available from auroral observations!

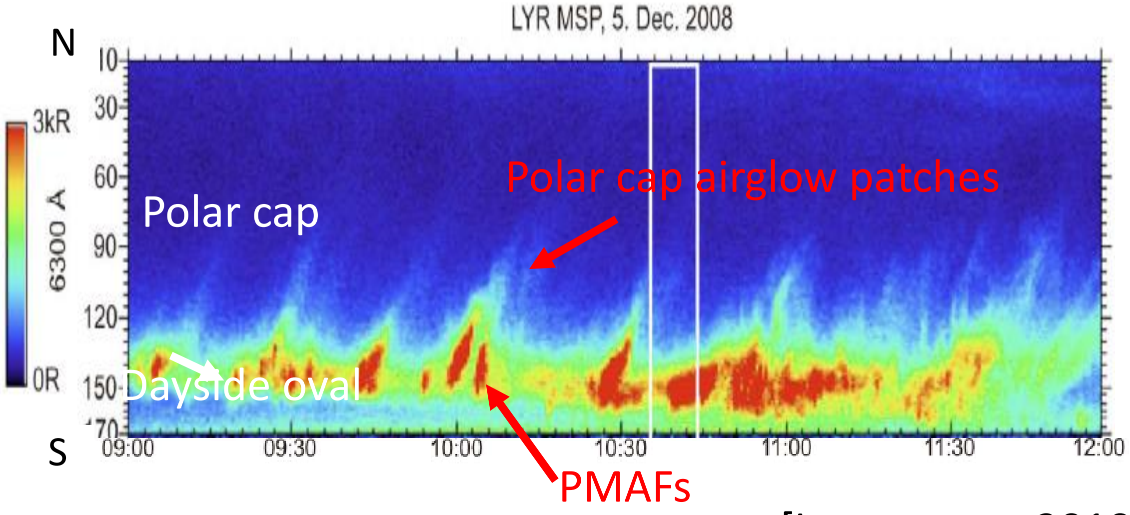
SuperDARN / IMAGE-WIC [Yong *Shi*+, 2012]



Structured Flow from Dayside to Nightside Through Polar Cap

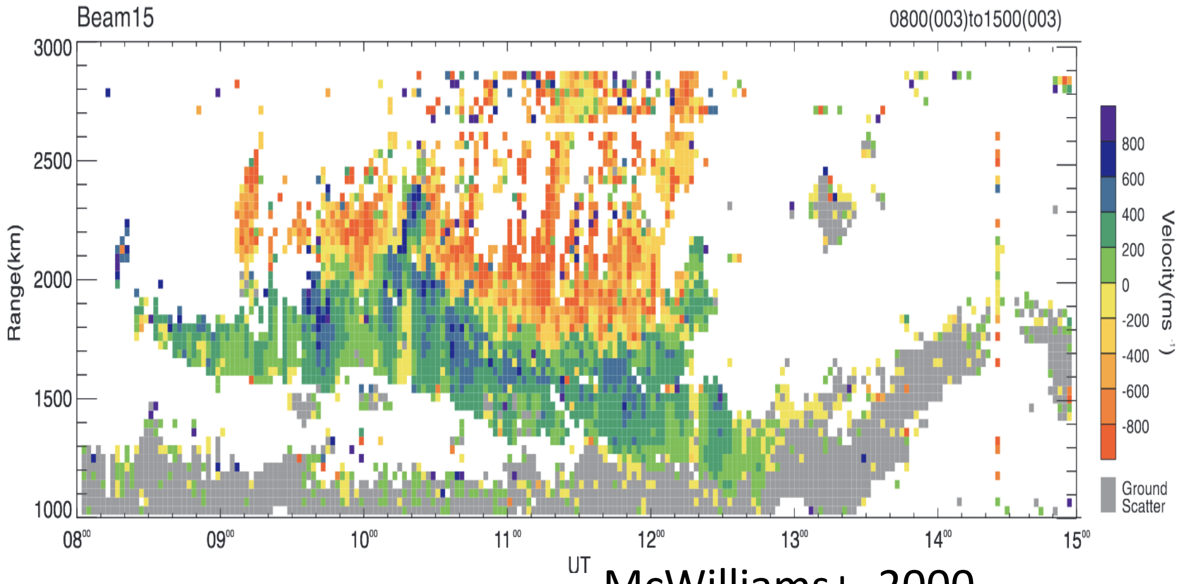
Structuring Starts near Dayside open-closed field-line boundary

Dayside 630.00 nm optical emissions



[Lorentzen+, 2010]

SuperDARN CUTLASS radar, poleward looking beam on dayside



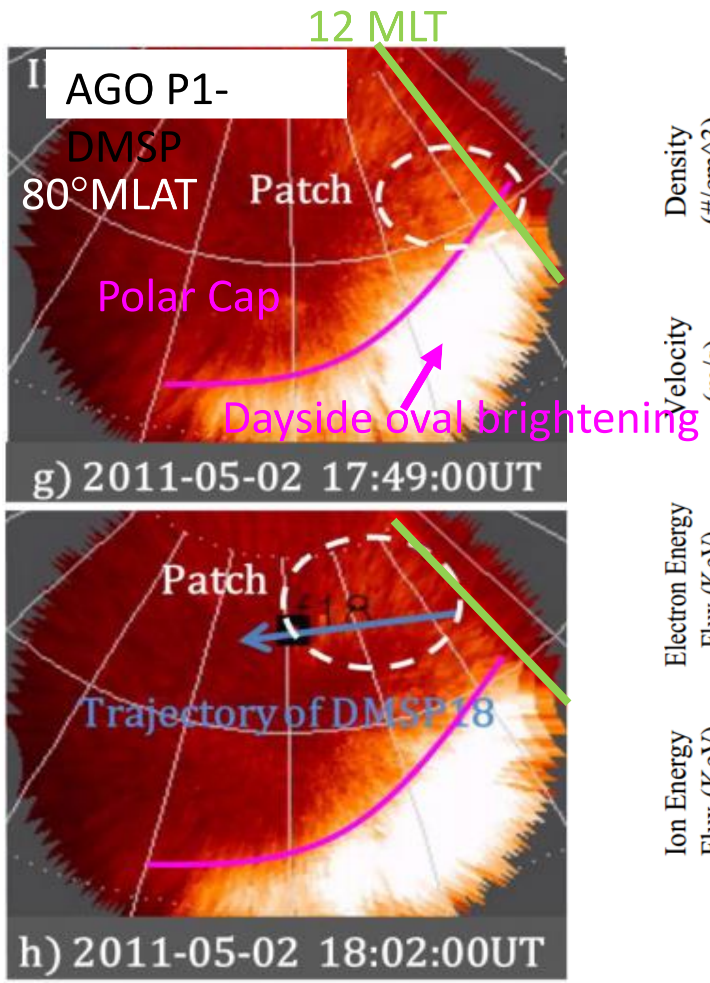
McWilliams+, 2000

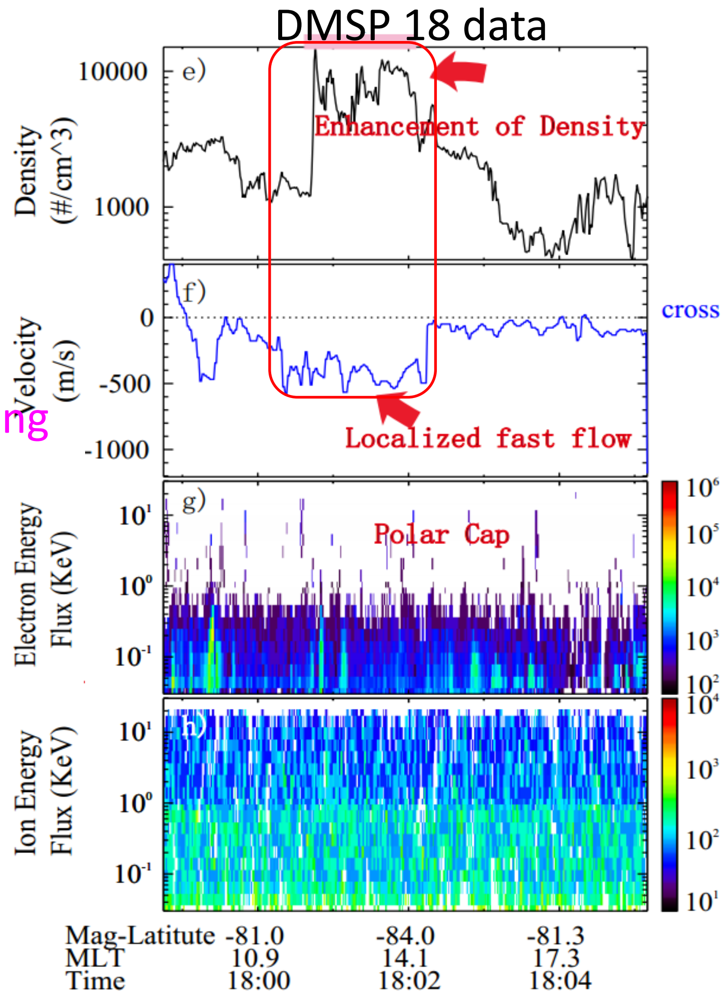
E-field connections to dayside magnetosheath highly variable

Likely ***associated with magnetosheath plasma and B variability***

Move into dayside polar cap as fast flow channels (coming from dayside cusp)

***Boyi Wang+* [2016]**
(Also Y. Zou+, 2015; deeper in polar cap)

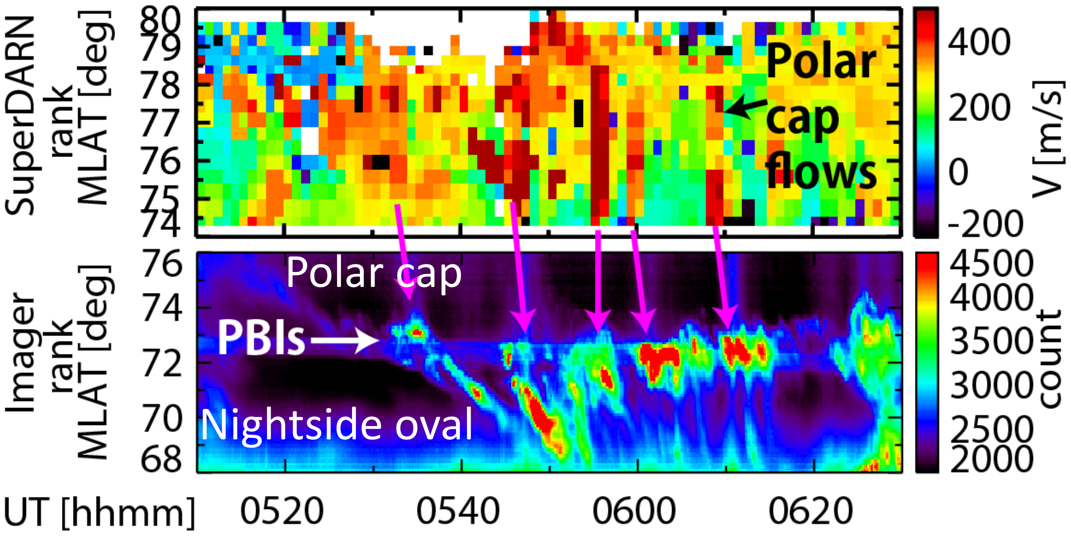


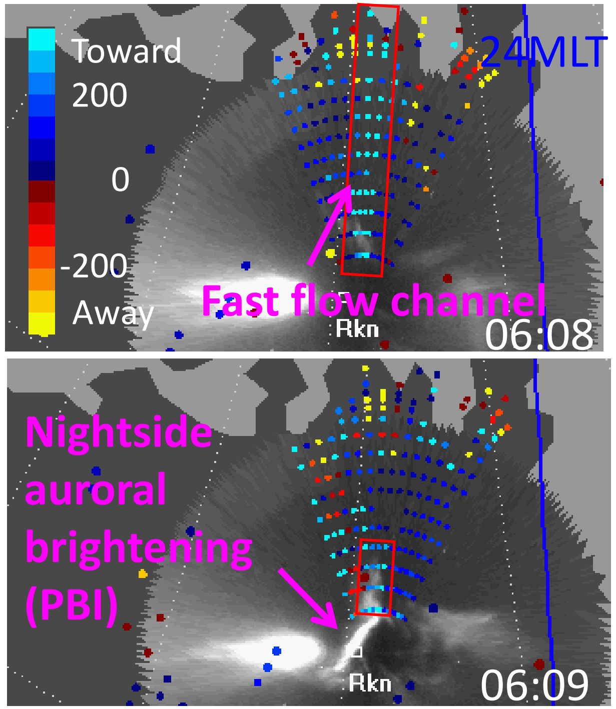


- A dayside polar cap patch detached from a dayside PMAF.
- The patch/high density plasma associated with localized fast flow channel.
  - → **Dayside fast flows/structured connections to magnetosheath propagate deep into the polar cap.**
  - → **Revealed by patches, polar cap arcs**

