The Substorm

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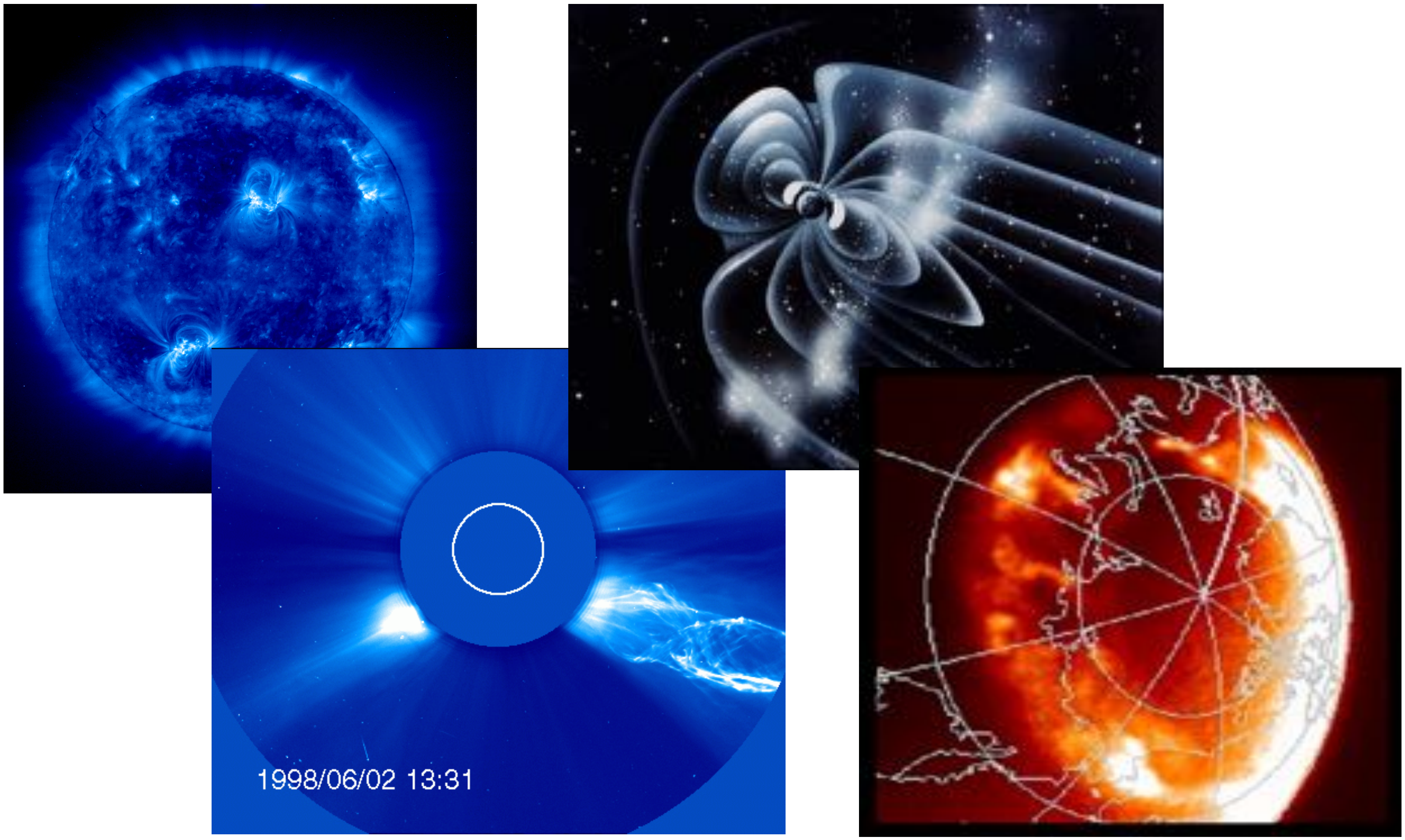
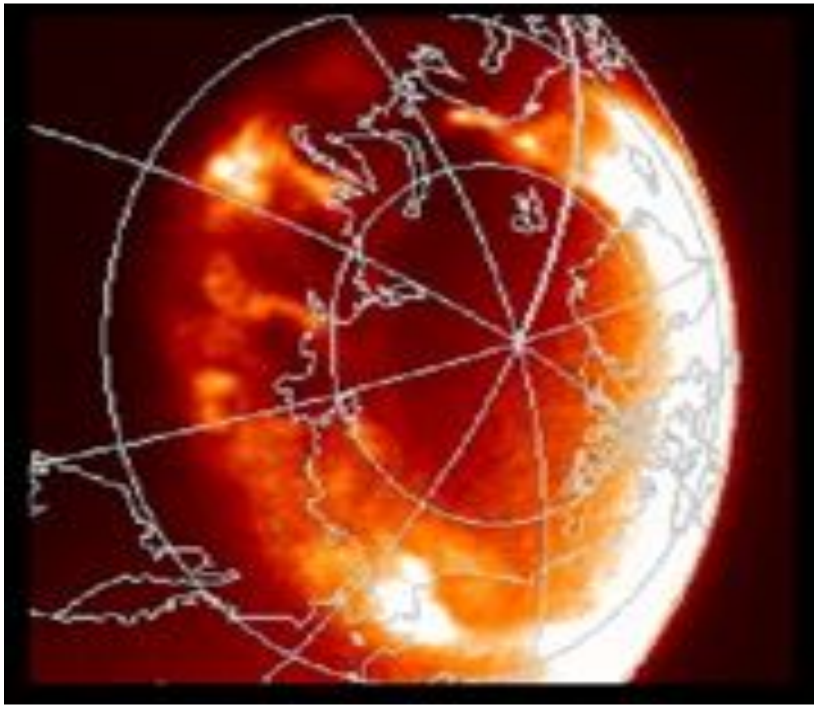
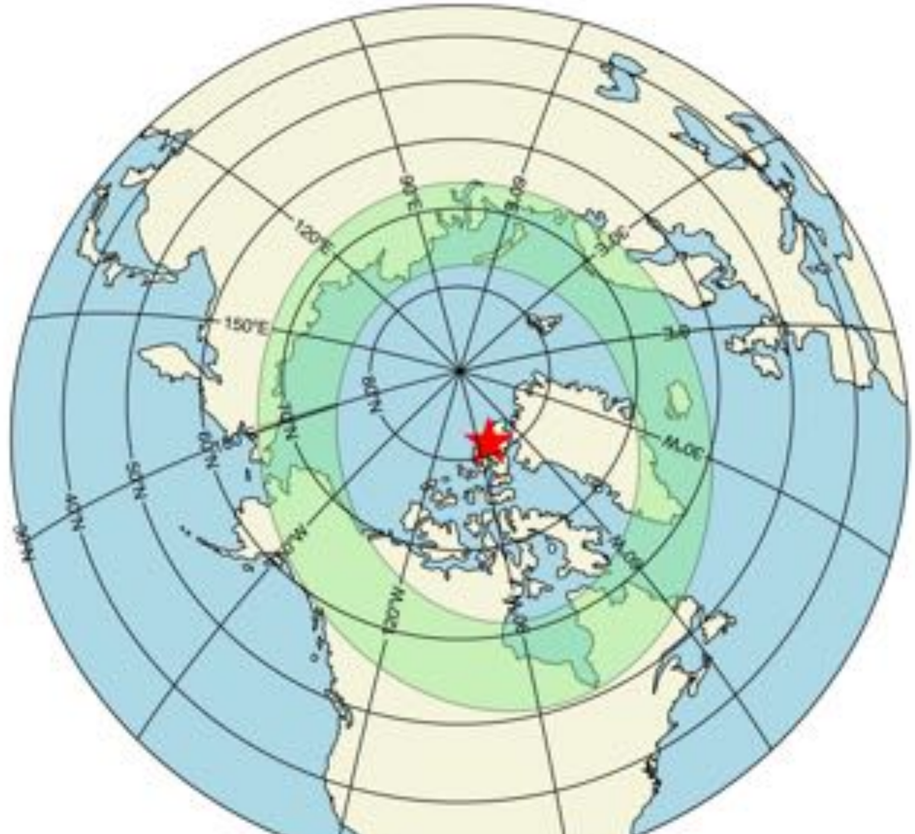
1. ***Brief statement as to why the aurora is important here***
2. ***Modes of the Magnetosphere (driven, normal, instability)***
3. ***The substorm - the phenomenology***
4. ***The substorm – definition***
5. ***The substorm – what's interesting (system-level, instability, universality).***
6. ***Attempts to determine the instability – THEMIS***
7. ***Where to from here?***

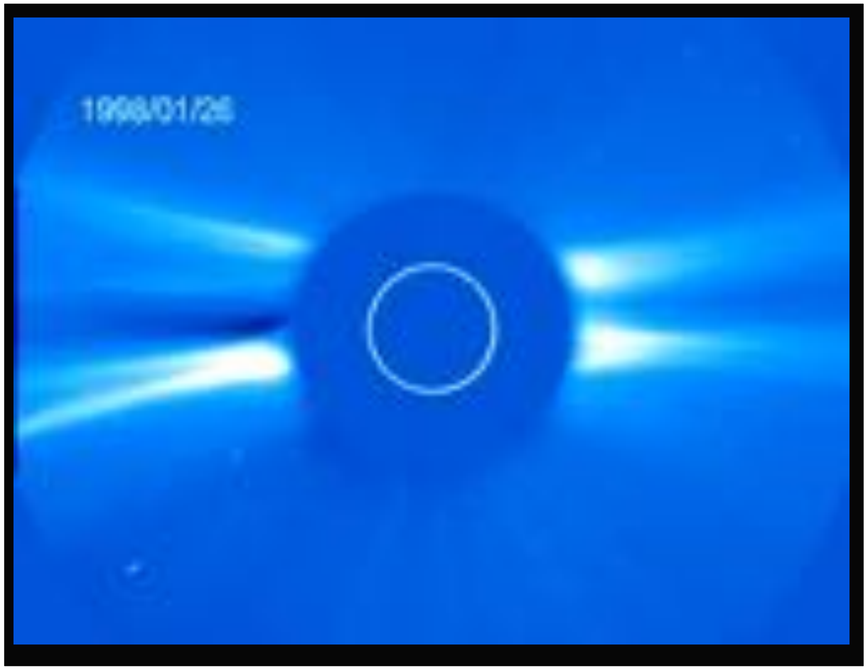
The Substorm





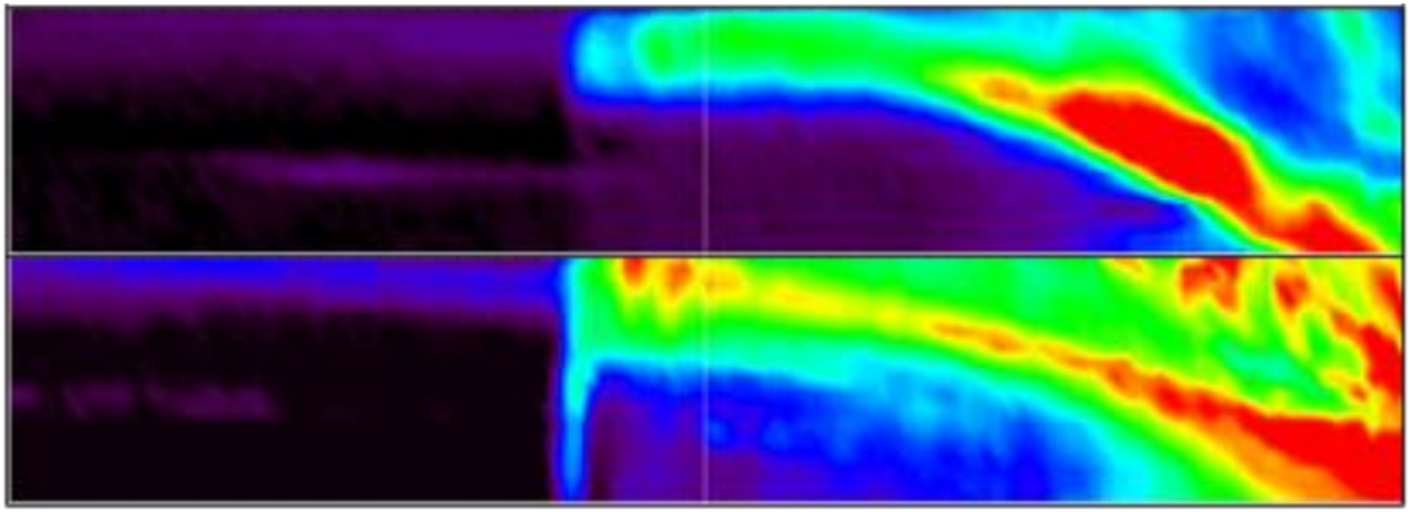


The aurora gives us a window (through the filter of MI coupling) into the global magnetospheric dynamics and plasma regimes. For reasons I will elaborate on, it often makes sense to use ground-based auroral (ionospheric) observations to remote sense magnetospheric dynamics. Note the "Canadian Advantage".

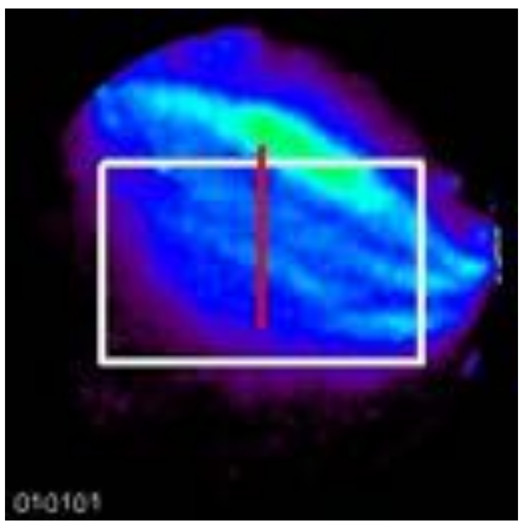


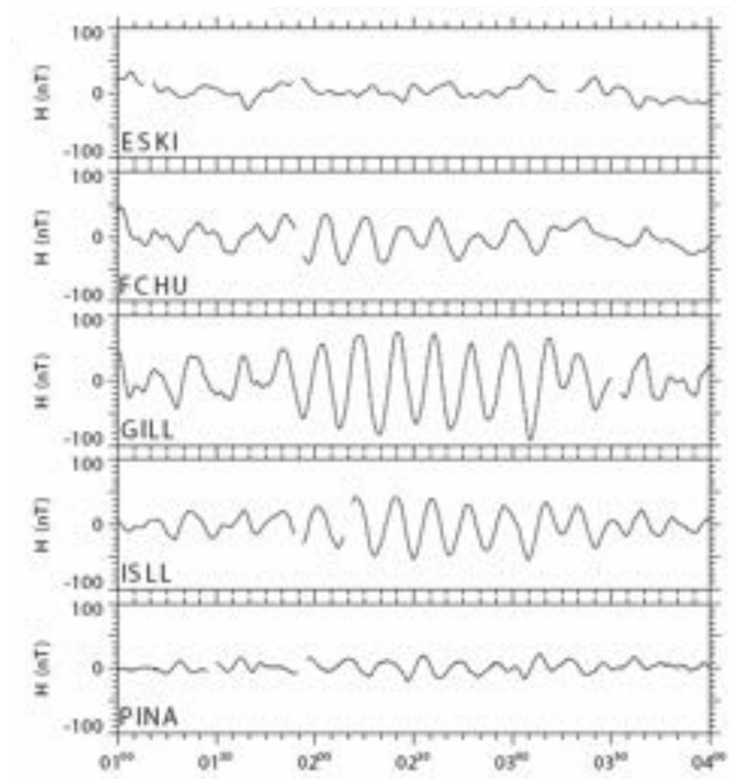
The magnetosphere is dynamic… an oversimplified view of why is as follows: (1) it is driven by the solar wind which is dynamic; (2) it has “normal modes” (for lack of a better term); (3) it gives rise to spontaneous instabilities.