Flow channels reach and cross nightside polar cap boundary

Nightside transients



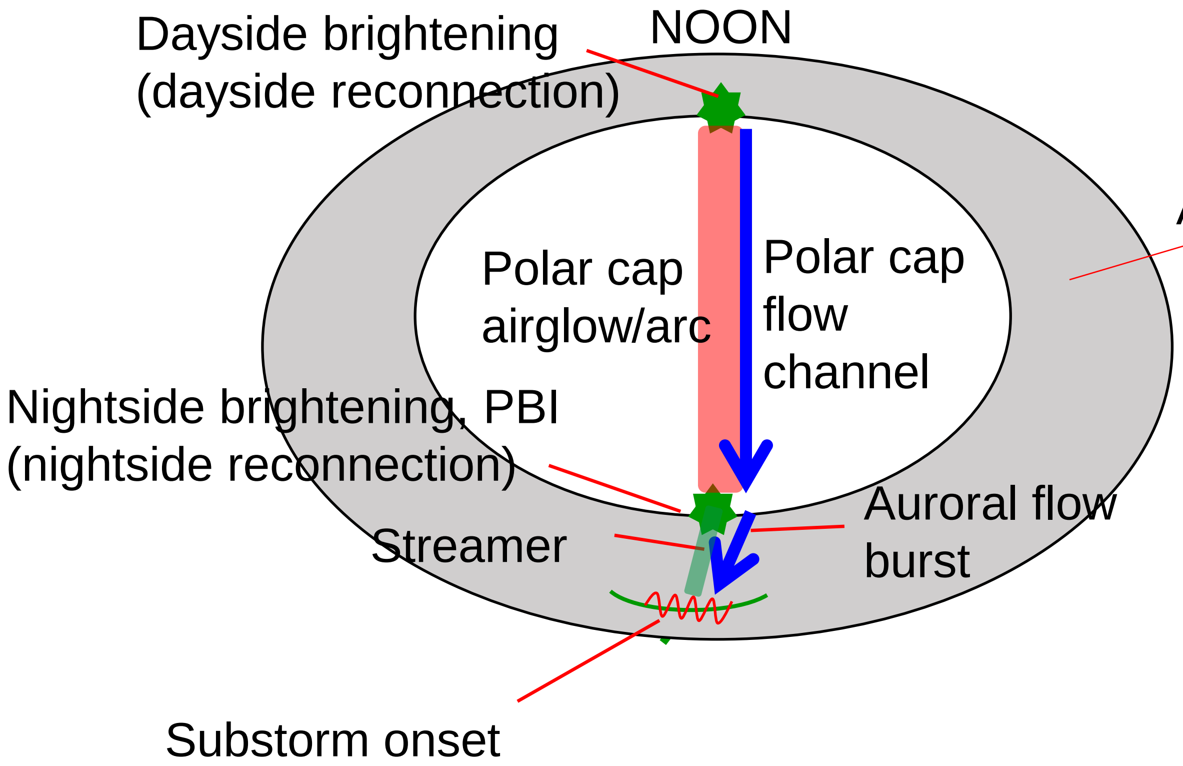


[de la Beaujardiére+, 1994; Nishimura+, 2010; Lyons+, 2011; Pitkänen+, 2011; Y. Zou+, 2014]

Structured connections to magnetosheath reach nightside p.c. bndry

Aurora ⟹ p.c. flow channels **drive highly variable nightside reconnection** and **enter plasma sheet**

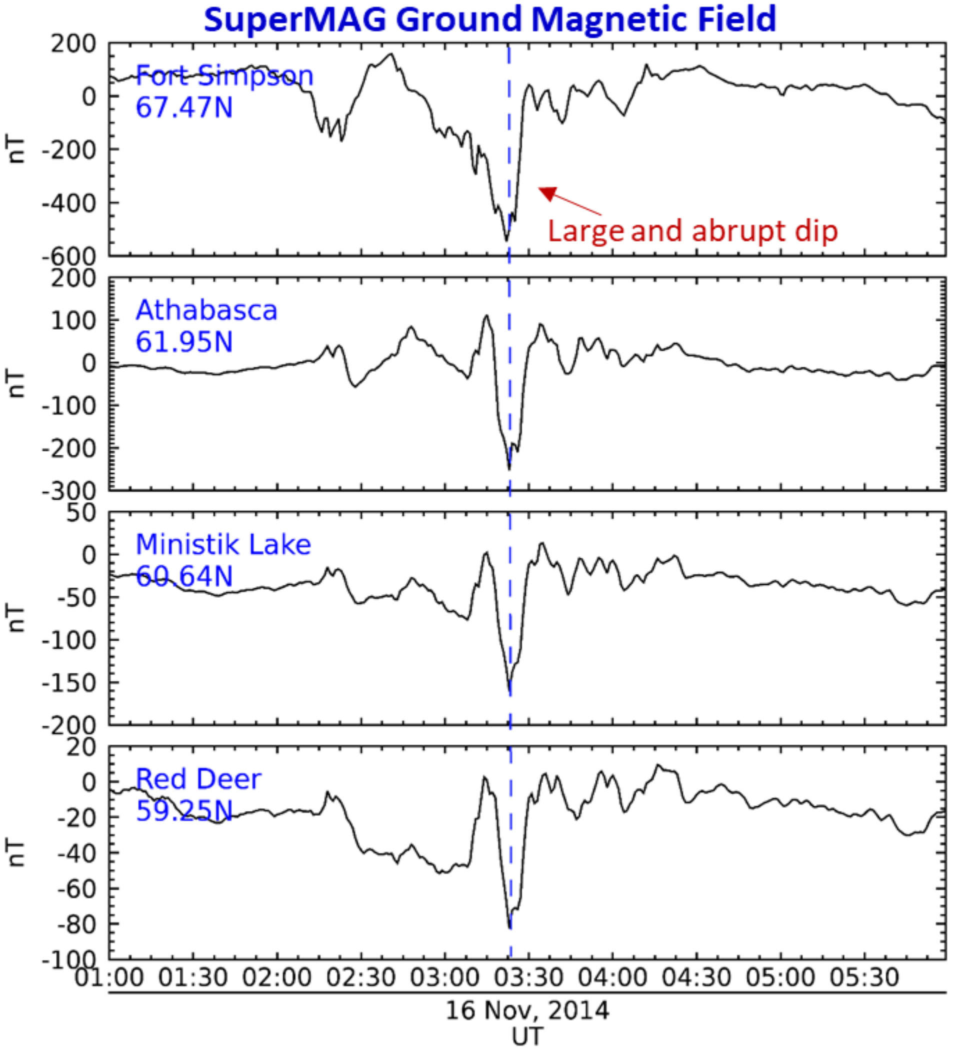
Summary of Flow Channel Propagation through Polar Cap



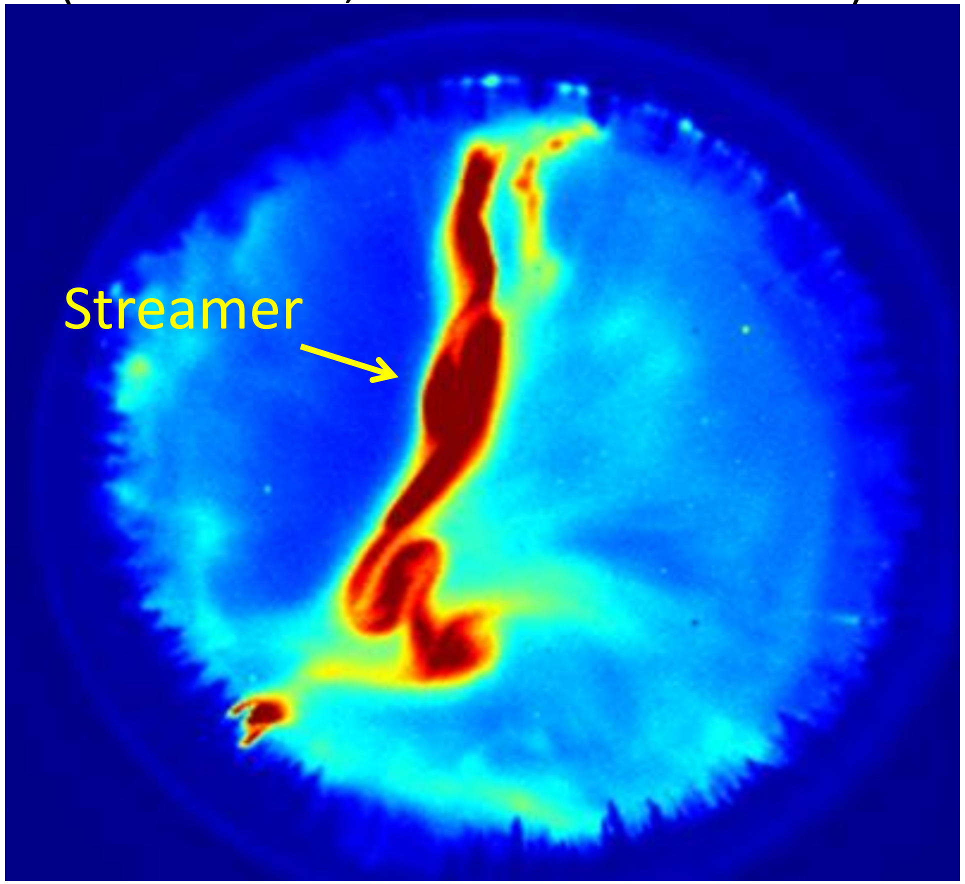
- **Flow channels** from dayside to nightside, trigger **nightside auroral brightening**.
- Some **lead to flow channels/streamers** in plasma sheet, auroral oval
  - Impinging channels **must lead to plasma with lower entropy** than surroundin**gs**
    - **New plasma from** lobes with different characteristics**?**
    - Reduced entropy via **driven localized reconnection?**
- **Dayside-polar cap-nightside interaction by flow channels:**
  - **Far from adequately studied**
  - **Large impact** on Space disturbances.

Streamers/Flow Channels: An Elemental Feature and Driver of Nightside Activity

Oval flow channel/Streamer: Elemental Feature of Much Nightside Magnetic Activity
(Many channels identifiable with auroral observations only!)



THEMIS White Light Imager
(well-defined, well isolated streamer)



0324 UT

Sneha Yadav+, in prep.,

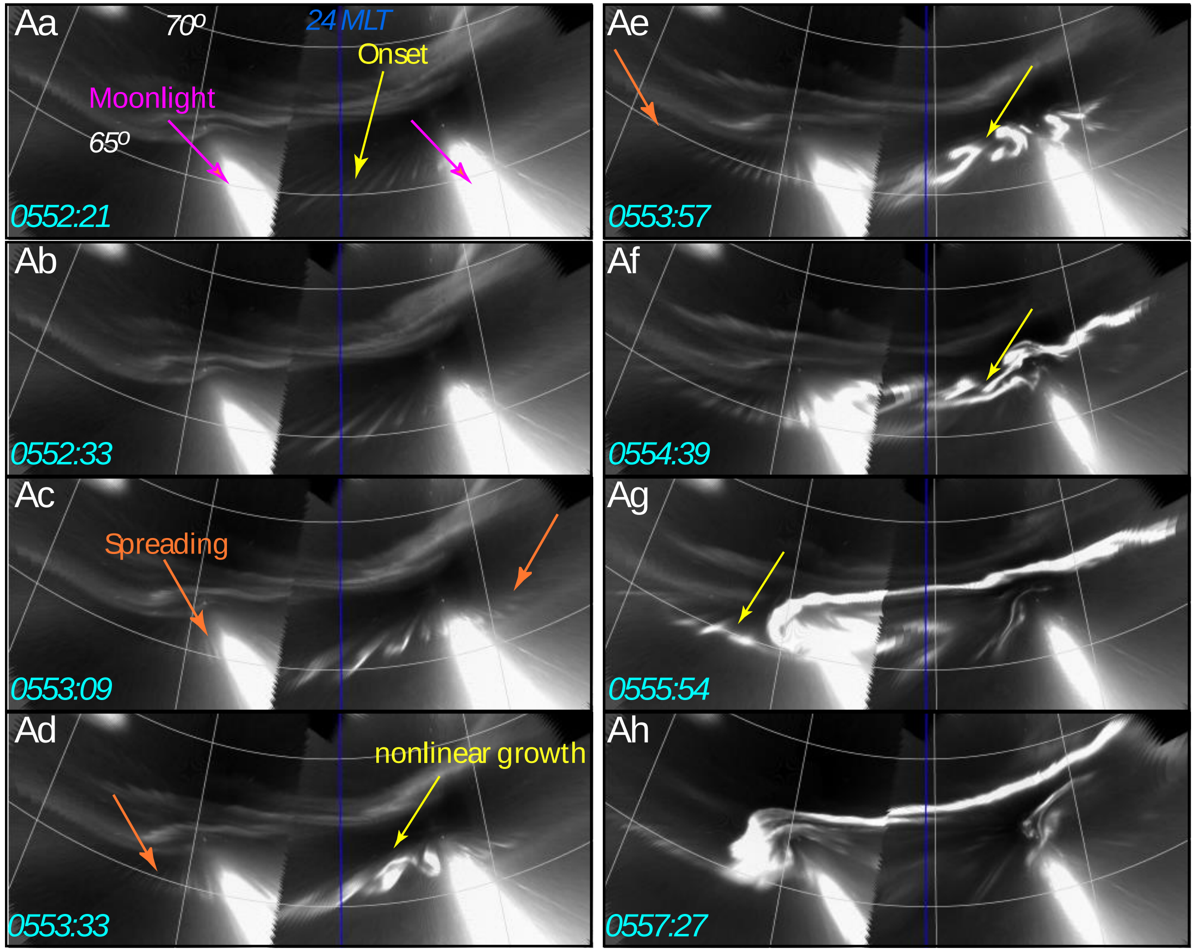
see *Cross-Scale Electrodynamics in MIT Processes*

Thurs. 1330-1530, Topaz 2; also Wed. poster

What is an auroral substorm and connection to streamers?

- **Initial brightening along E-W oriented arc** near e**quatorward boundary of auroral oval** (*Akasofu*, 1964; *Samson+*, 1992; *Deehr and Lummerzheim*, 2001)
- **Starts as "beading"** (*Donovan+*, 2006; *Liang+, 2008*; *Henderson+*, 2009, *Rae+, 2010*)

2007 March 7



Beading

- **Seen for virtually all cases** (100's examined) (*Kalmoni+*, 2017; *Nishimura+*, 2016)
- Initially **aligned E-W** over limited longitude range.
- **Regularly spaced** like waves.
- **Grow in intensity and amplitude** as wave structures **expand longitudinally**
- Develop **non-linearities** that form active aurora of a substorm

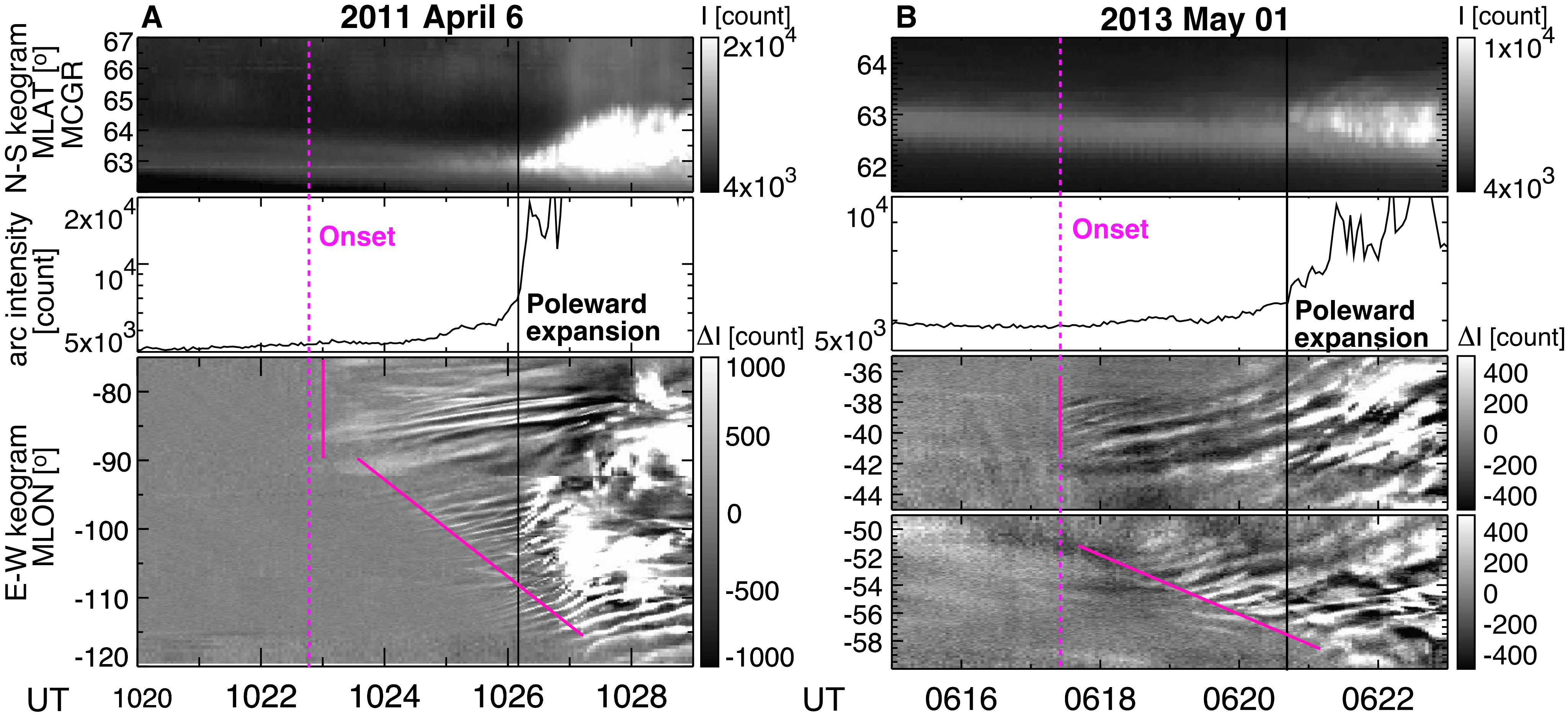
Aurora: Classic signature of instability

- **Instability E-W aligned**
- **Onset within inner plasma sheet**
- **No streamer until non-linearity**

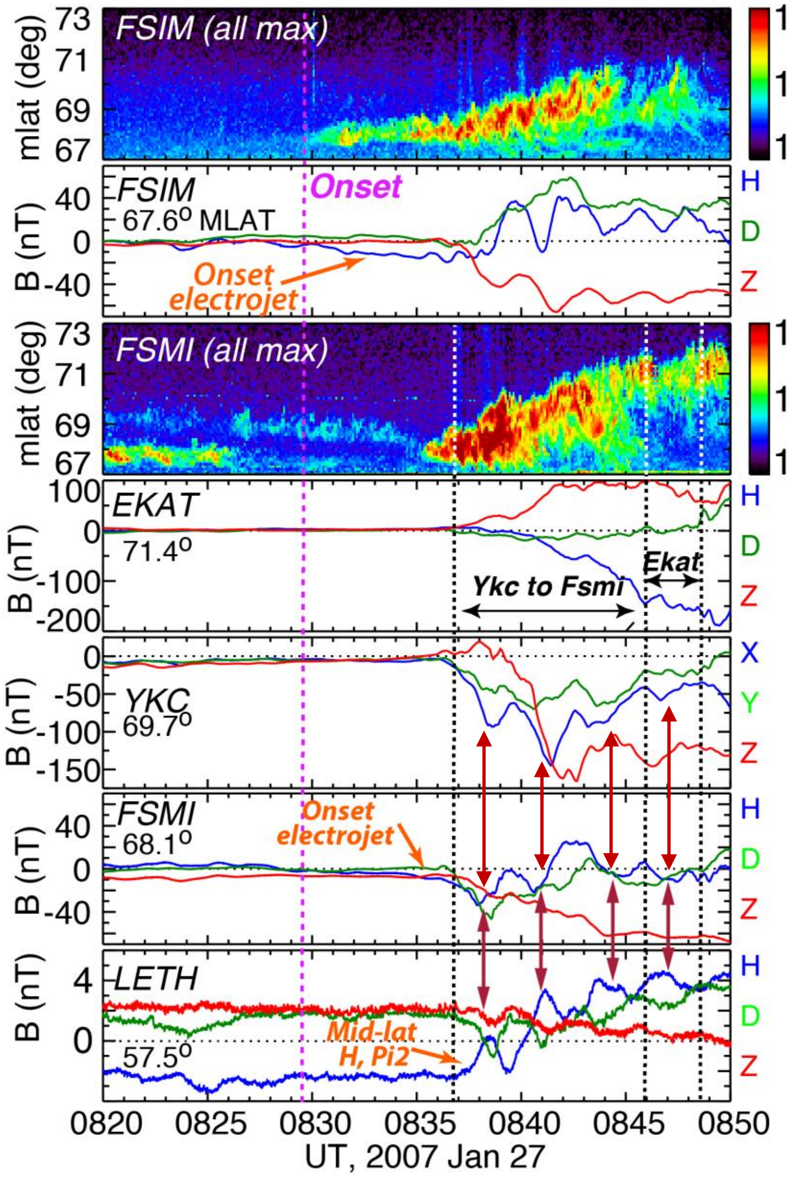
Another view: E-W keograms of differential intensity along onset arc

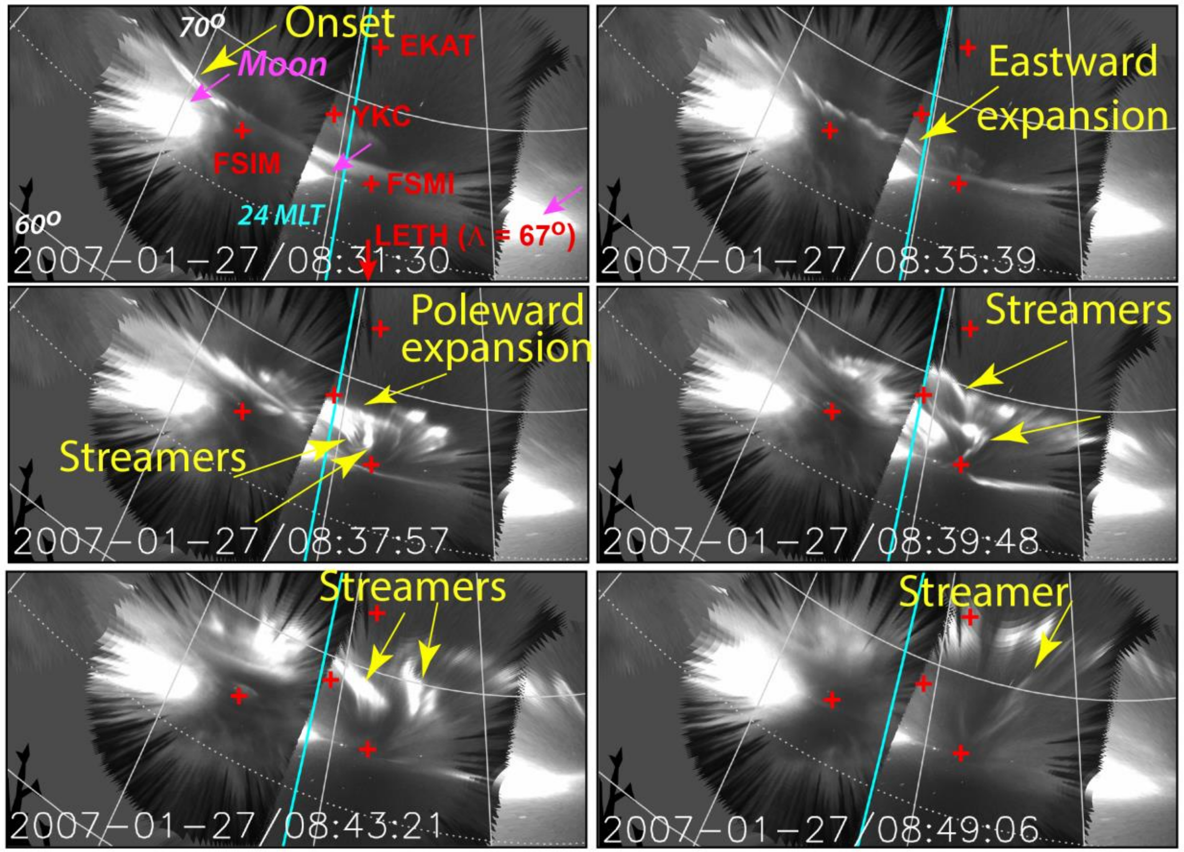
- **Longitudinally aligned wave onset**
- **Longitudinal expansion**
- **Wave growth, evolution to bright substorm aurora**

Nishimura+ (2016)