(1) Variations in the solar wind driver: these include sudden impulses.



(2) Normal modes: these include global oscillations (e.g., ULF waves).





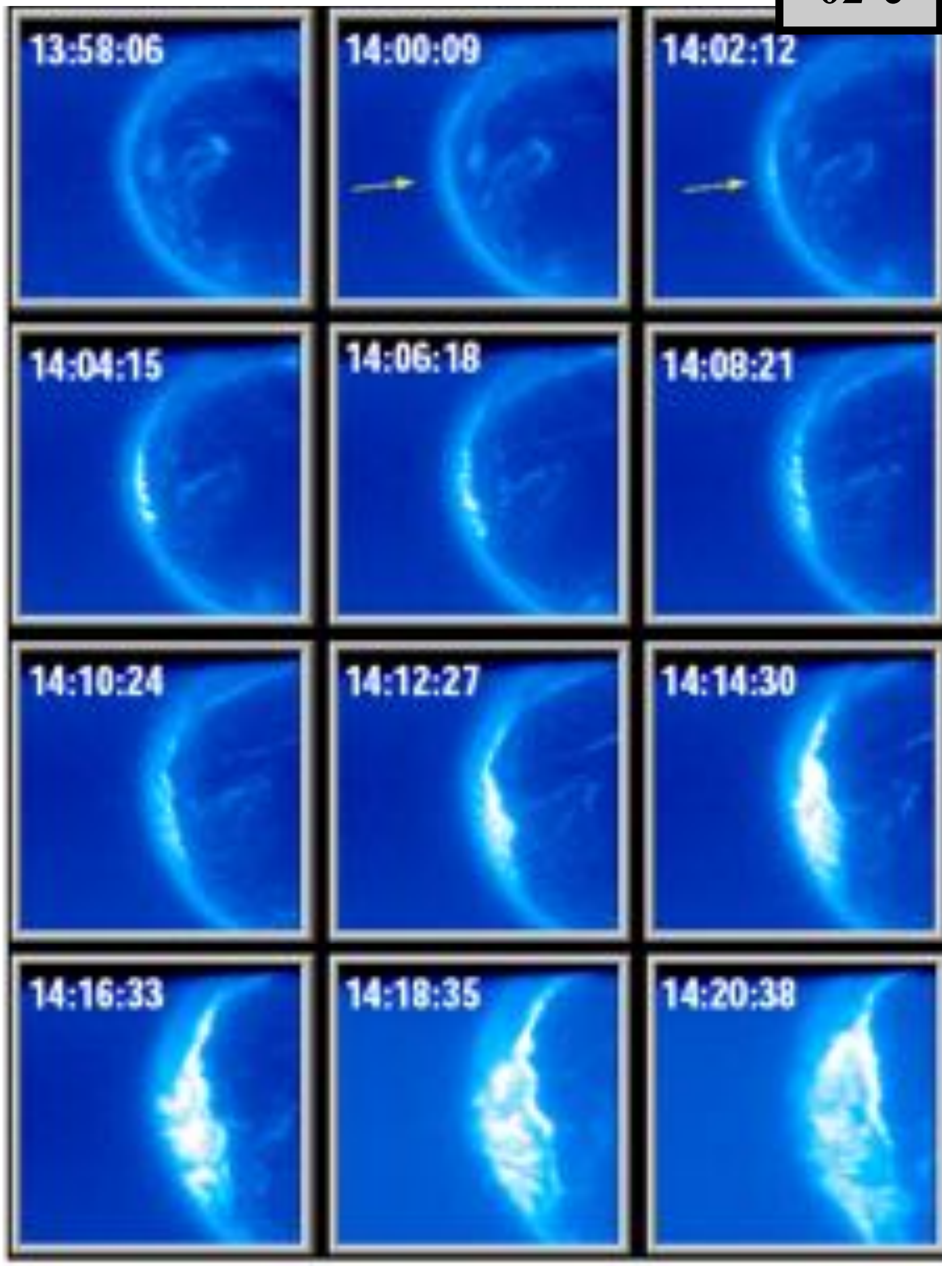
(3) Instabilities: these include the substorm.

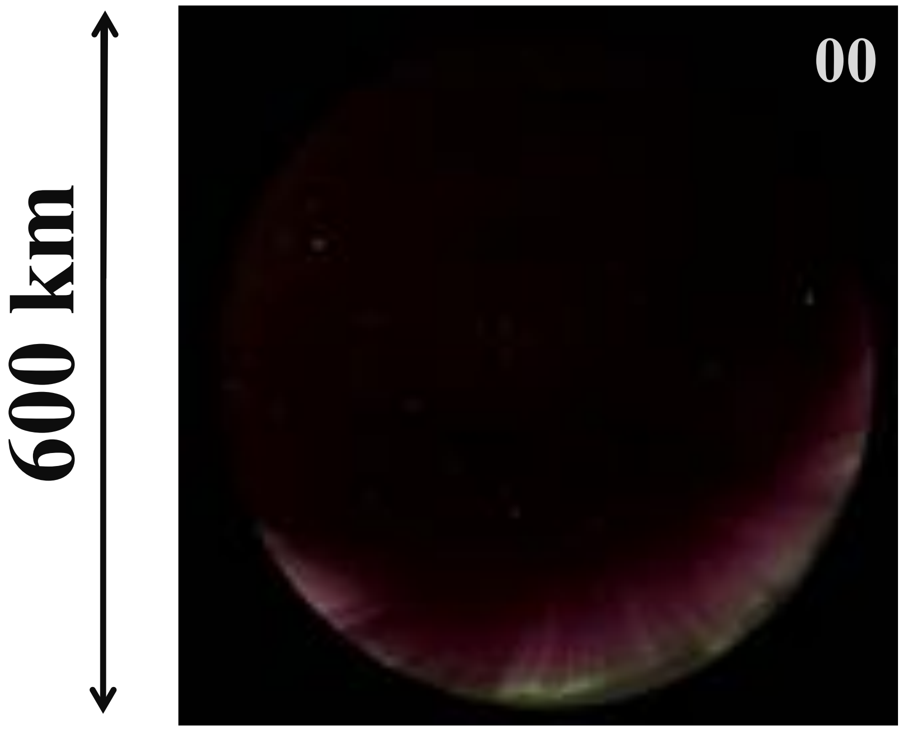
Shown at right are nearly-global FUV images of the northern hemisphere auroral oval from the WIC instrument on IMAGE.

Note the *emergence* of the disturbance from deep inside the nightside auroral oval, on field lines that thread the CPS.

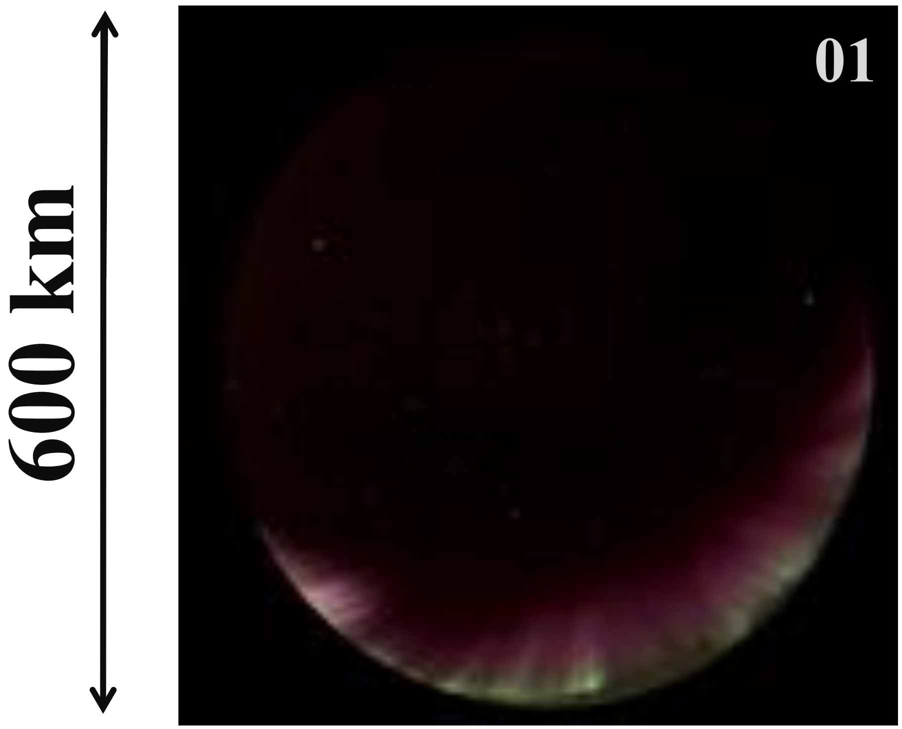
Note the evolution to a nearly global disturbance.

Figure from Henderson, Annales Geophysicae, 2009.



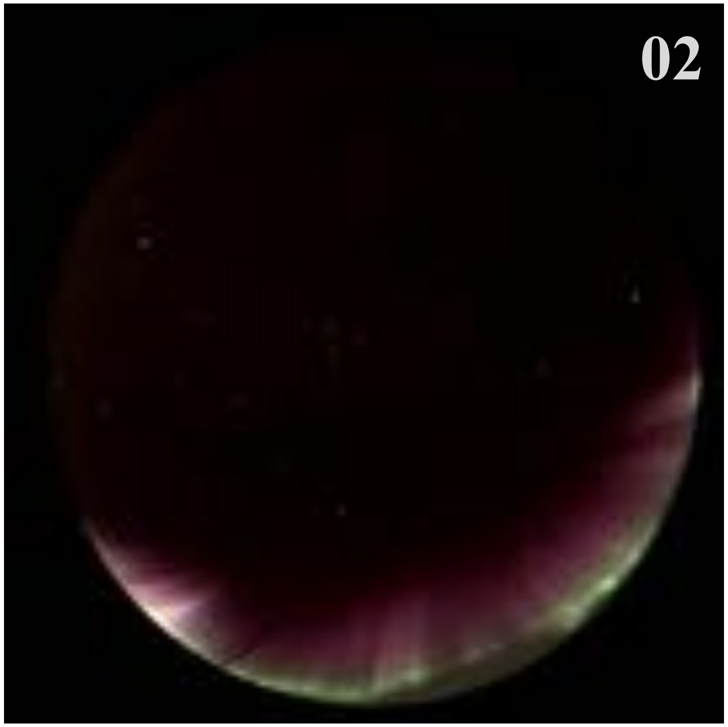


I want to give you an idea of how dramatic this is. The images in this sequence were taken by Mikko Syrjäsuo with a color All-Sky Imager. The aurora in frame 00 is barely visible, well to the south of the imager (which was in Athabasca, Canada). The frames are 10 seconds apart.



Keep in mind these frames are 10 seconds apart, and the field of view is roughly 600 kilometers across.

600 km



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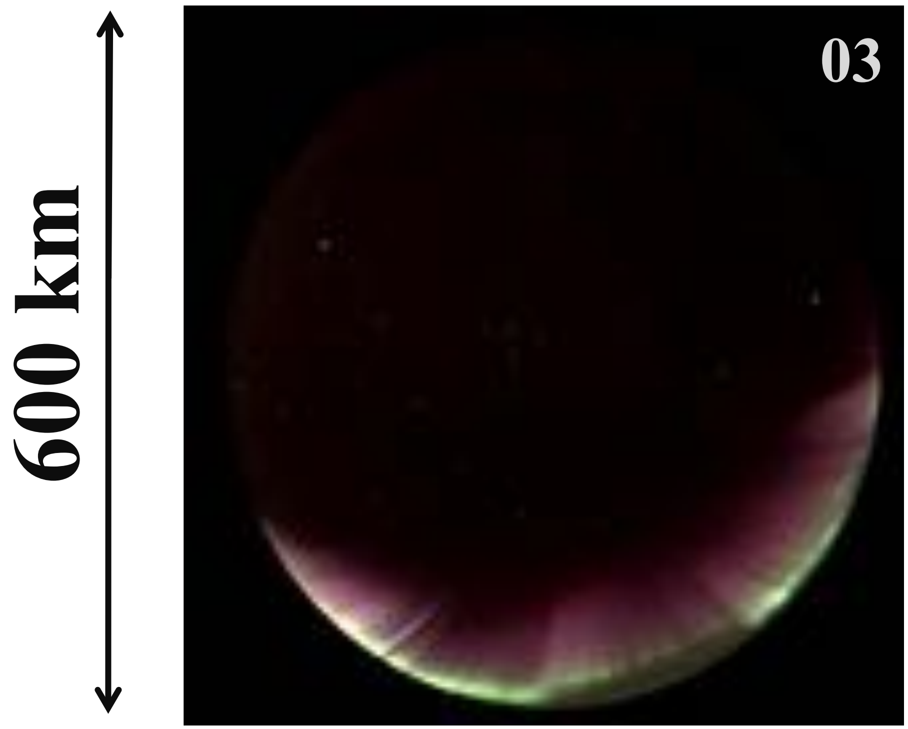

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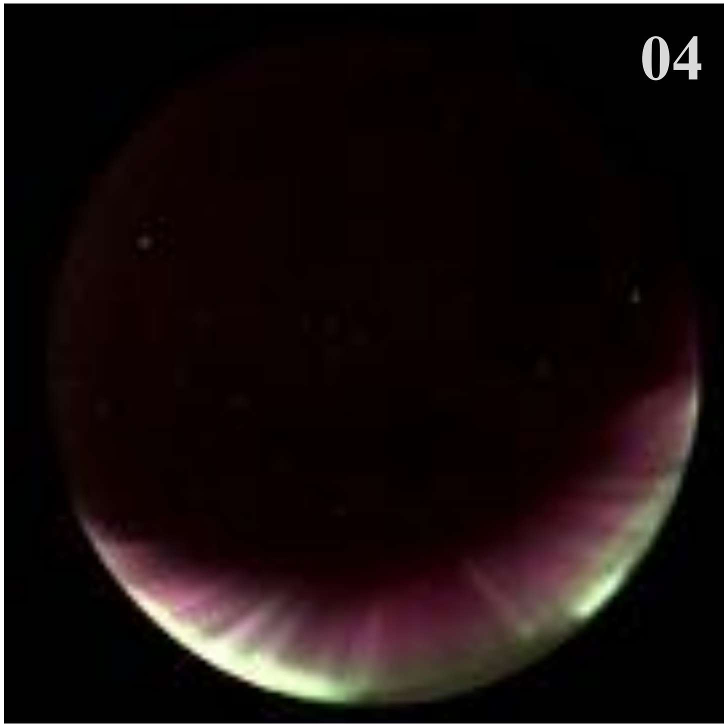