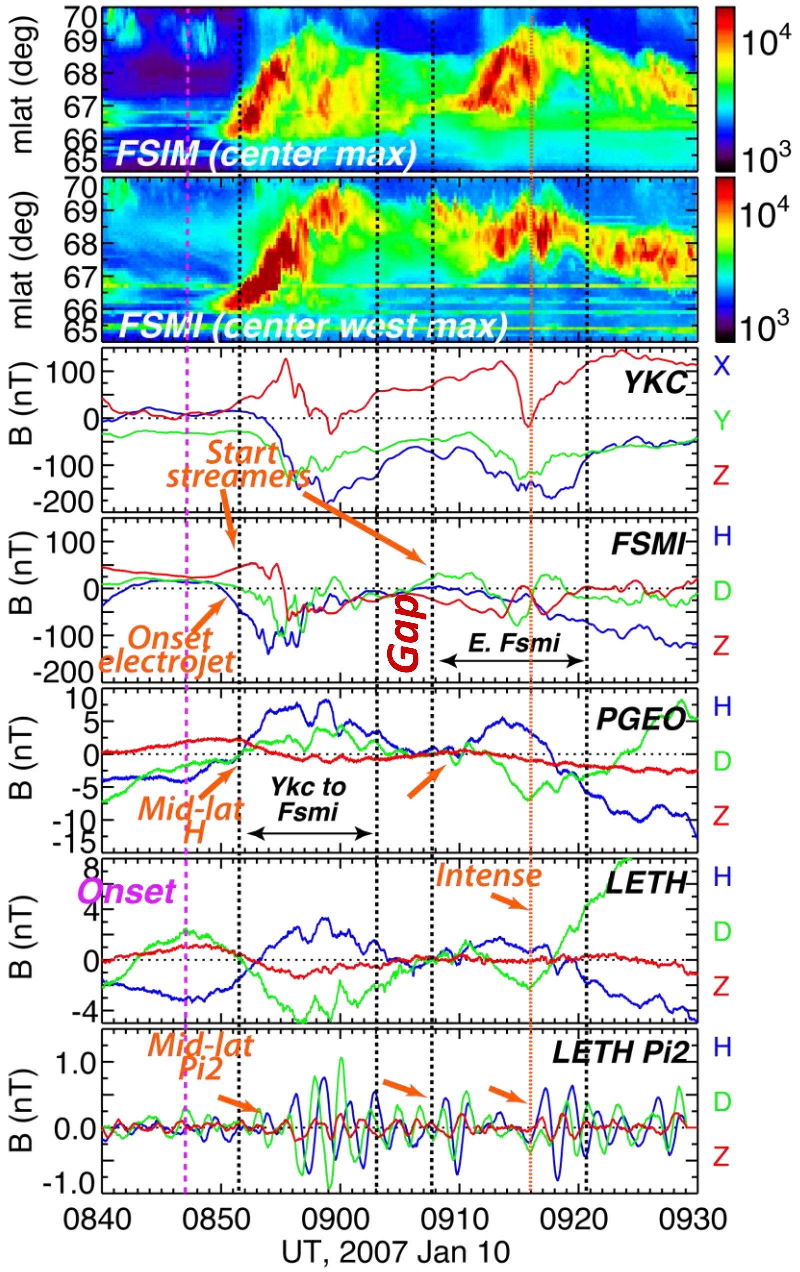
Onset instability aligned and expands longitudinally

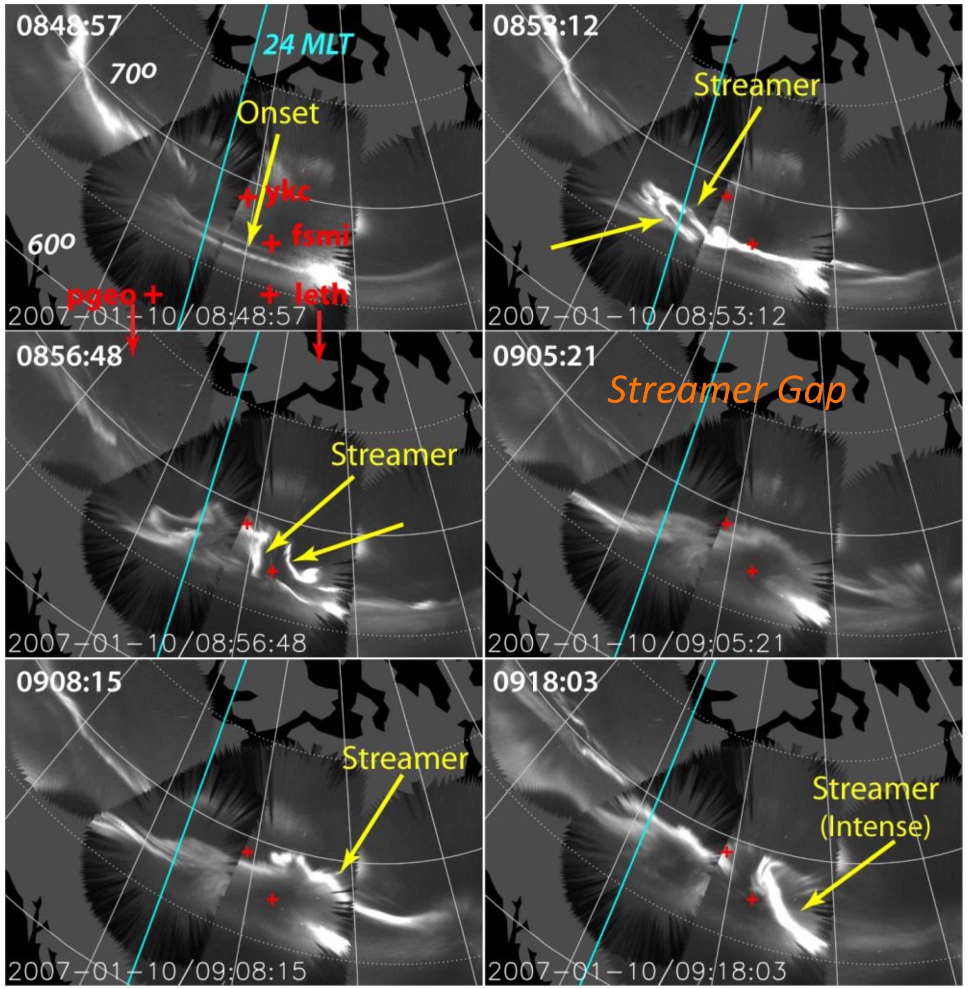




- ***Electrojet very weak during beading and its eastward expansion***
- ***Much larger H drops** from currents of streamers within bulge*
- ***Midlat H increases** anti-phase with auroral zone streamer H response*
  - *Post-onset streamers **primary source traditional onset B signatures (H drops, midlat +H bays, Pi2's**) [Nishimura+, 2012]*

Ground B Responses when multiple post-onset streamer intervals





Auroral ΔB; mid-lat. pos. bay, Pi2:

- ***Signatures of multiple onset***
- ***But only first is auroral onset***

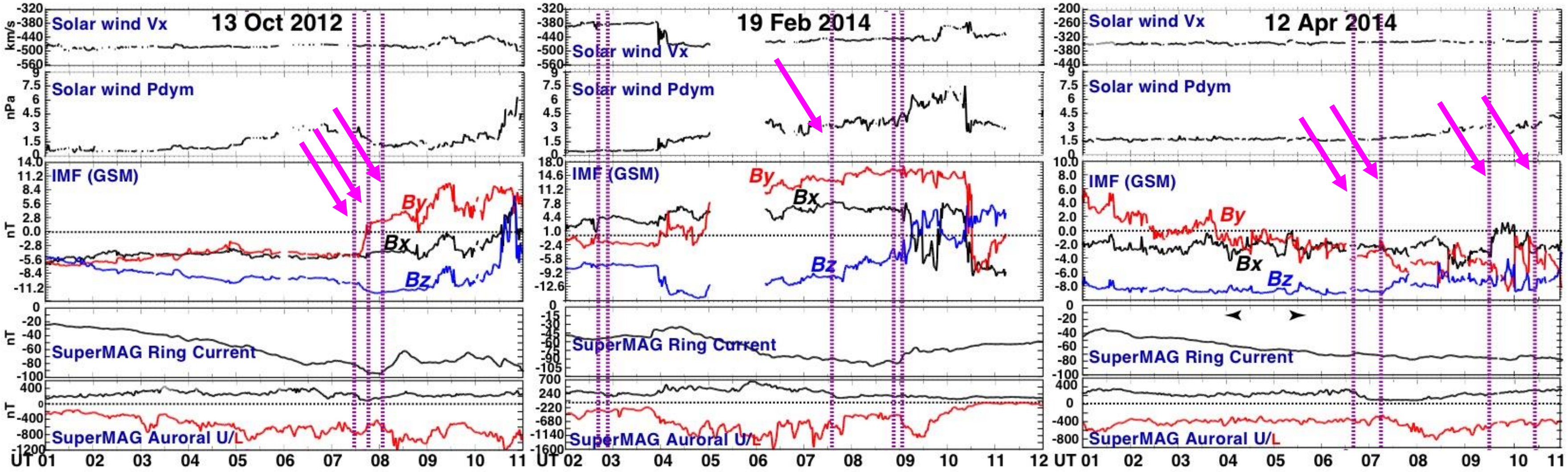
see *Sneha Yadav, Wed. poster or* Thurs. 1330-1530, Topaz 2

10 Jan 2007

Stormtime substorm onsets seen by Themis ASIs:

3 CME storms with extended smooth IMF

CME storms: 8 (2) during 21 (15) hrs strong steady south (south and E-W) IMF

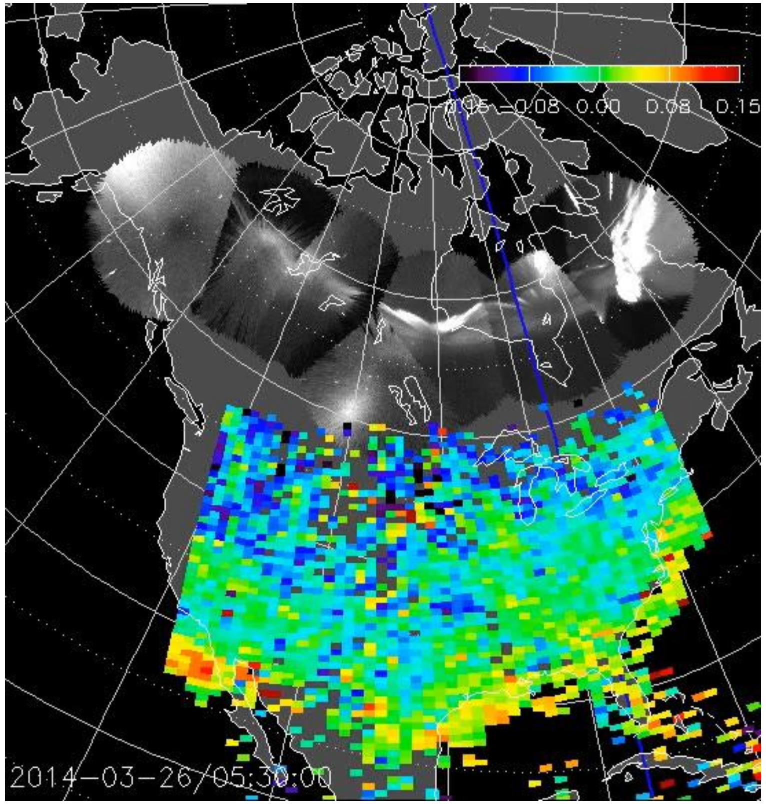


AL large throughout main phase ⟹ **~continuous activity**

- *Aurora shows* ***very few substorms!***
- ***Most storm main phase activity due to streamers/flow channels.***

Streamer Impact on thermosphere

Well know: auroral zone disturbances give large-scale traveling atmospheric/ionosphere disturbances (TADS/LSTIDs) propagating equatorward from oval.



Lyons, L. R., Nishimura, Y., Zhang, S.-R., Coster, A. J., Bhatt, A., Kendall, E., & Deng, Y. (2019)

Looked at with auroral , TEC images together

- LSTID following substorm

Oval flow channel/streamer gives substorm ionospheric currents**;** so expect to be **fundamental oval activity driver of TADS/LSTIDs**

Simultaneous oval imaging, radar flows, and TEC coverage over Alaska

- Allows **examination of direct connection** of LSTIDs to auroral streamers and associated flow channels

Poker 557.7 nm keogram

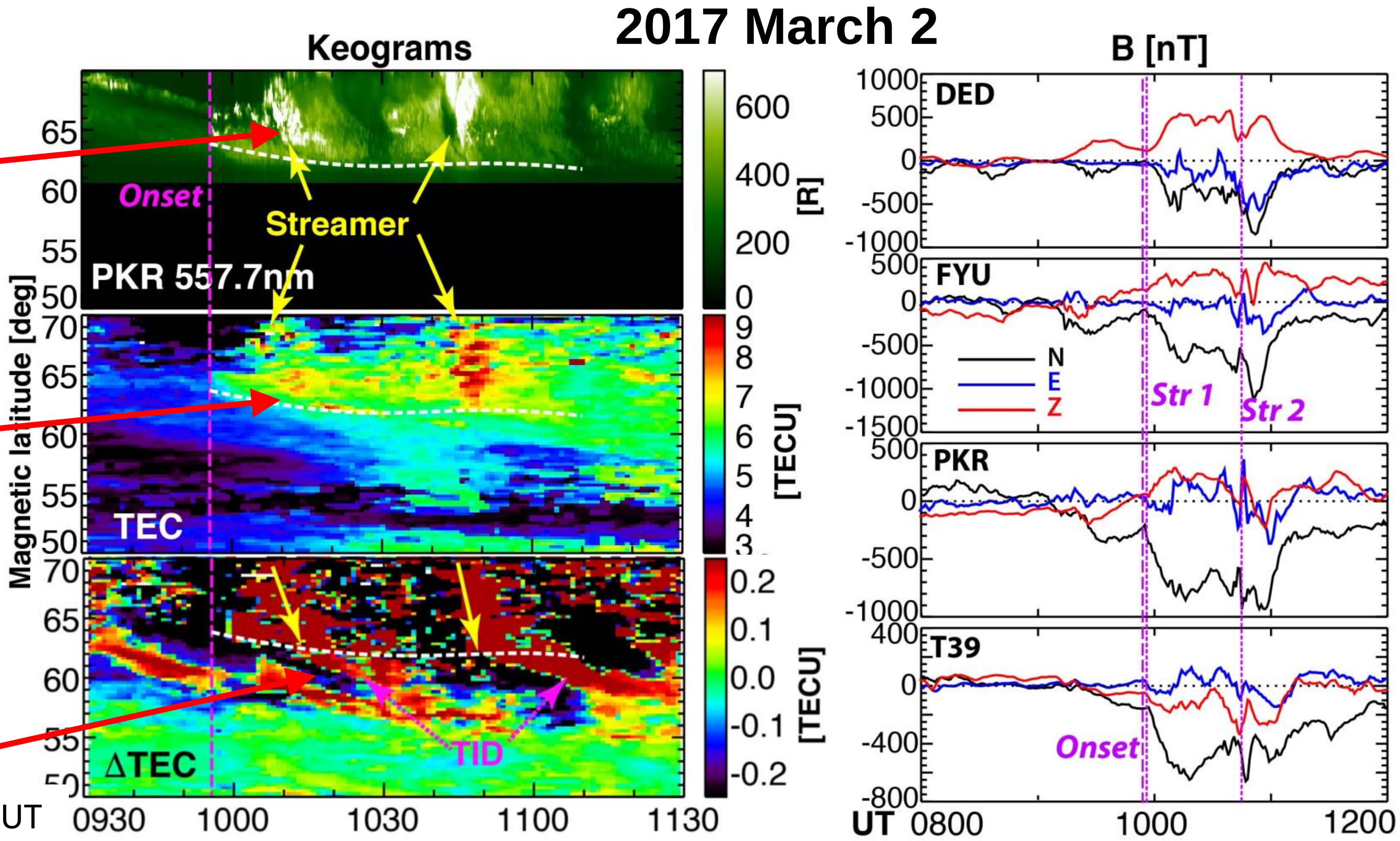
- **2 streamers to oval equatorward bndry**
- **With ground ΔB**

TEC keogram

- **Streamer ionization to equatorward bndry**
- **Some subauroral enhancement**

ΔTEC keogram

- **30 min sliding filter**
- **Subauroral TIDs**
  - **Direct connections**
  - **Slower equatorward speed**
  - **See to Λ ~ 55º,** limited data at lower Λ



Lyons LR, Nishimura Y, Zhang S, Coster A, Liu J, Bristow WA, Reimer AS, Varney RH and Hampton DL (2021)

Similar flow channel TID driving on dayside [*Nishiumura+*, 2020]

Mesoscale F Region Neutral Winds Associated With An Auroral Streamer

(Y. Zou+, 2018]

Before

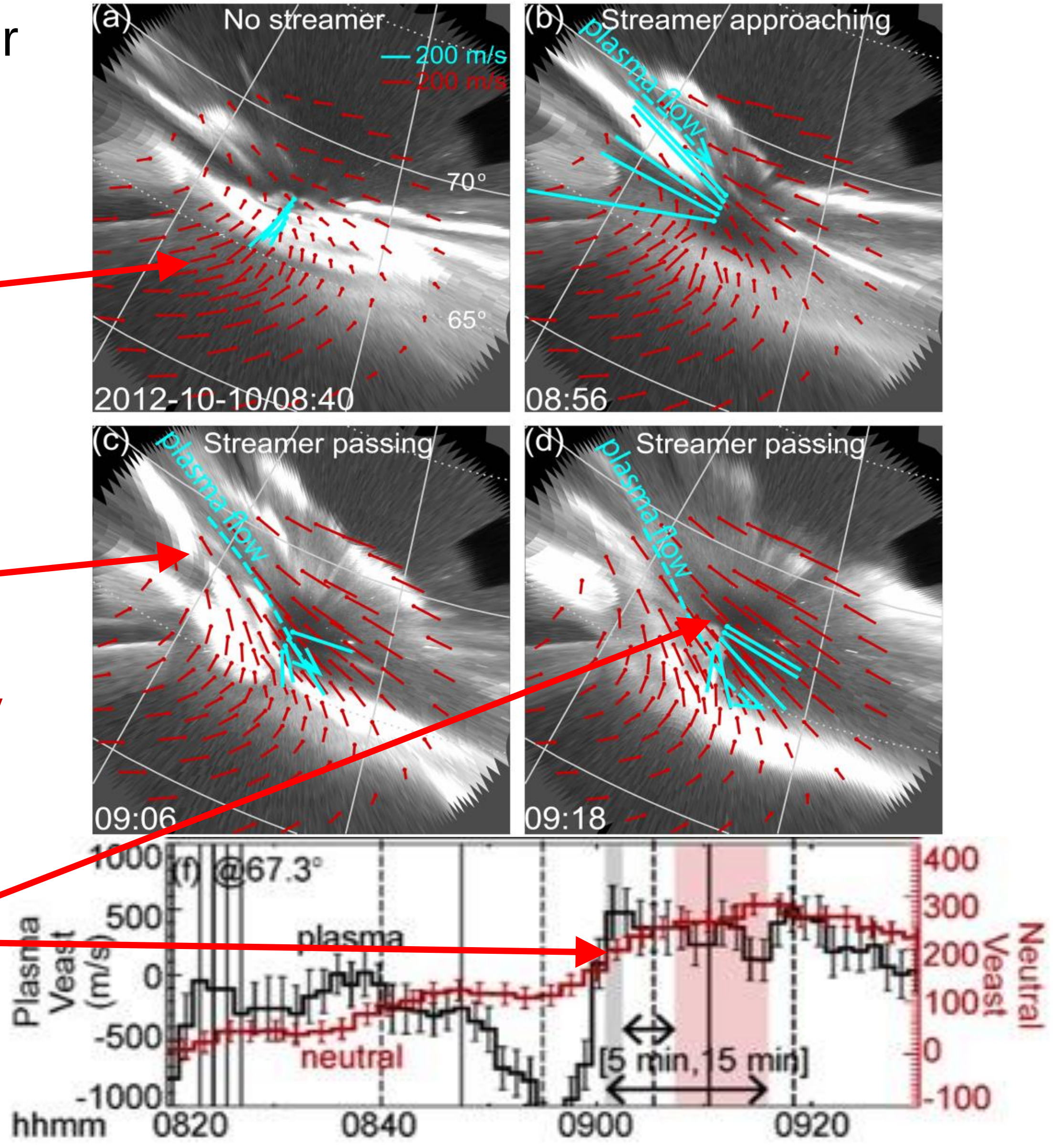
- **Weak plasma V**
- **Neutral V turns from eastward to westward**

With streamer passing

- **Plasma V**
  - **Enhanced**
  - **Transitions from westward to persistently eastward**

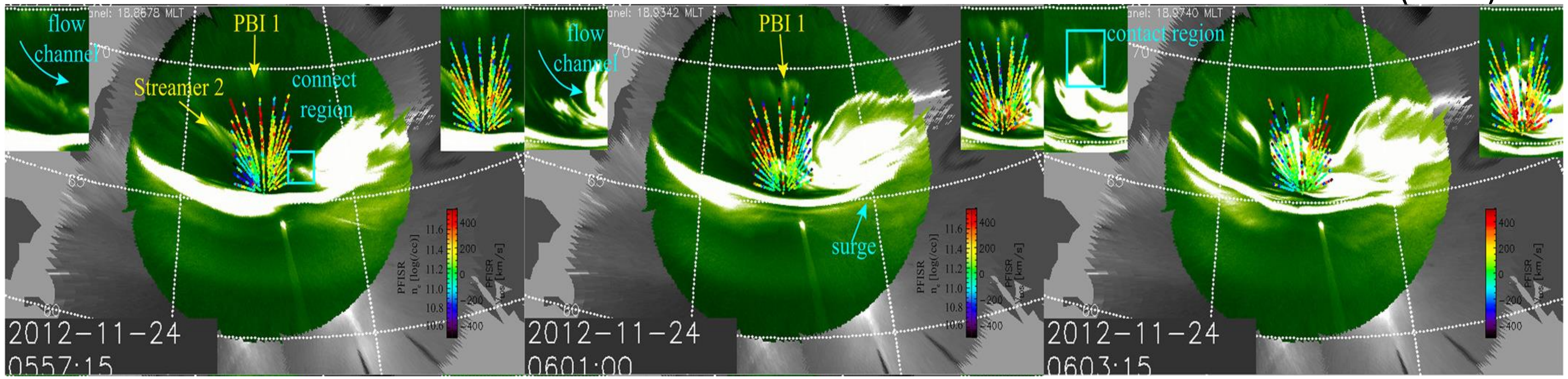
Westward neutral V

- **Increases by 200 m/s**



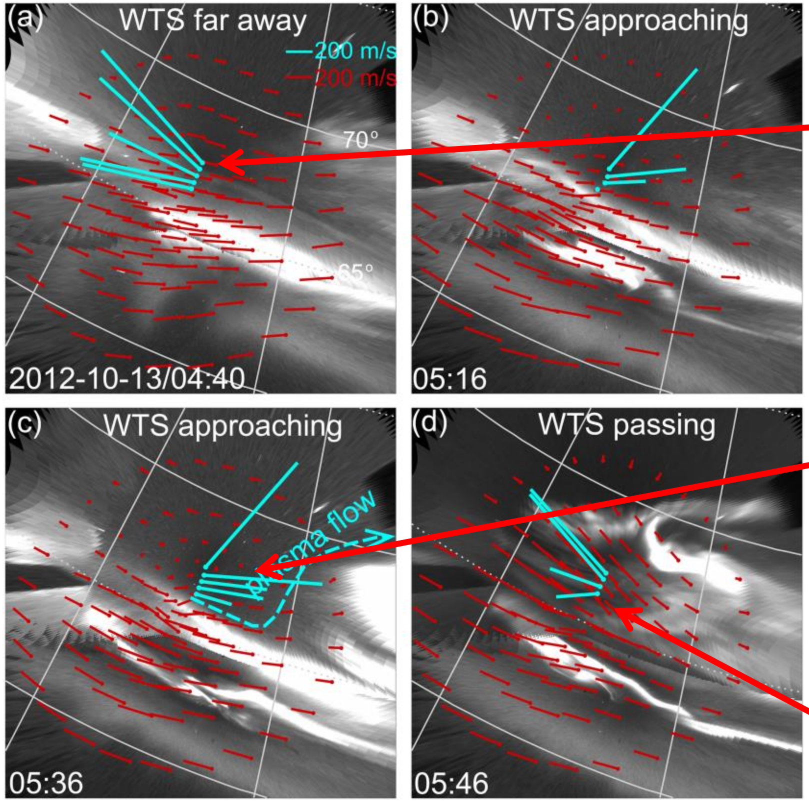
Polar Cap Flow Driving of Westward Travelling Surge Driven?