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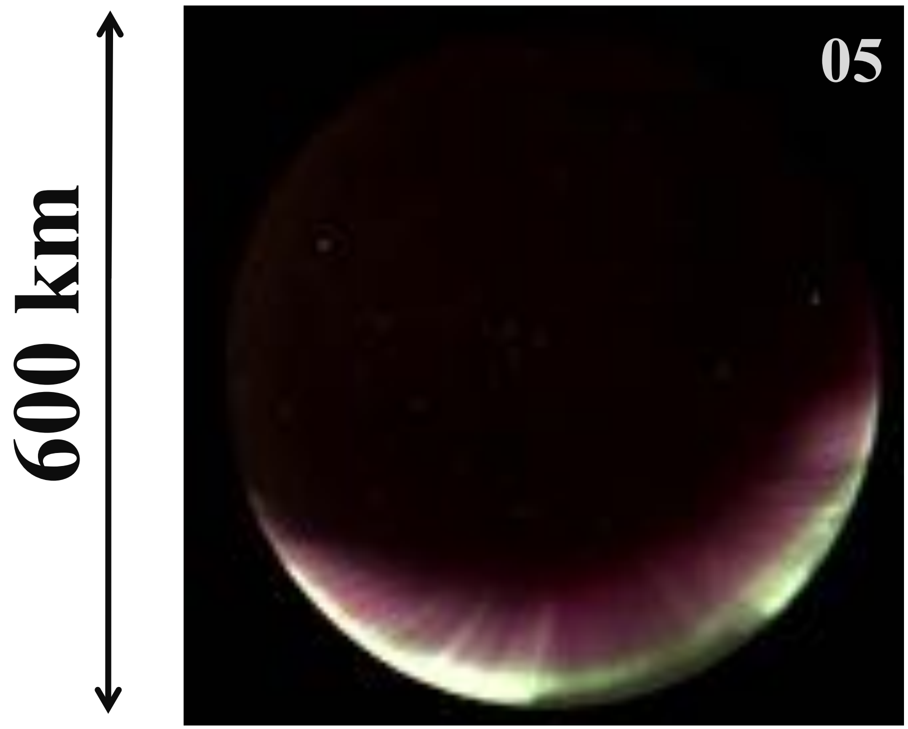

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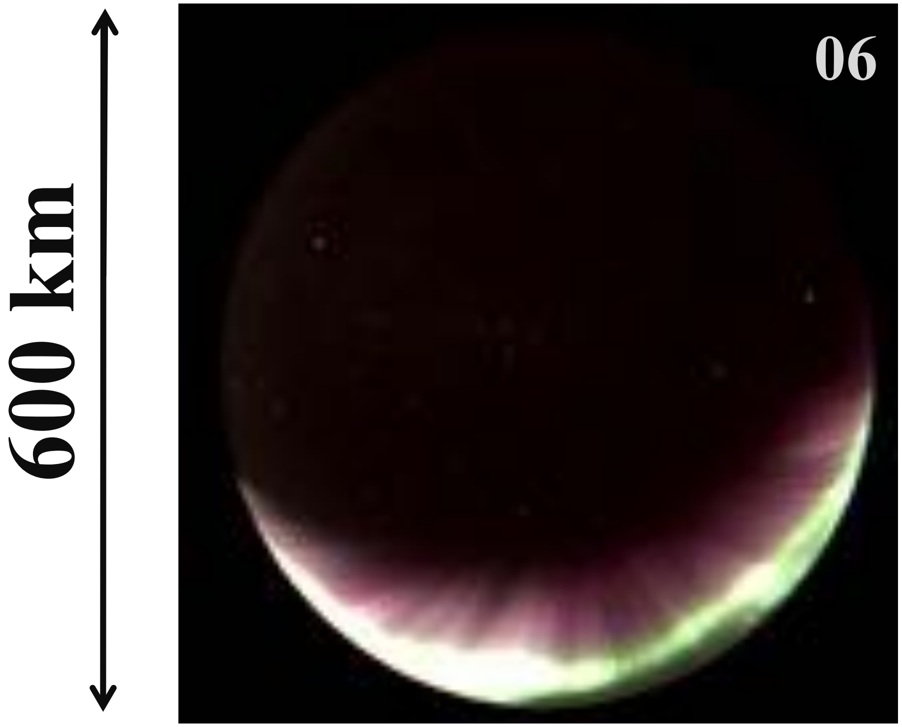

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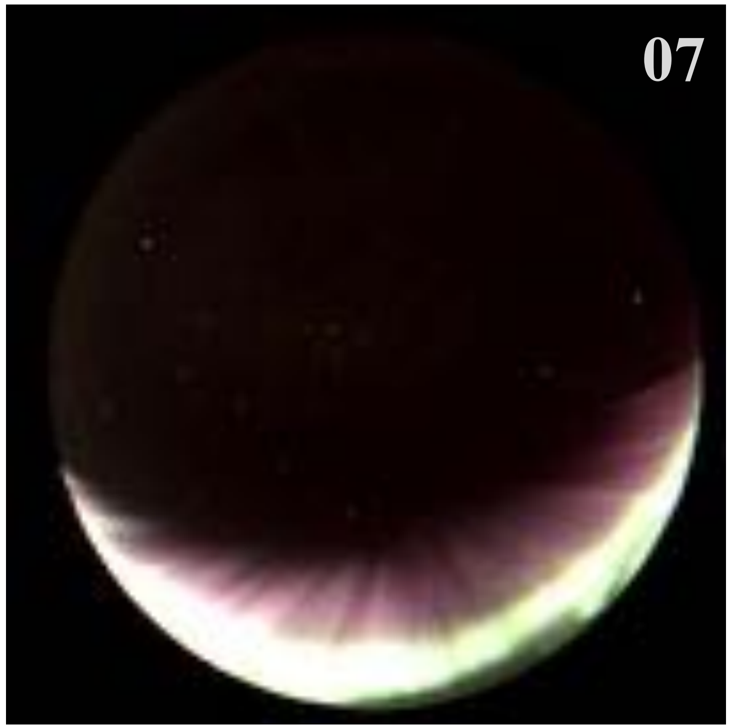

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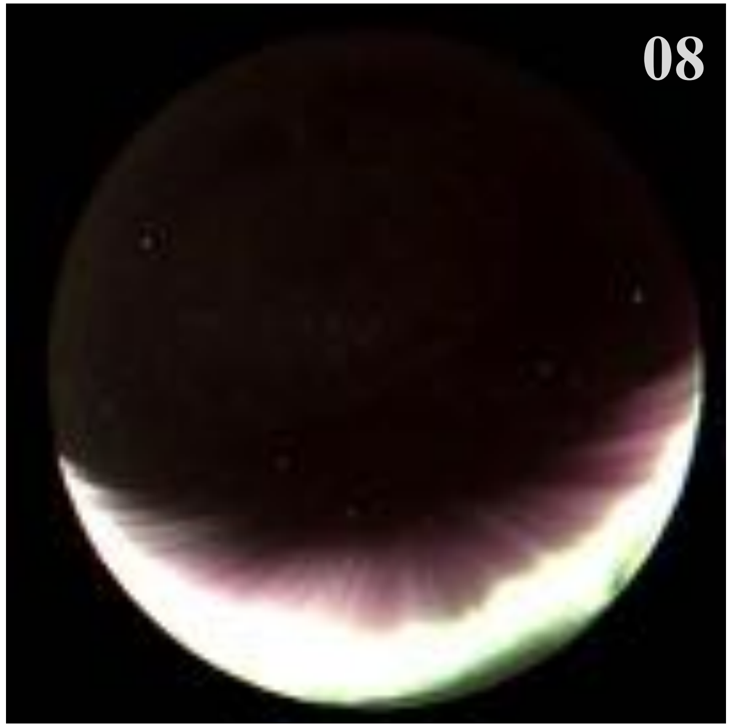

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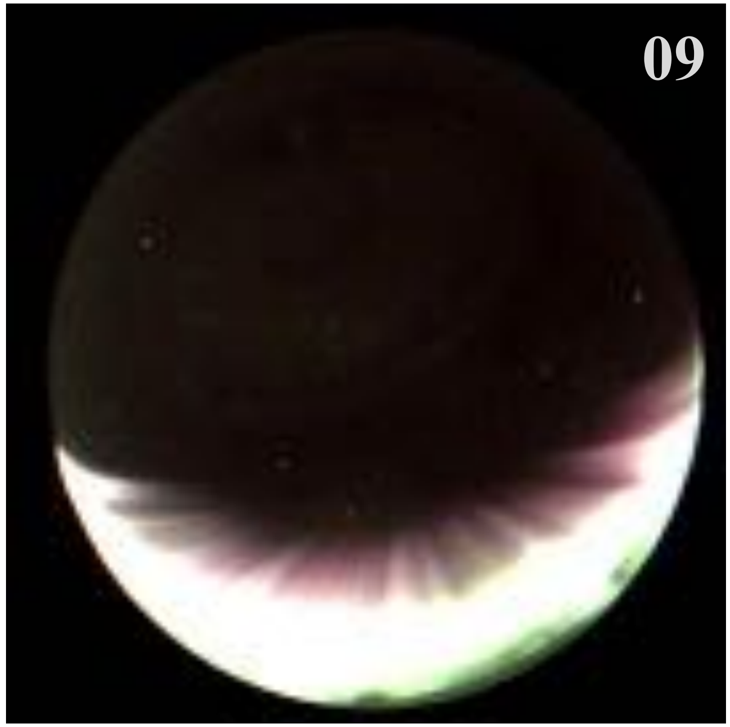

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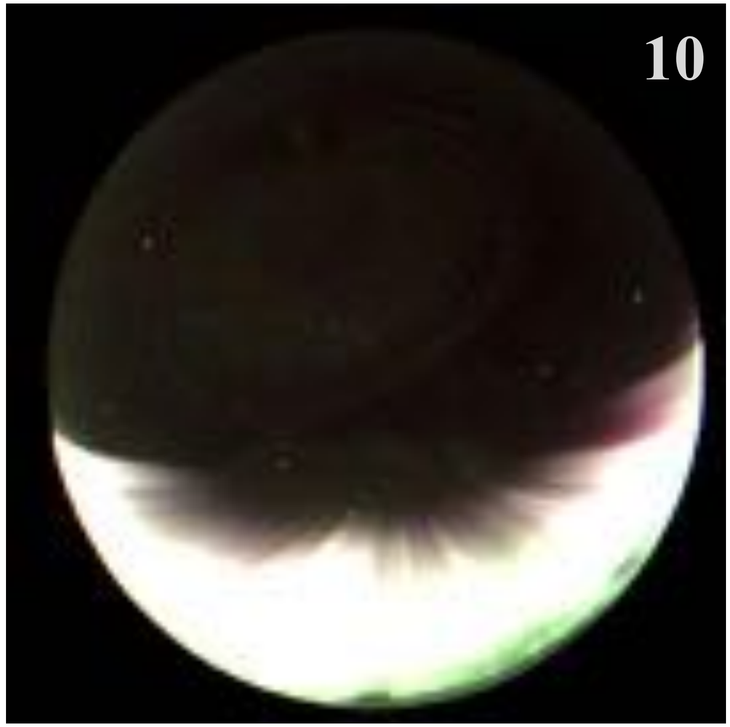

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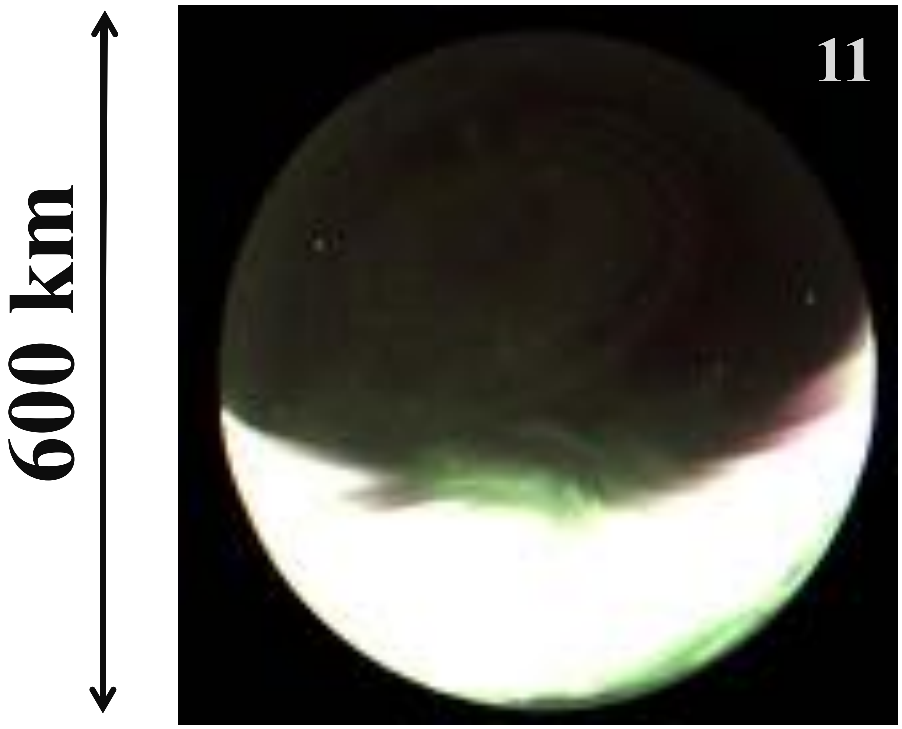

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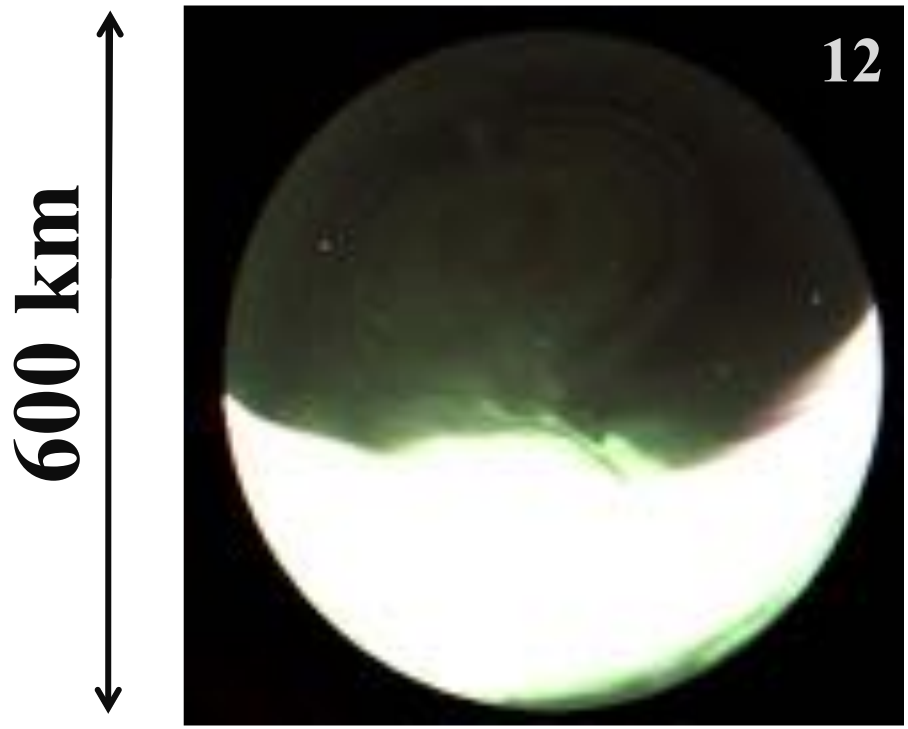

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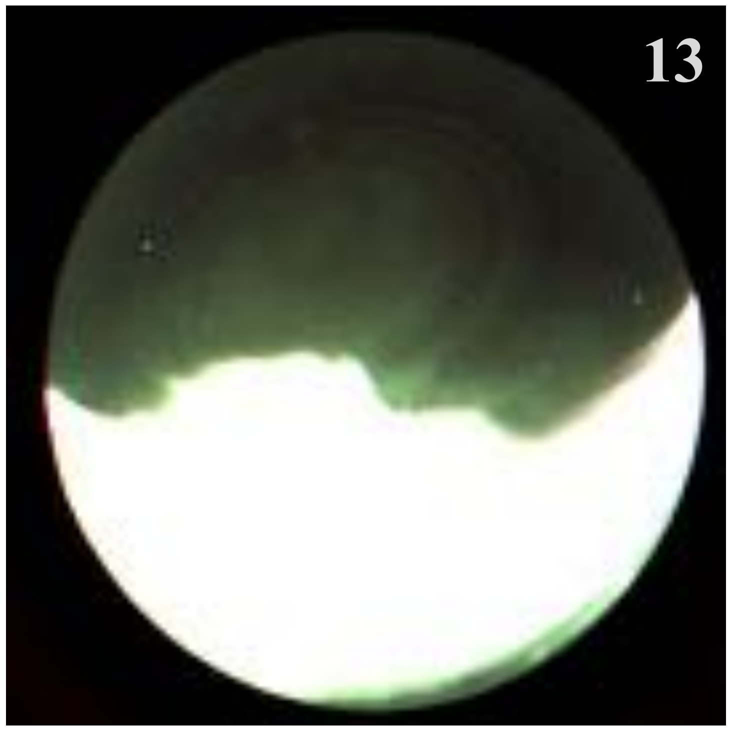

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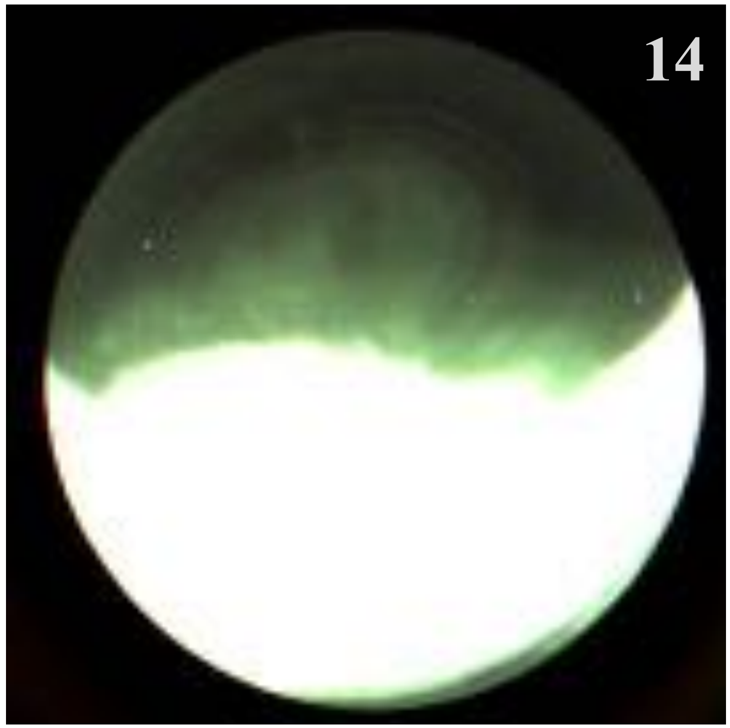
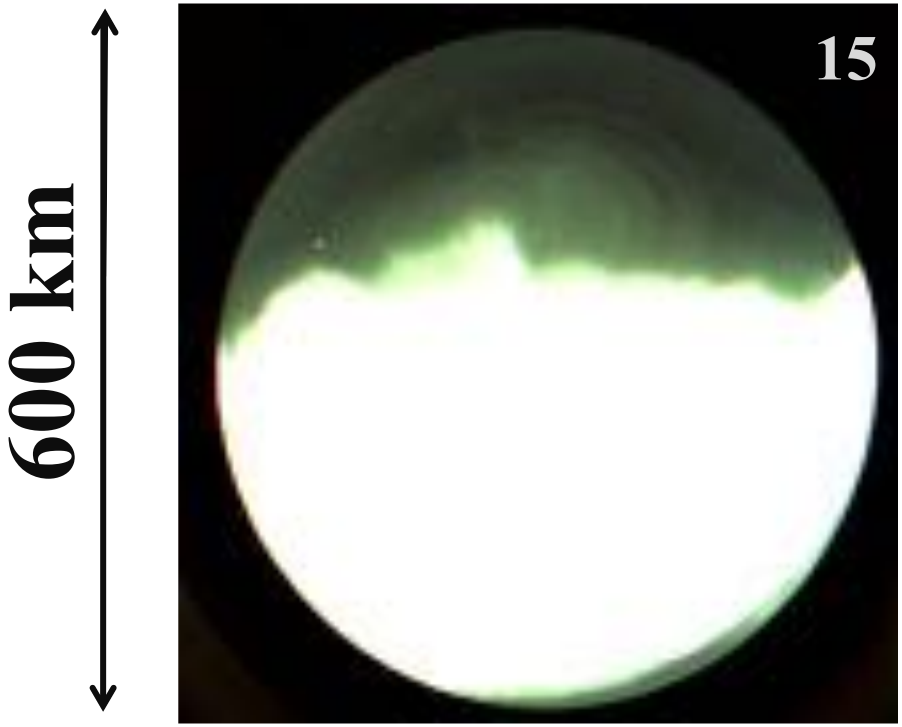


Keep in mind these frames are 10 seconds apart, and the field of view is roughly 600 kilometers across.

The Substorm

03-b



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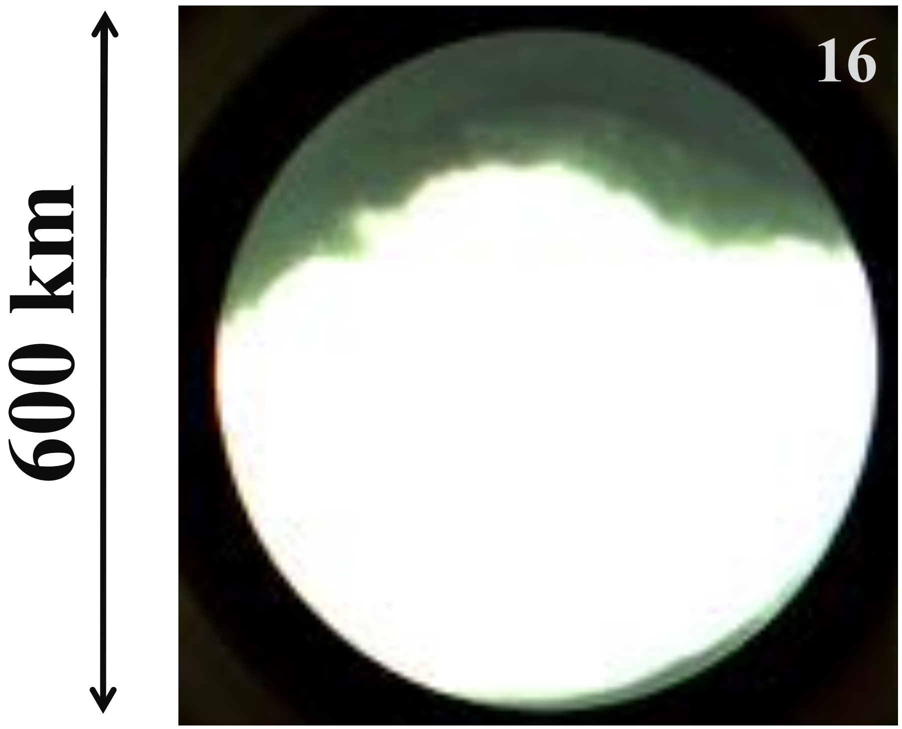

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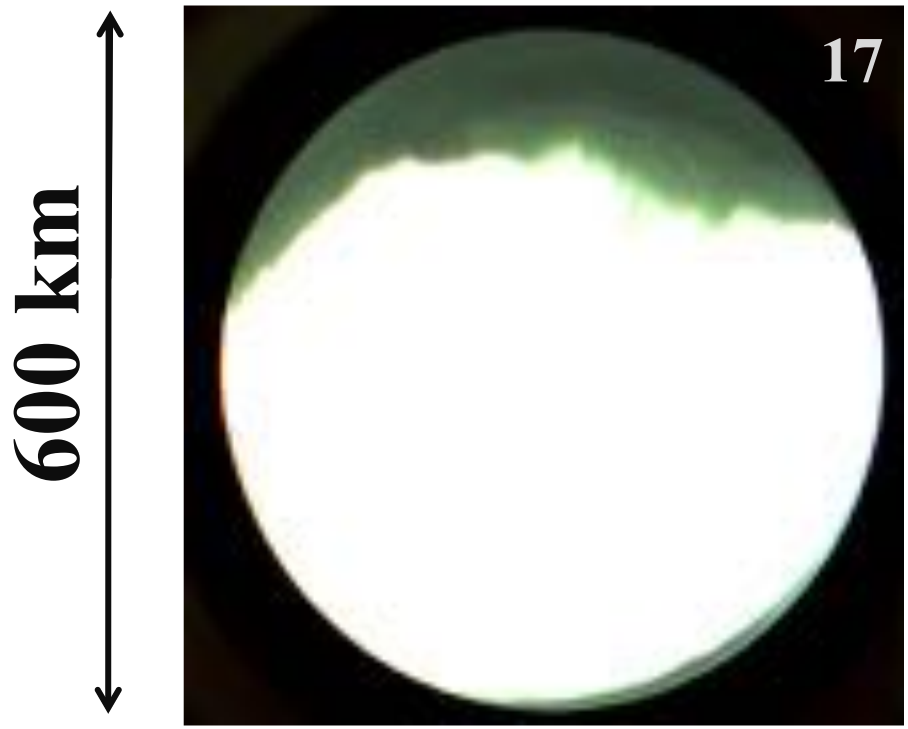

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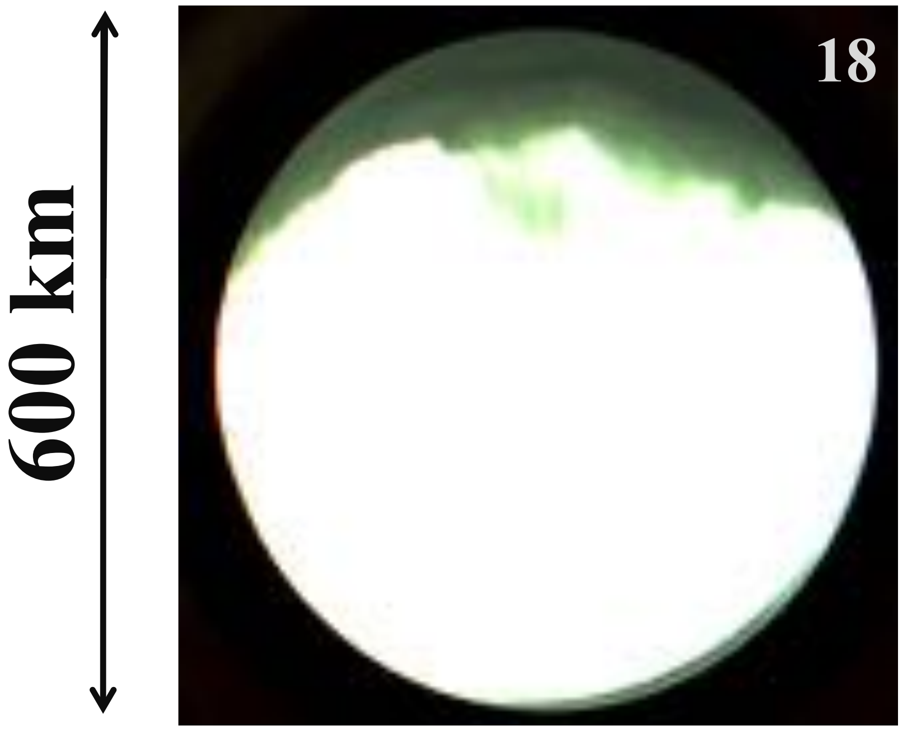

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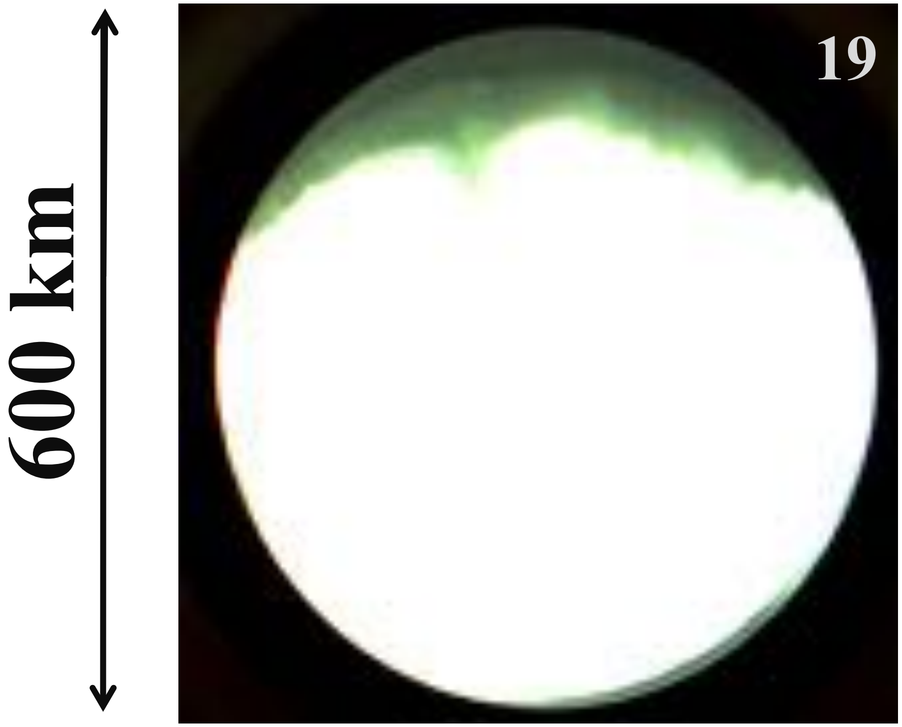