Y.-Z. Ma+ (2021)



- Common for streamer to connect and remain connected to surge
- PFISR obs in this case show **flow to head of surge**
  - Appears to "**feed" polar cap plasma into surge**
  - **Important for surge activity?**
  - Significantly **affects neutral winds**

Mesoscale F Region Neutral Winds Associated With Westward Traveling Surge Over Alaska *(Y. Zou+ [2018])*



Before surge:

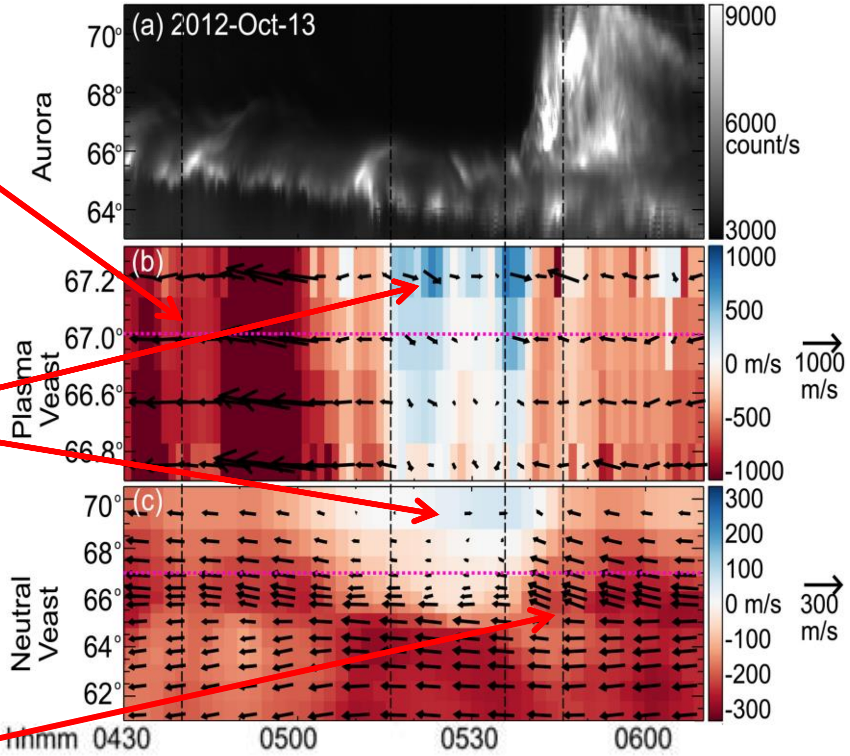
- Westward plasma flow and winds

As surge approaches:

- Plasma flow turns eastward towards surge head
- Winds slow, then turn eastward

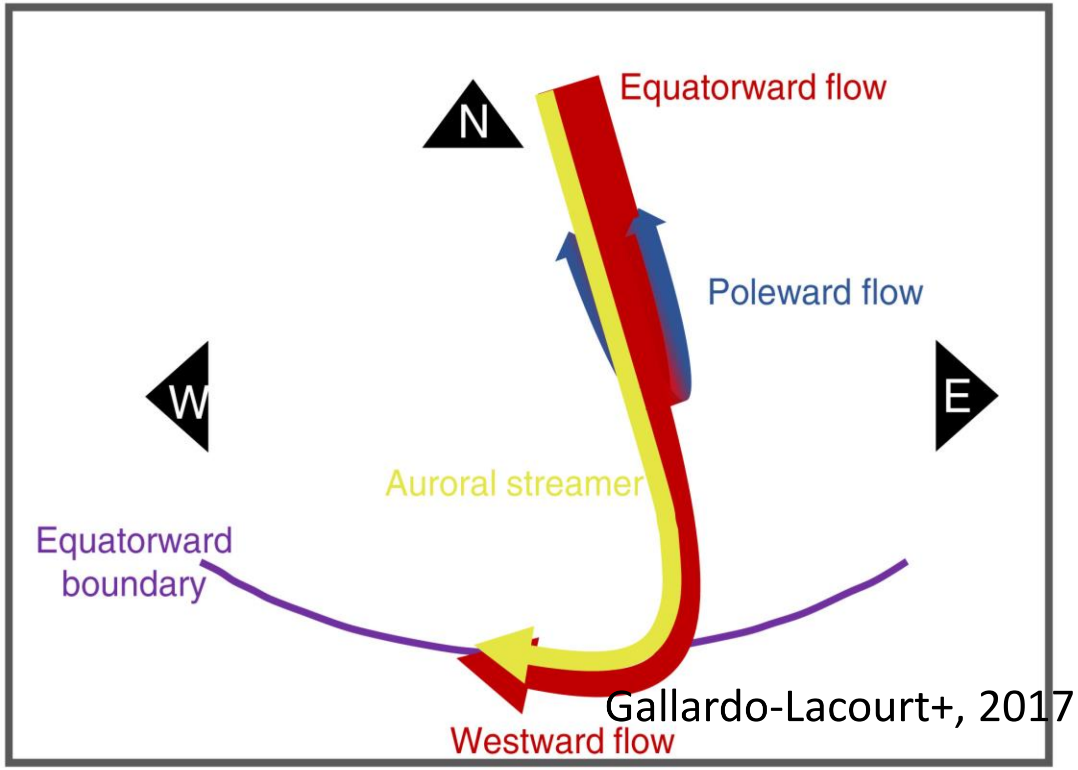
With surge passing:

- Westward plasma flow and winds return



Some Auroral Streamers/flow channels Reach Subauroral SAPS Region.

- Cause rapid enhancement enhancements in SAPS flows
  (*Makarevich+*, 2011; *Lyons+*,2015; *Gallardo-Lacourt+*, 2017)
- Leads to STEVE (MacDonald+, 2018,Archer+2019, Nishimura+ 2020), subauroral proton aurora (Nishimura+, 2014), more?

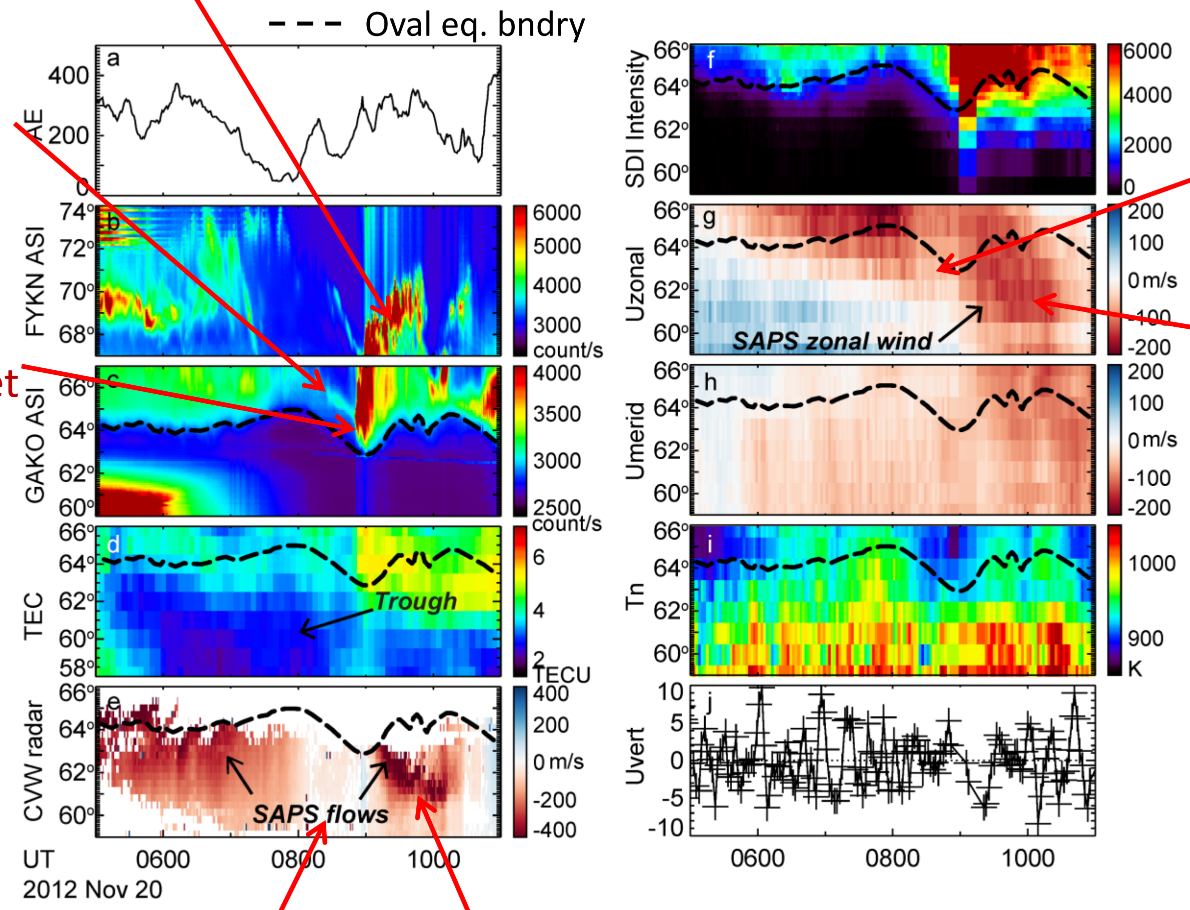


Gallardo-Lacourt+, 2017

SAPS Flows and Wind Relative to Aurora [*Y. Zou+* 2022]

ASI Keogram:

1. Growth phase
2. Substorm onset
3. Expansion phase streamers



SAPS Zonal Wind:

Growth phase: **weaken**

Streamer phase: **Strongly enhanced**

SAPS Flows:

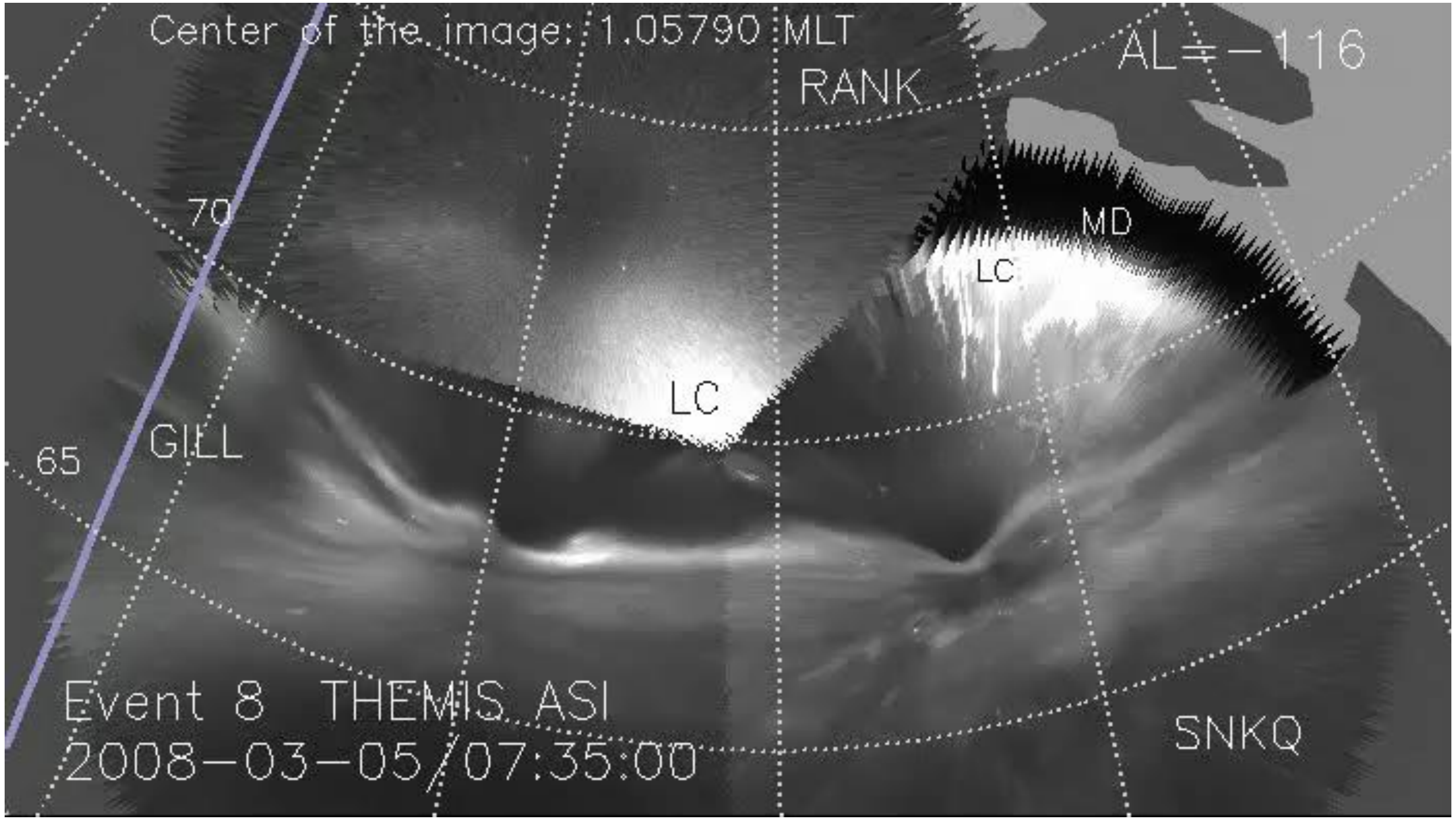
Growth phase: become **weak**

Streamer phase: **Strongly enhanced, bursty**

Streamer vs. enhanced convection control of SAPS, thus also of SAPS winds??