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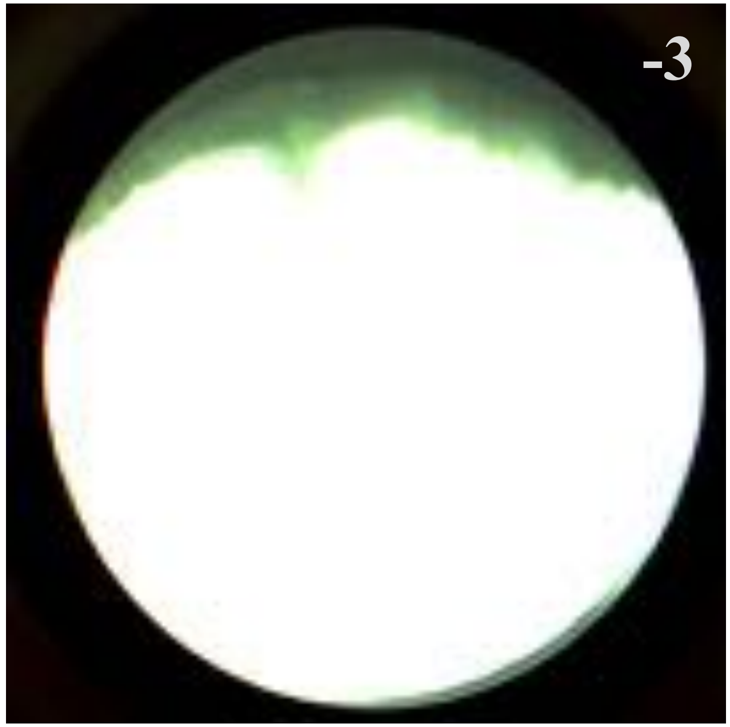

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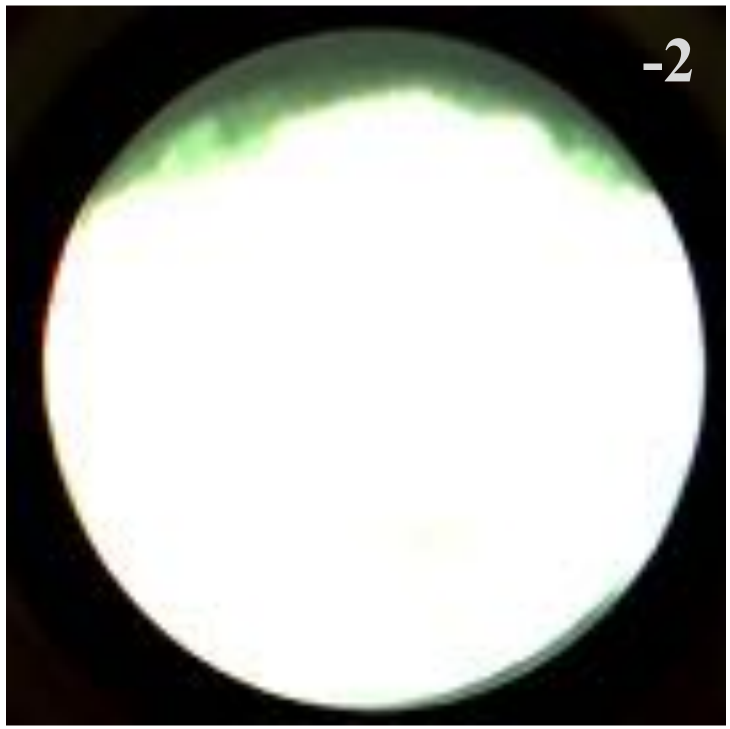

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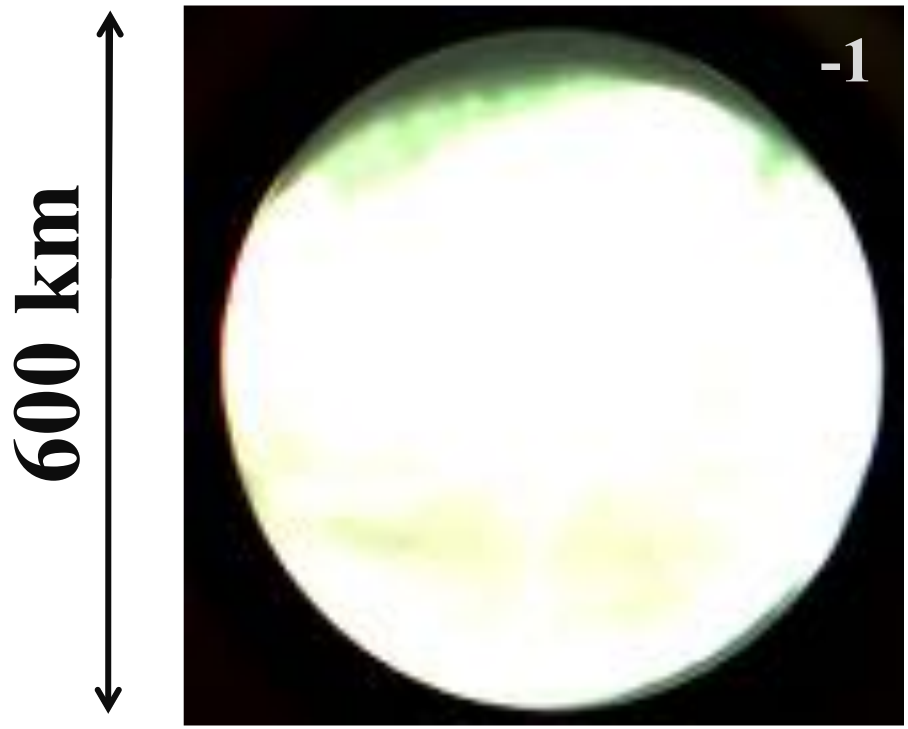

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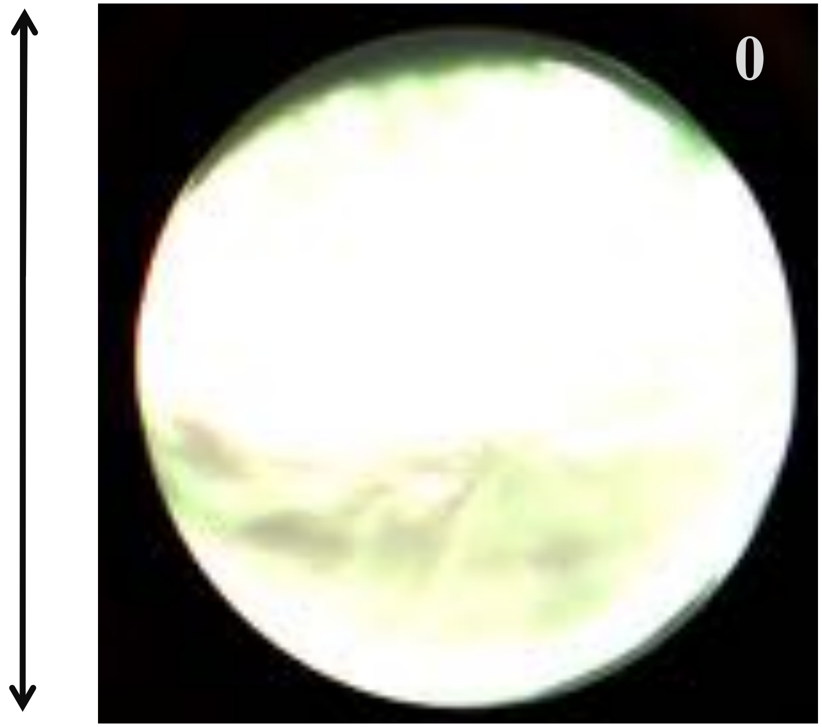
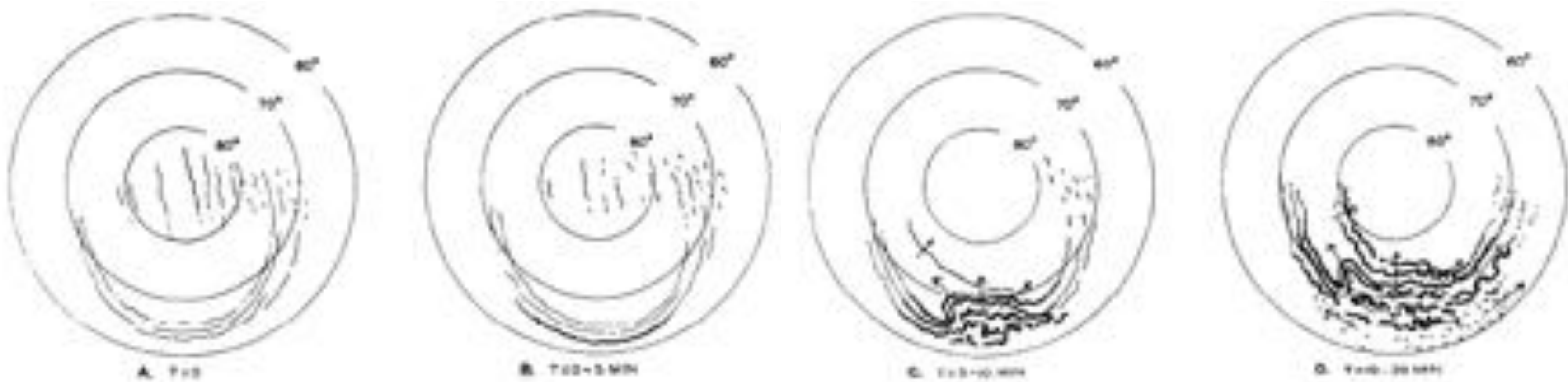


About three minutes after “onset” (I’ll come back to that phrase), the sky is full of blazingly bright, dynamic aurora. If you have the chance to see this in person, it is one of Earth’s most breathtaking spectacles. This is the substorm… the topic of this lecture.

What is a substorm?



THE DEVELOPMENT OF THE AURORAL SUBSTORM

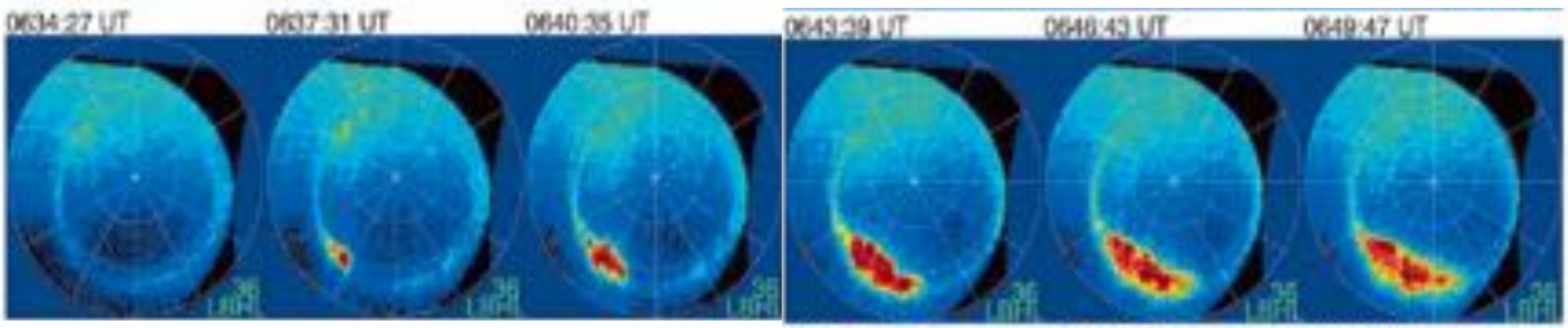
S.-I. AKASOFU
Geophysical Institute, University of Alaska, College, Alaska

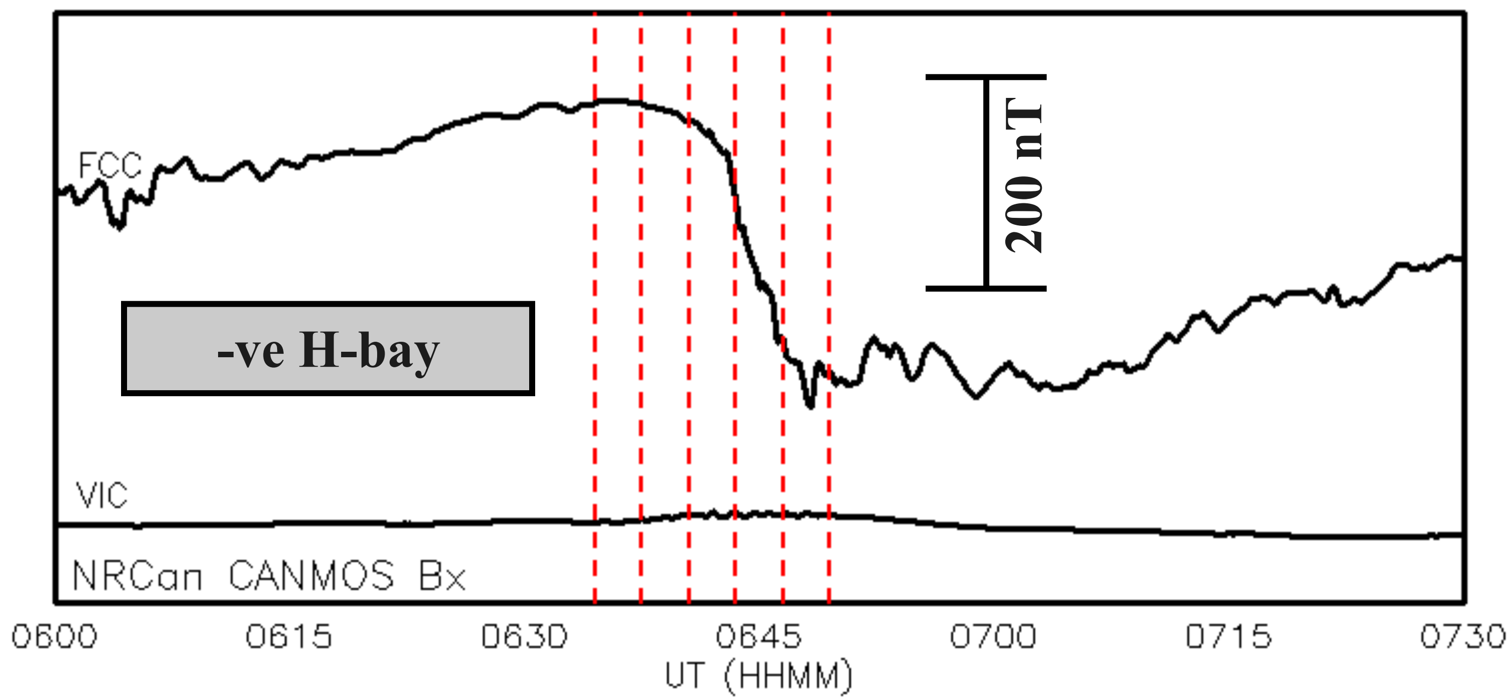
(Received 13 January 1964)

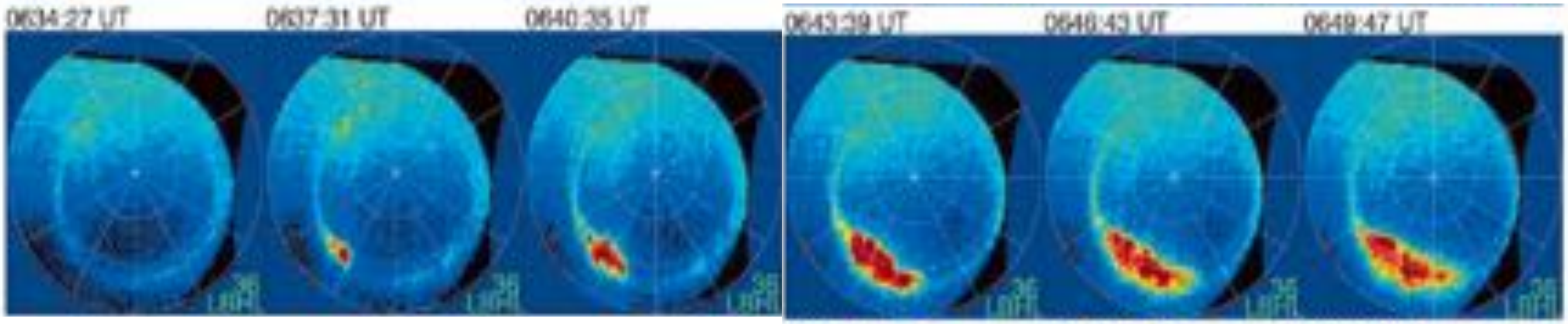
Abstract—A working model of simultaneous auroral activity over the entire polar region is presented in terms of the auroral substorm. The substorm has two characteristic phases, an expansive phase and a recovery phase. Each phase is divided into three stages, and characteristic auroral displays over the entire polar region during each stage are described in detail. Further, all the major features seen at a single station are combined into a consistent picture of large-scale auroral activity.

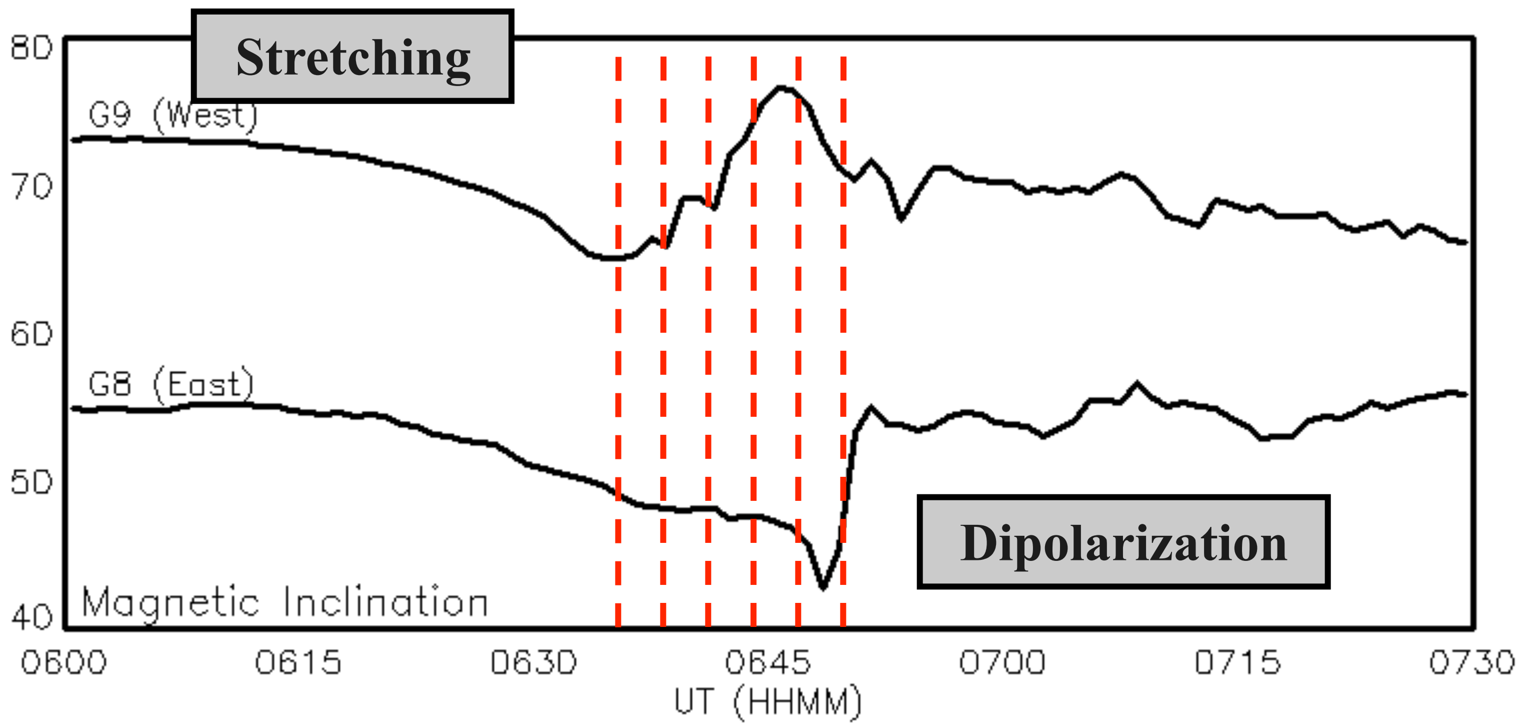
The Substorm

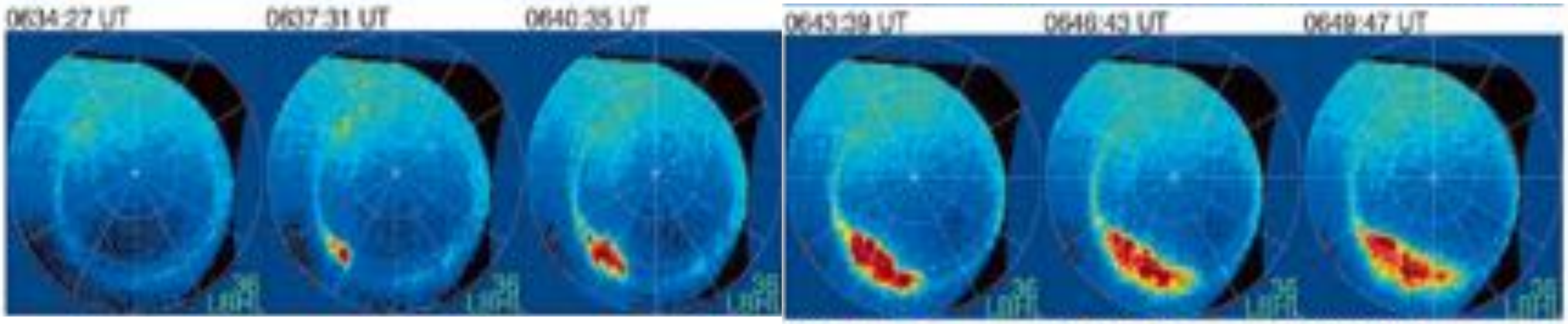
04-b






0634:27 UT
0637:31 UT
0640:35 UT
0643:39 UT
0646:43 UT
0649:47 UT


Stretching
G9 (West)
G8 (East)
Dipolarization
Magnetic Inclination
80
70
60
50
40
0600
0615
0630
0645
0700
0715
0730
UT (HHMM)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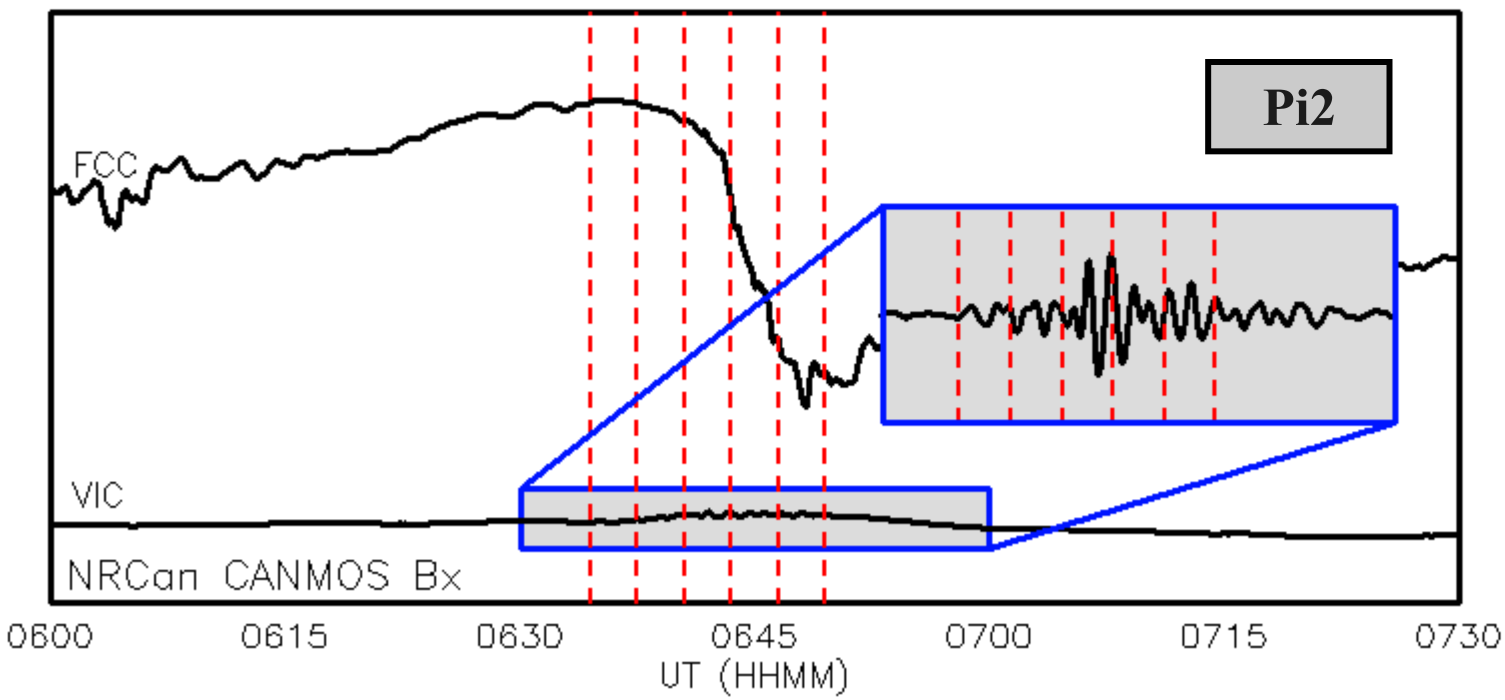
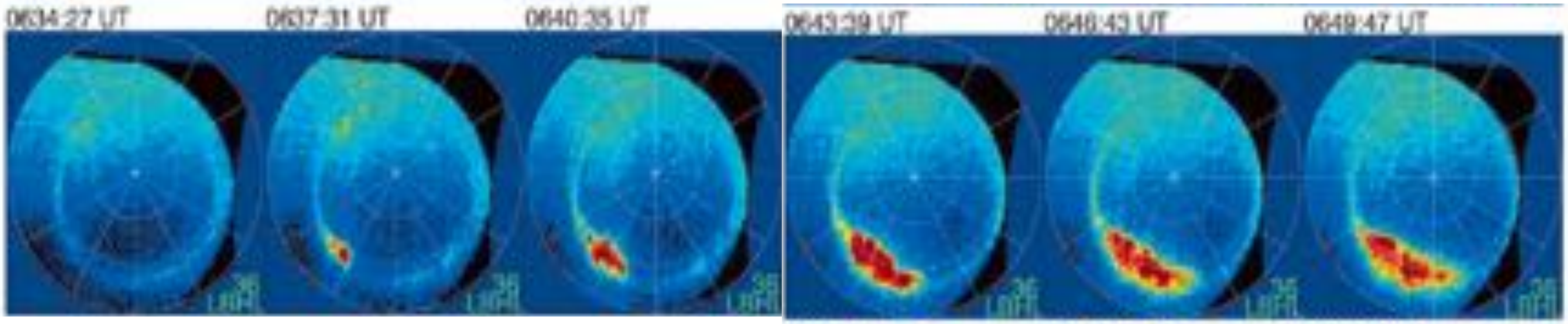
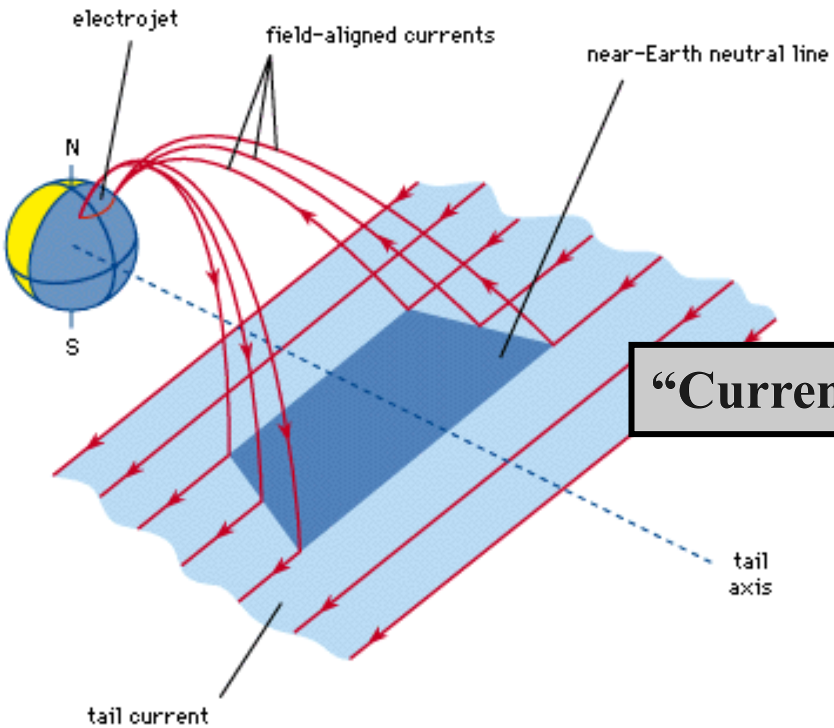

Pi2
FCC
VIC
NRCan CANMOS Bx
0600
0615
0630
0645
0700
0715
0730
UT (HHMM)