Streamers/flow channels lead to Omega bands

- **1st reported by reading the aurora** **(*Henderson et al*. 2002)**
- Major Dawnside Disturbance (up to several hundred nT).



From J. Liu

Omega Bands: Major Dawnside Disturbance

(up to several hundred nT)

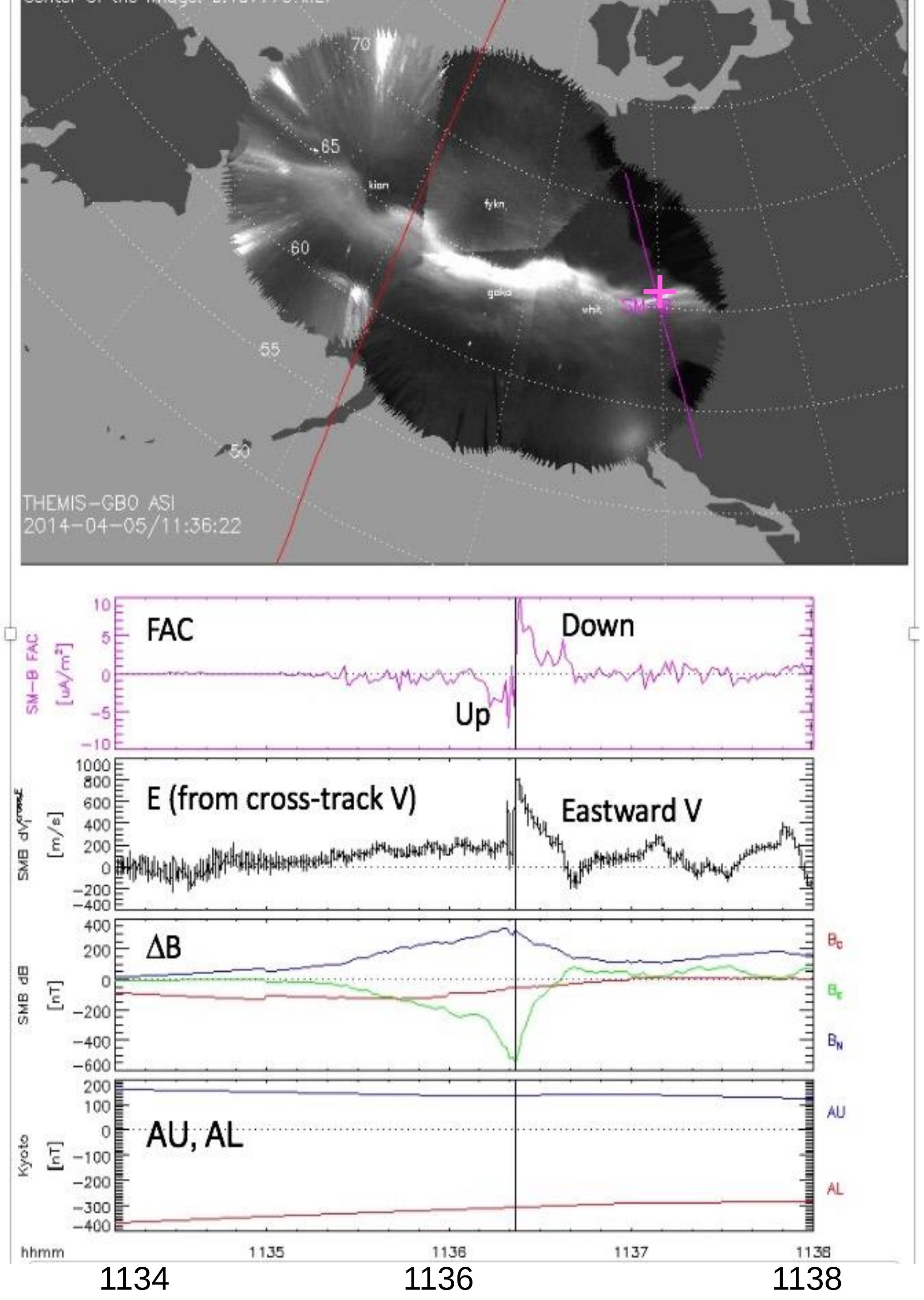
SWARM – THEMIS ASI conjunctions:

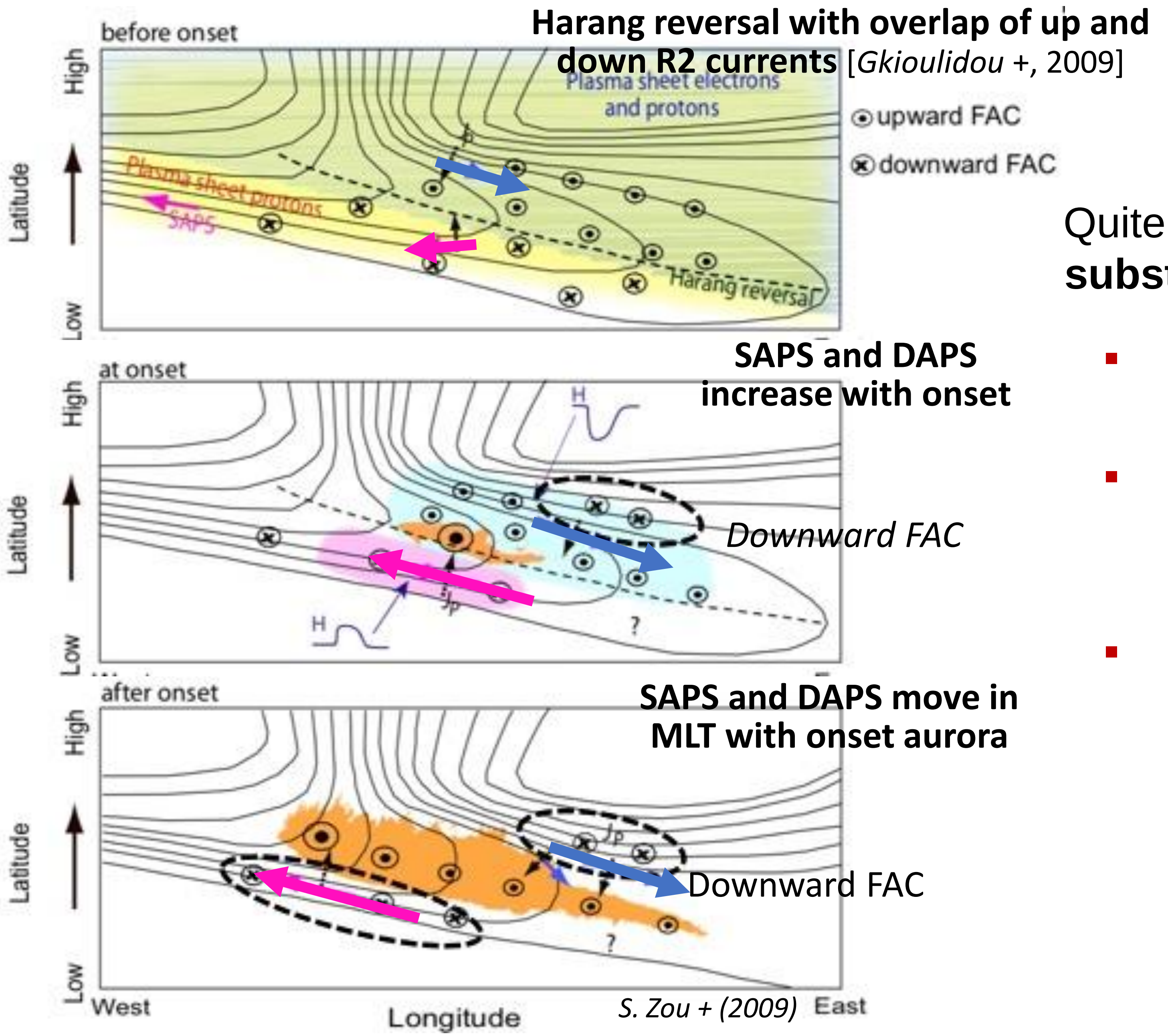
- Show **flow shears at** omega band **poleward boundary** *(Jiang Liu+,2018)*

Example event (2014 April 5)

- **Abrupt boundary between upward (R2) and downward (R2)** at band poleward boundary
- **Strong eastward flow channel (DAPS, Liu+, 2020) immediately poleward** of omega band poleward arc.

DAPS, omega bands effects on thermosphere??





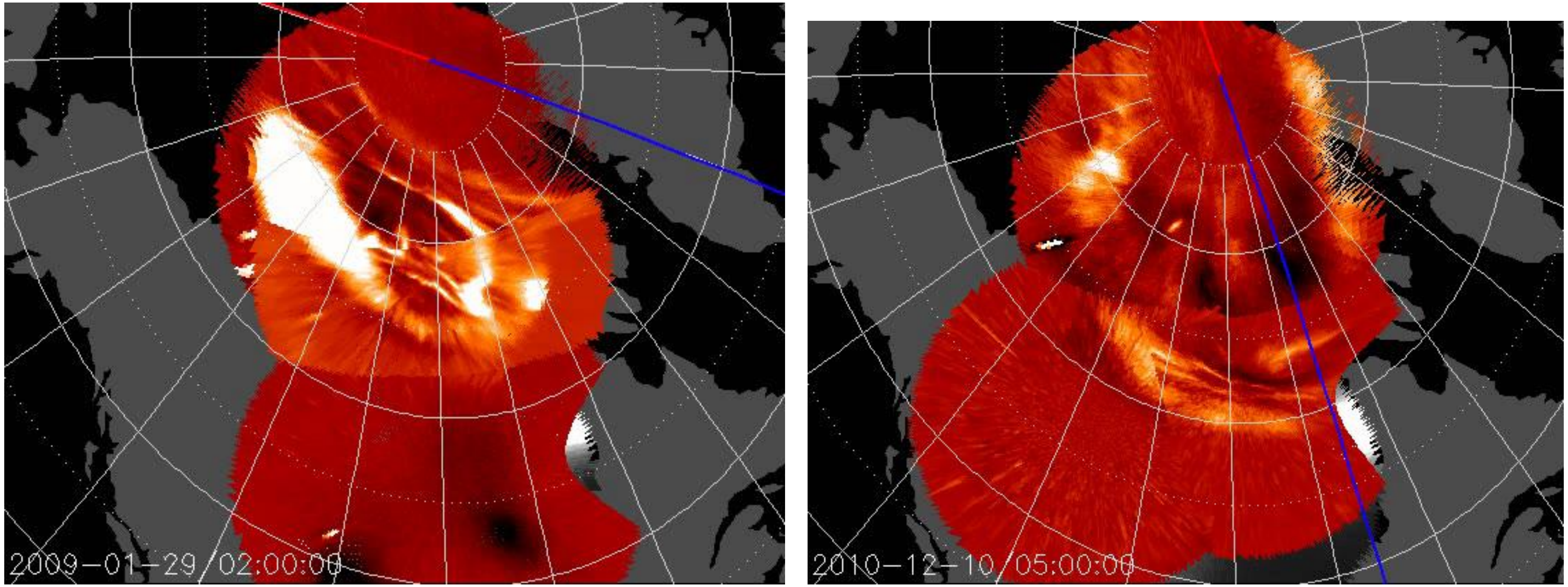
Quite clear now that **flow channels trigger substorm onset**