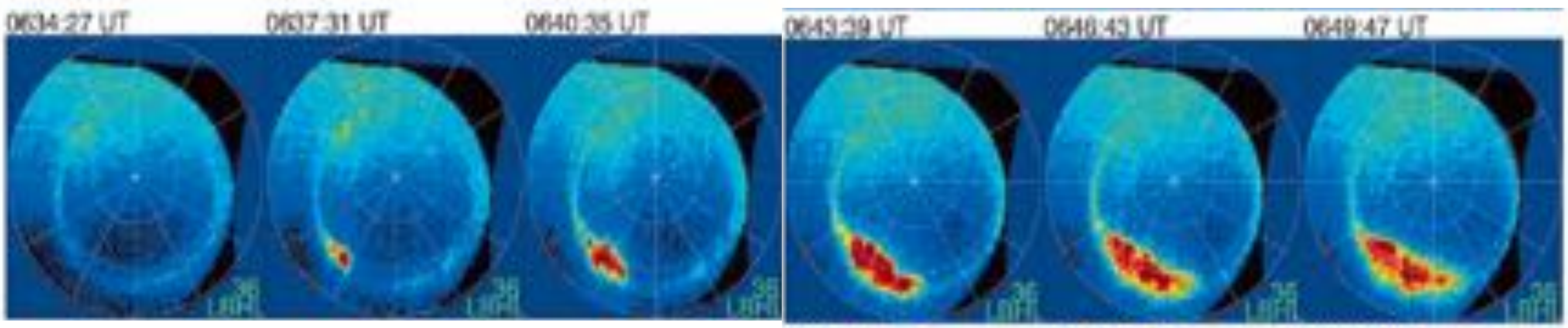
The Substorm

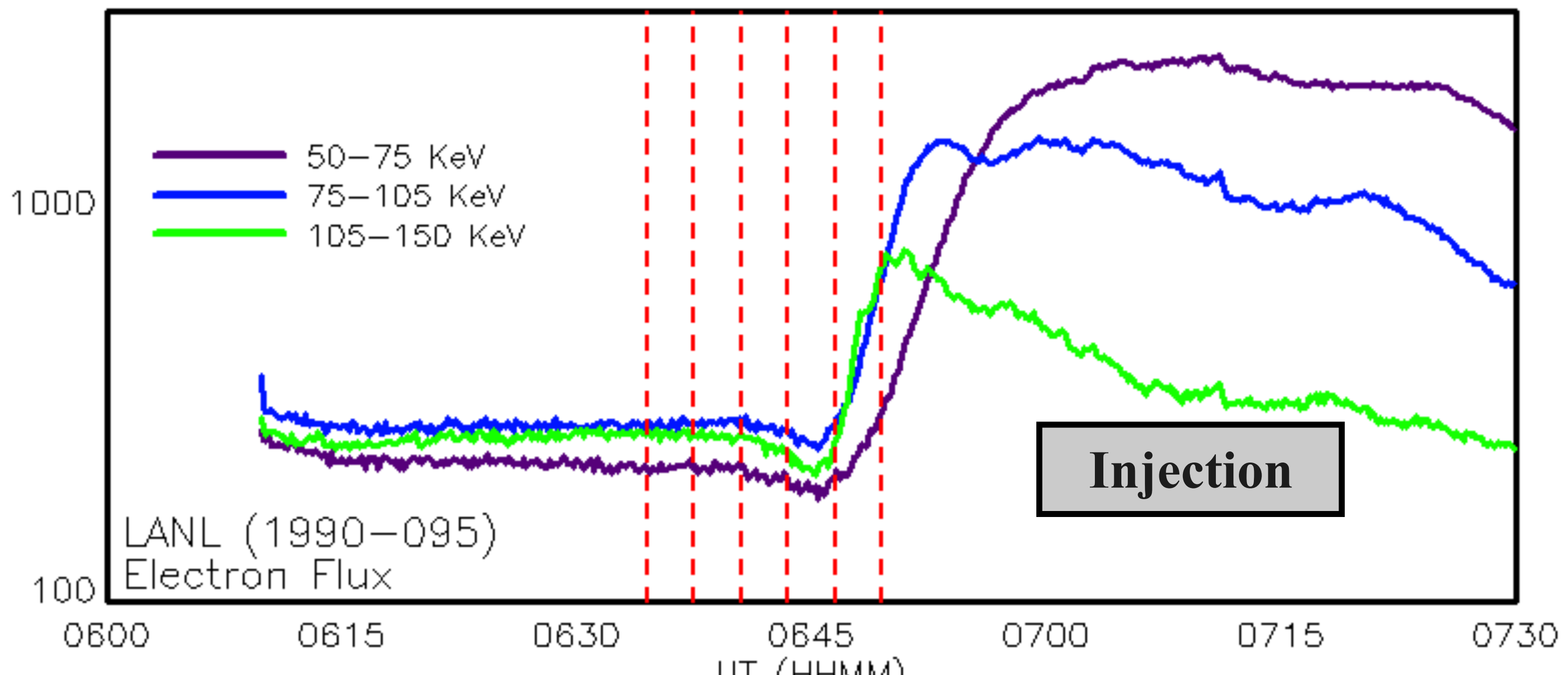




"Current Wedge"

The Substorm

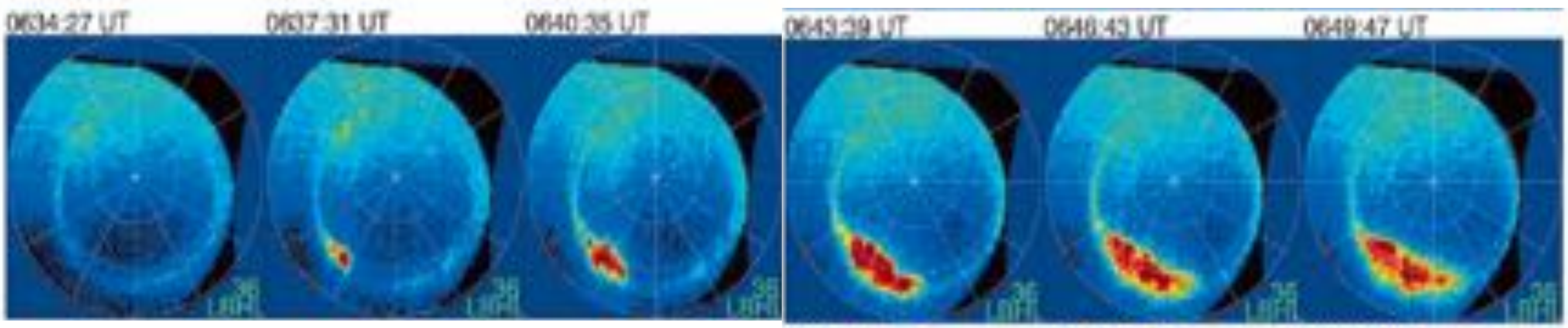


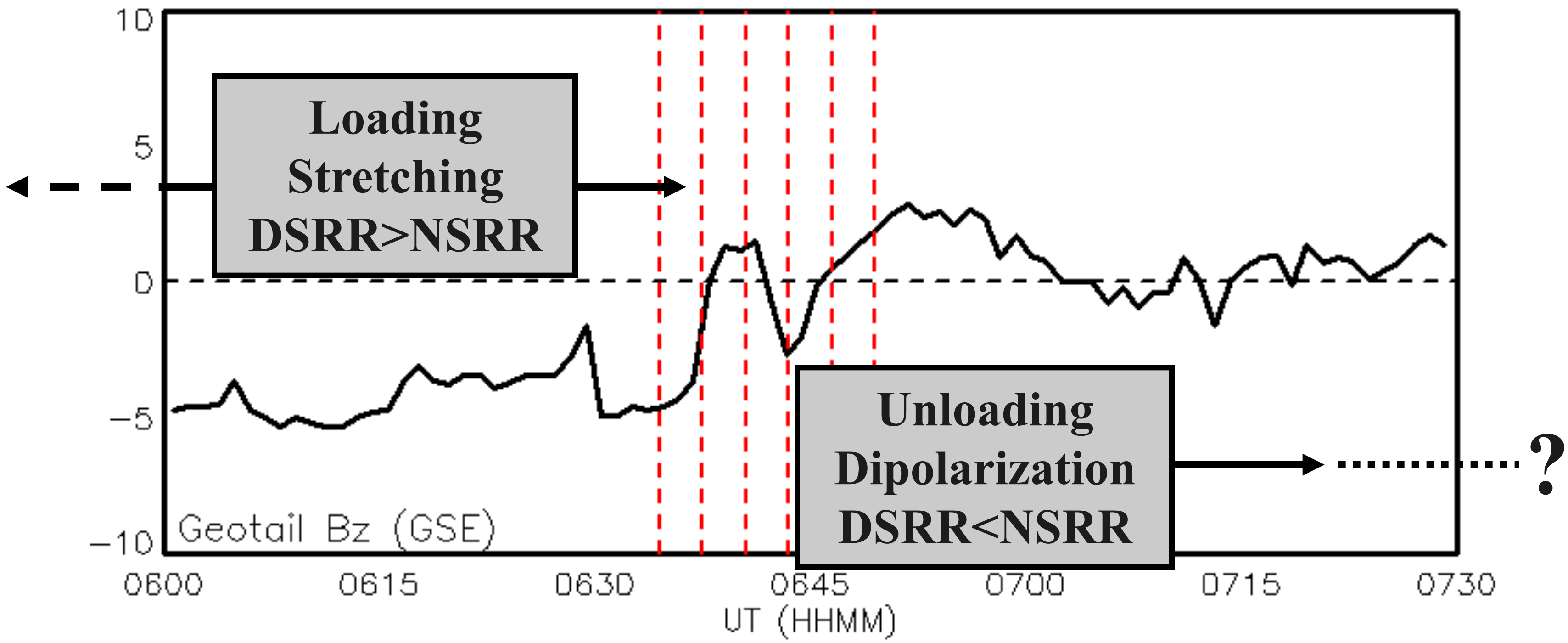


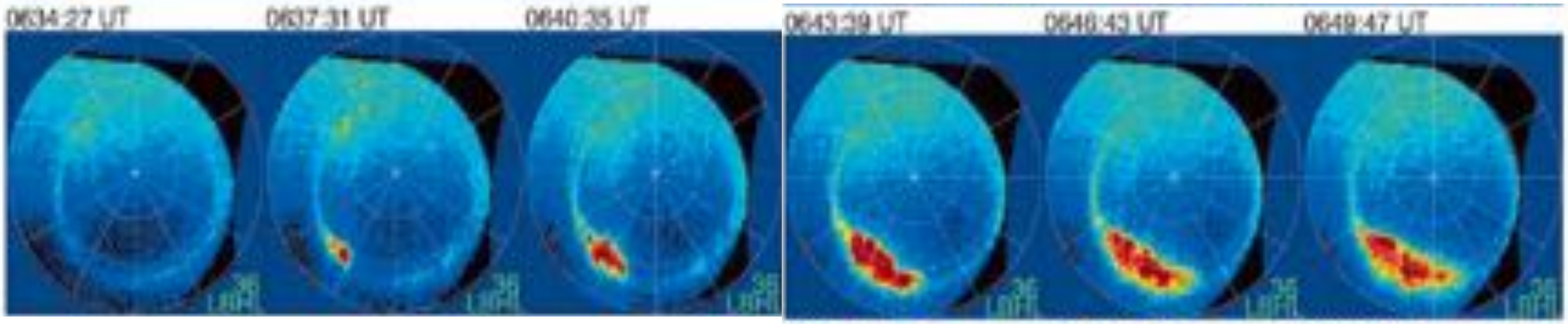
I want you to think about this figure when you are working through question 2.

The Substorm

04-g






0634:27 UT
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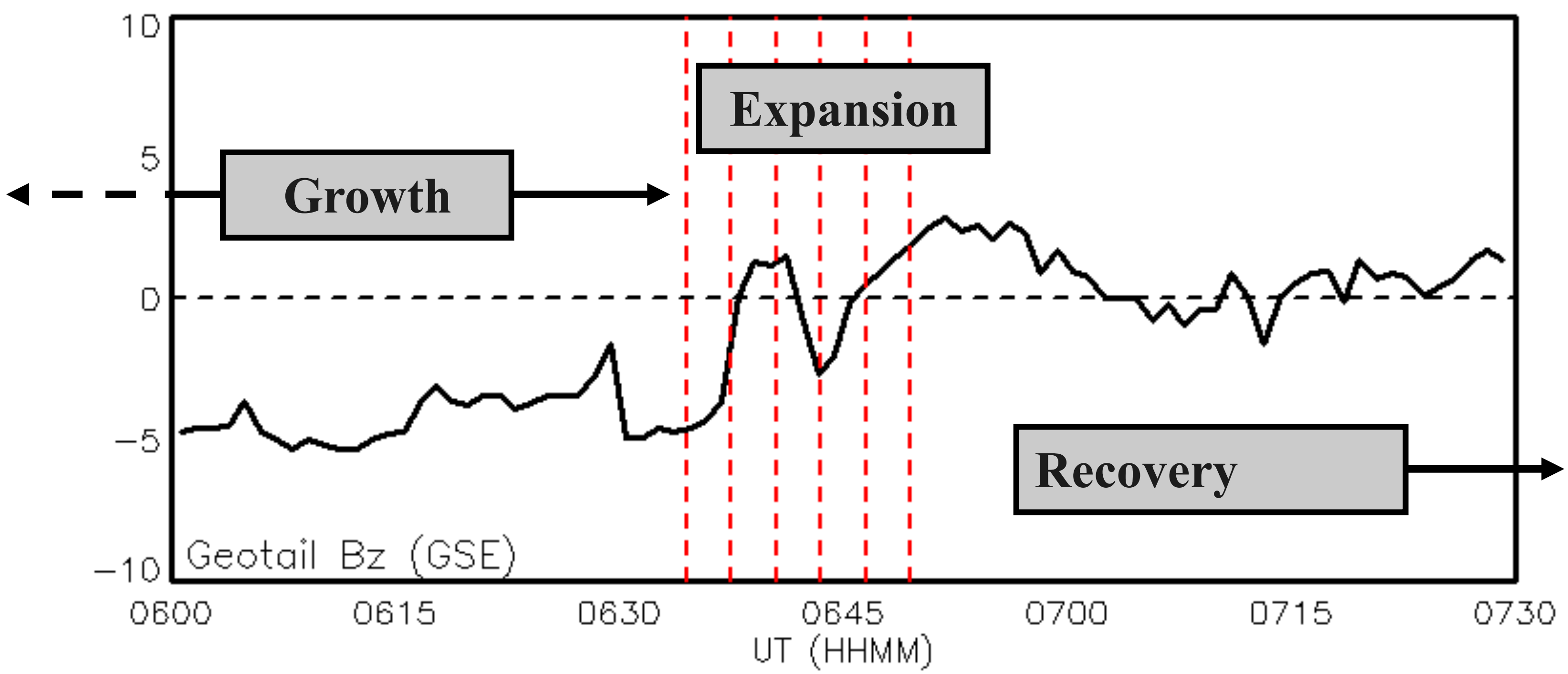
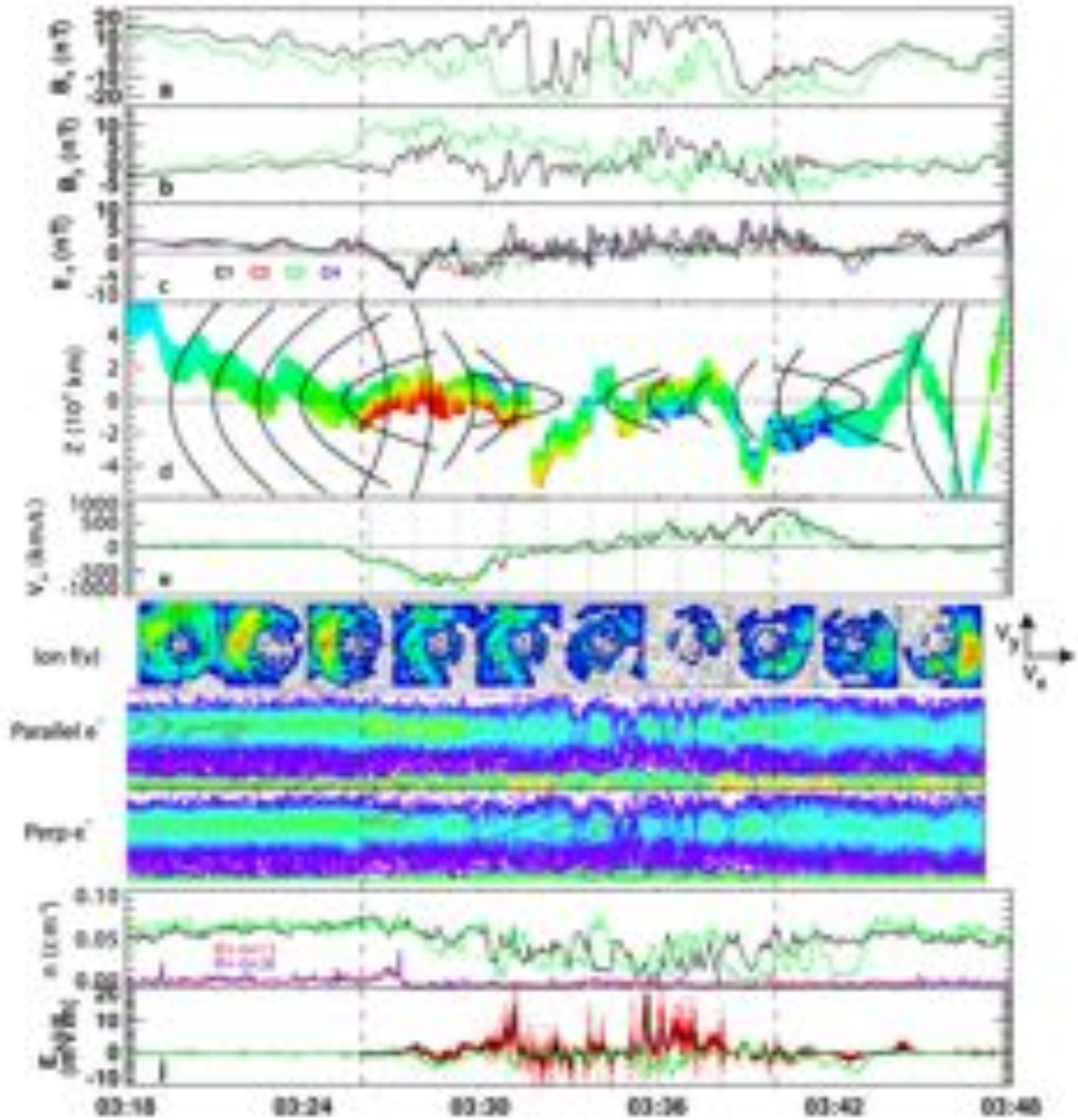