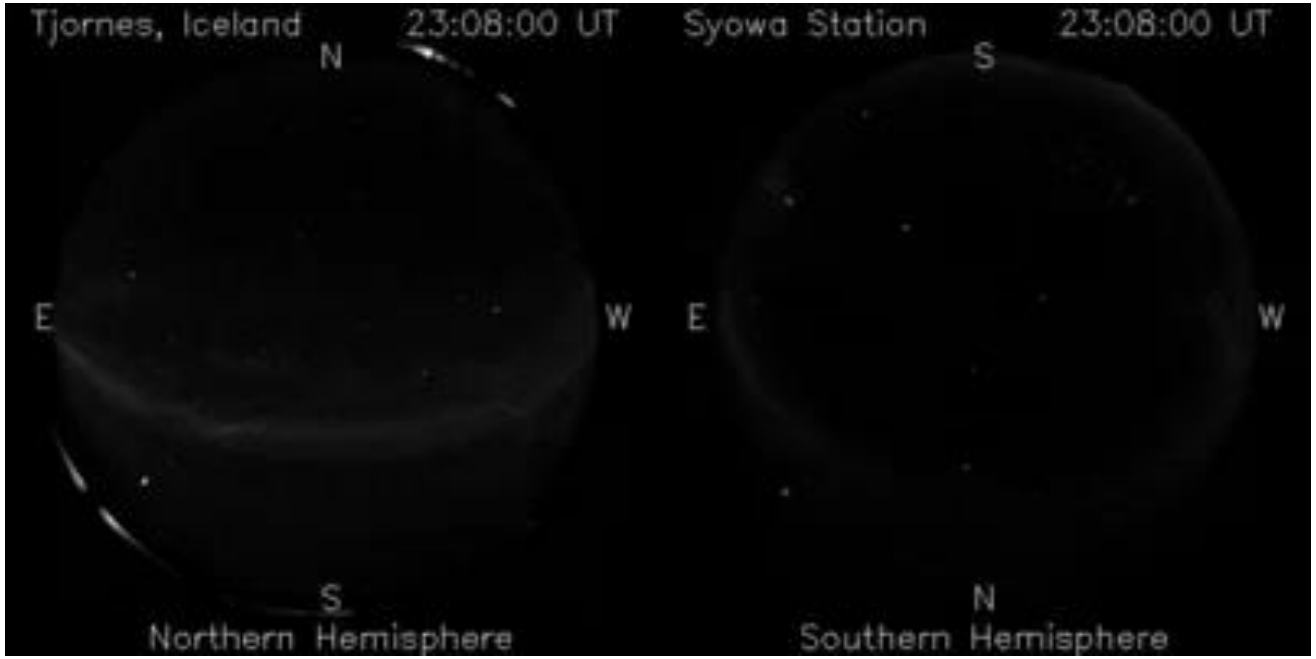
- **Discovered by reading the aurora** ***[Nishimura+, 2010].***
- **FACs, flow, and longitudinal expansion with time predicted by RCM** ***(C.-P. Wang+, 2018).***
- **Accounts for flow, current pattern of substorm onset first reported by S. Zou+ [2009] with aurora, radar, and ground B observations.**

Reading the Aurora: A tool for Interconnections

- **Reading shows**
  - **Structured flow from dayside to nightside**
    - **Connections to magnetosheath structure** from dayside to nightside through polar cap field lines**.**
    - ***Physics of these connections and how flow channels are carried over the polar caps??***
  - **Connection to nightside oval flow channels**
    - **Driven, localized reconnection**
    - ***Physics of the driven reconnection how it leads to low-entropy plasma sheet plasma of oval flow channels??***
  - **Oval flow channel/Streamers**
    - **An Elemental Feature of** Nightside Magnetic **Activity**
    - ***Much to learn of role in different nightside disturbances***
    - ***Much to learn on connections to neutrals using realistic specifications.***
    - ***Full ramifications of connections to subauroral regions***

Red line movie from Ying Zou: Connections across polar cap to oval and disturbances





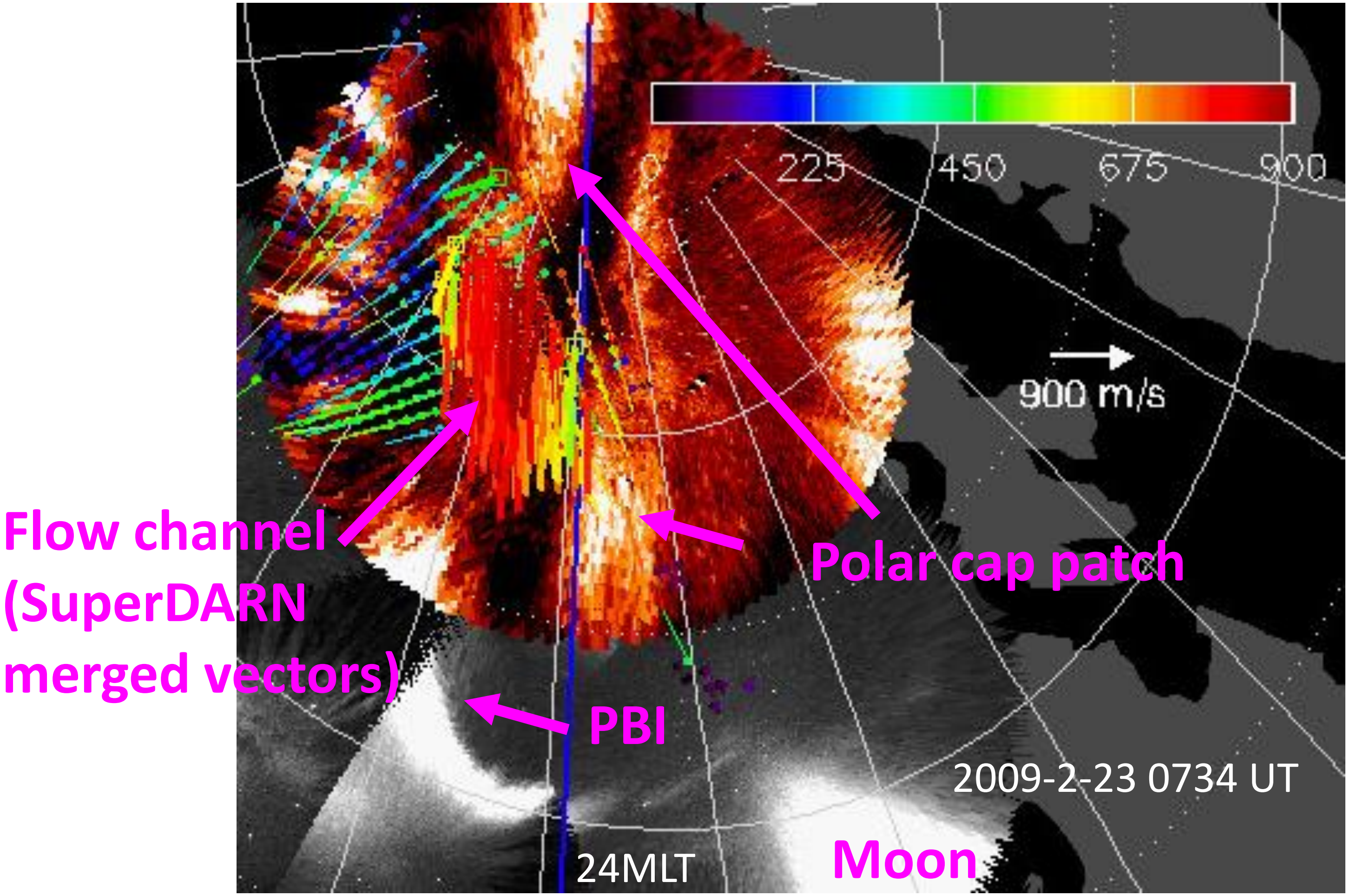
Motoba+, 2012

- **Beads simultaneous both hemispheres**; similar wavelengths and periodicities
  - Thus **generated within plasma sheet.**
- **~30–90 s** frequencies **in onset aurora and ground magnetic field** (*Rae*+, 2010)
  - Period of auroral beads passing overhead .
  - **Same 10's** of second frequencies **seen in space** (*Takahashi*+, 1987; *Roux*+, 1991*; Lui*+, 1995; *Ohtani*+, 1998; *Cheng & Lui*, 1998; *Shiokawa*+, 2005; *Park*+, 2010).
  - Wave ionospheric flow speed ~1000 m/s (***Bea Gallardo-Lacourt+, 2014***)
  - Wavelength ~plasma sheet ion gyroradius in onset region (*Nishimura*+, 2022)

Aurora ⟹ Onset is plasma sheet instability connected to ionosphere

Now Move to Central Polar Cap

Radar-630 m ASI combination nightside example **(*Ying Zou*+, 2015)**

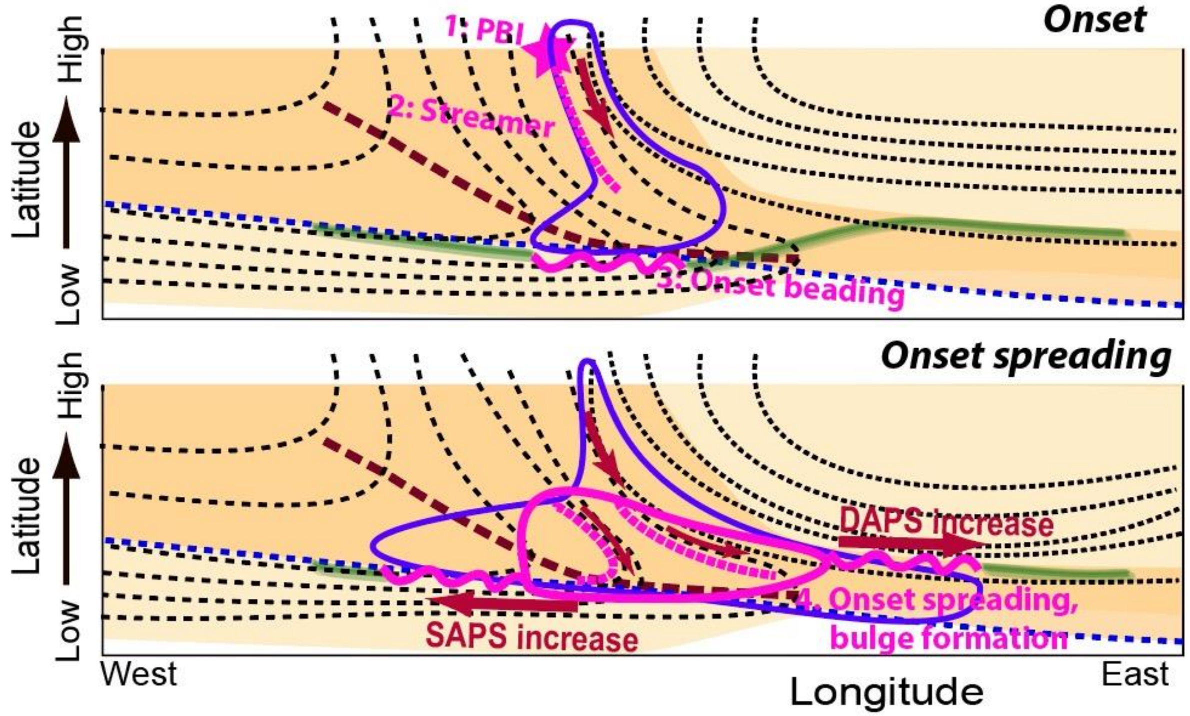


- F**ast flow channel colocated with an airglow patch, also seen with pc arcs.**(also B. Wang et al., 2016)
- Flow channel and patch **directed toward a PBI.**
- Polar cap flow channels importance:
  - **Drive PBIs**
  - One can account for a **substantial portion** (~30%) **of cross-polar-cap potential drop**.

Expansion picture here **very similar to S. *Zou*+ [2009]**

(prior to concept of onset instability due to bubble and RCM bubble modeling)

Picture presented here



Zou+ [2009] picture

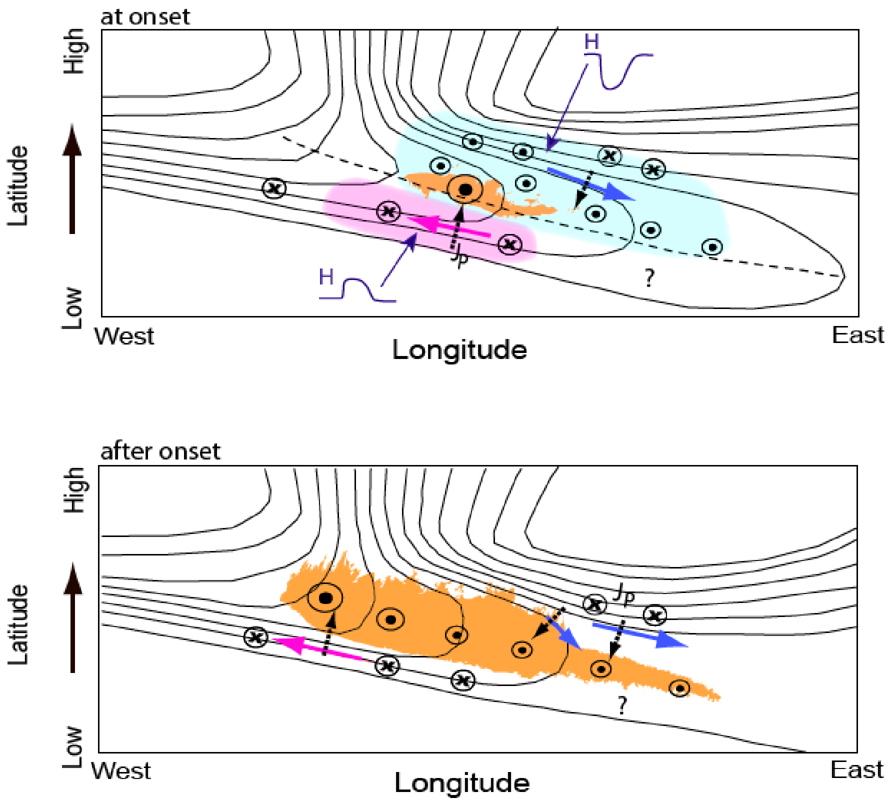


Figure 14