Expansion
Growth
Recovery
Geotail Bz (GSE)
10
5
0
−5
−10
0600
0615
0630
0645
0700
0715
0730
UT (HHMM)

The Substorm

04-i



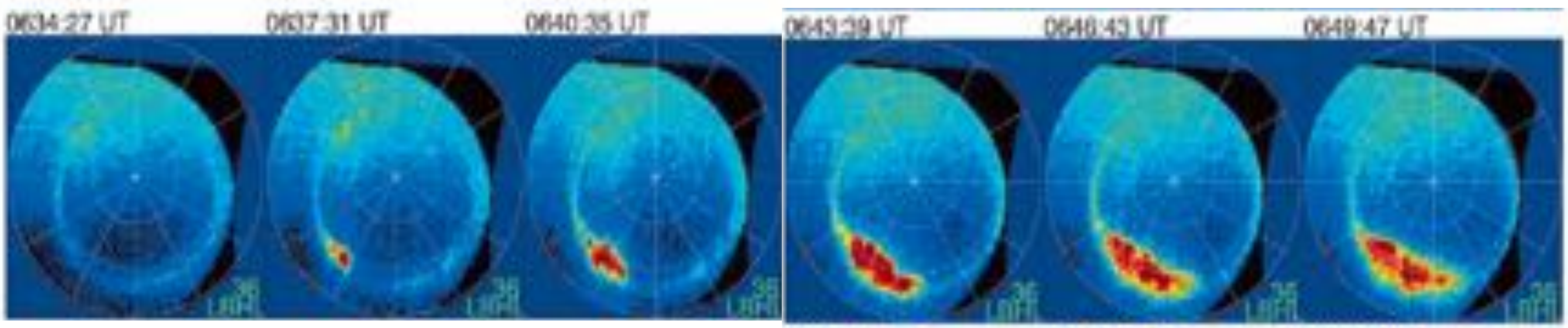
Near-Earth Reconnection around onset

The Substorm

04-j

Near-Earth Reconnection around onset and plasmoid ejection downtail.

The Substorm



Ionospheric & Magnetospheric things that happen around onset…

Auroral Brightening	**-ve H-bay**	**Pi2**
AKR	**Near-Earth Reconnection**	**Absorption Spike**
Absorption Bay	**VHF Burst**	**Injection**
Pi1B	**Auroral Breakup**	**BBF**
BBF Braking	**Convection Pulses**	**Dipolarization**
Current Disruption	**Current Diversion**	**Current Wedge**
Plasmoid	**CPS Expansion**	**Streamer**

OK, so… What is a substorm?

"… magnetospheric substorm describes an interval of increased energy dissipation confined, for the most part, to the region of the auroral oval. The onset of this process is signalled by explosive increases in auroral luminosity in the midnight sector, and the entire process encompasses an interval during which the strength of the current in the auroral electrojets increases from and returns to the background level from which the substorm arose. During this interval there may be a sequence of intensifications of the westward electrojet, each associated with a Pi 2 micropulsation burst and a westward travelling surge. As the substorm develops, the region of discrete auroras in the midnight sector expands poleward and westward (the poleward bulge). Eventually, the region of disturbed aurora reaches a maximum latitude and begins to recover toward its pre-substorm location. The interval of time between the first Pi2 burst and the time the aurora reaches a maximum latitude has been called the expansion phase. The interval during which the aurora in the midnight sector returns to lower latitudes is called the recovery phase." *Rostoker et al., JGR, 1980.*

"Substorms are global reconfigurations of the magnetosphere involving storage of solar wind energy in Earth's magnetotail and its abrupt conversion to particle heating and kinetic energy." *Angelopoulos et al., Science, 2008.*

OK, so… What is a substorm?

"(1) The process occurs in two steps: first mechanical stresses deform the magnetic field into a configuration of increased energy; second, the magnetic configuration becomes unsustainable and changes quickly, releasing the energy. Both steps are in general associated with magnetic topological changes."

(2) In most cases, the mechanical stress is related to plasma flow, which transports magnetic flux and, with field lines attached to a massive body, increases the magnetic energy.

(3) Why the magnetic configuration becomes unsustainable and what causes the quick change remain highly disputed questions; many possibilities can be imagined, and there may not be a universal answer.

(4) A potentially universal aspect is magnetic flux return; inability to return the flux smoothly seems to play a role."

Heliophysics, Volume 2, Page 291 (Section by Vasyliunas).

I assure you – <u>these are very sensible statements!</u>

I would add that this is (5) cyclic, (6) the cycle takes 1-3 hours and may (sawteeth) or may not repeat, and (7) growth, expansion, and recovery appear to all be accomplished by Earthward flow on the nightside (the substorm is a disturbance in convection).

Energy Budget

What does the substorm accomplish for the geospace system?

Check out *Baker et al., JGR,* 1994 and papers that reference it.

Joule Heating
Injection
Precipitation
Radial Transport
Topological reconfiguration
Outflow
Plasmoids
•
•

Instability

What is the onset mechanism?

We do not know what the instability is, but THEMIS, soon RBSP (& ERG), GOES, and exciting new ground-based programs (StormDARN, CGSM, TREx, THEMIS-ASI, etc mean that **now is the time!**

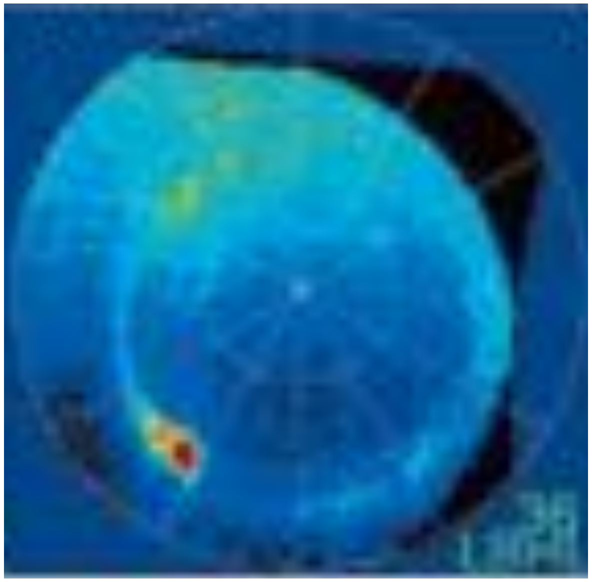
NER (tearing mode instabilities)
Current limiting instabilities
Interchange and ballooning inst.
•
•

Universality

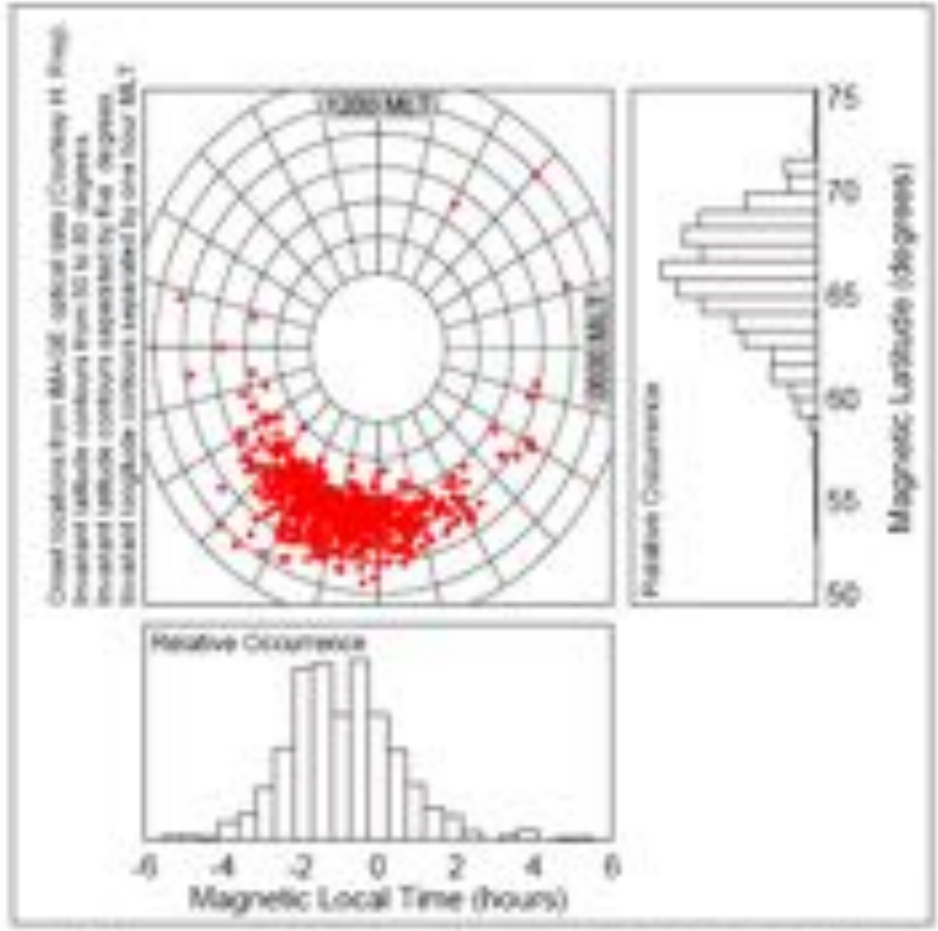
What does this teach us?

The substom is an interesting phenomenon, as an exemplar of plasma processes that happen in other cosmic systems, and a strange process where small scale local physics evolves to have global consequences....

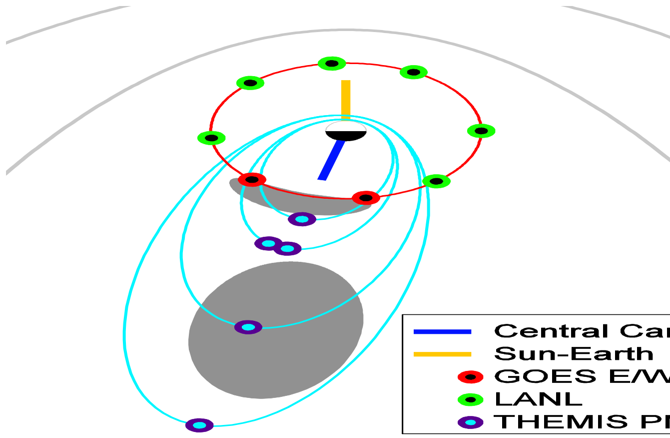
Jupiter
Saturn
Mercury
Solar flares
Neutron stars
Magnetars
SOC
Scaling Laws
•
•



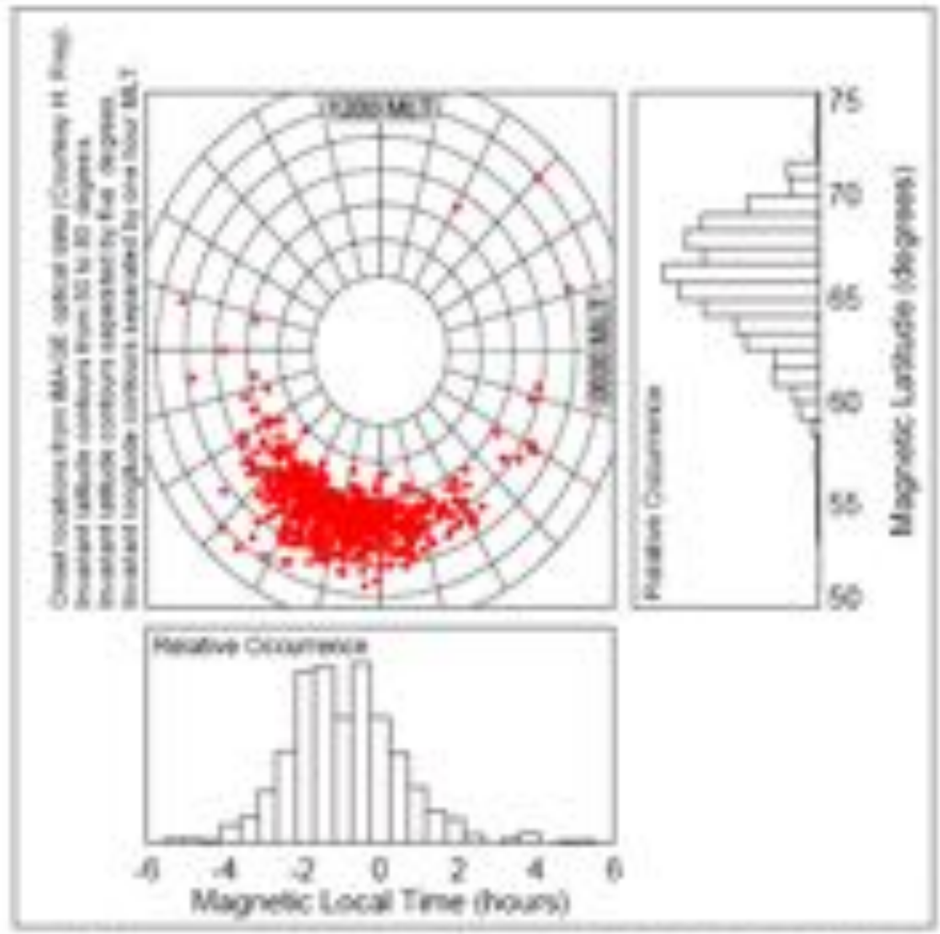
800 onsets



MLT and MLat distribution of ~800 onsets identified in the IMAGE WIC data (see paper by *Frey et al.*, *JGR*, 2004).

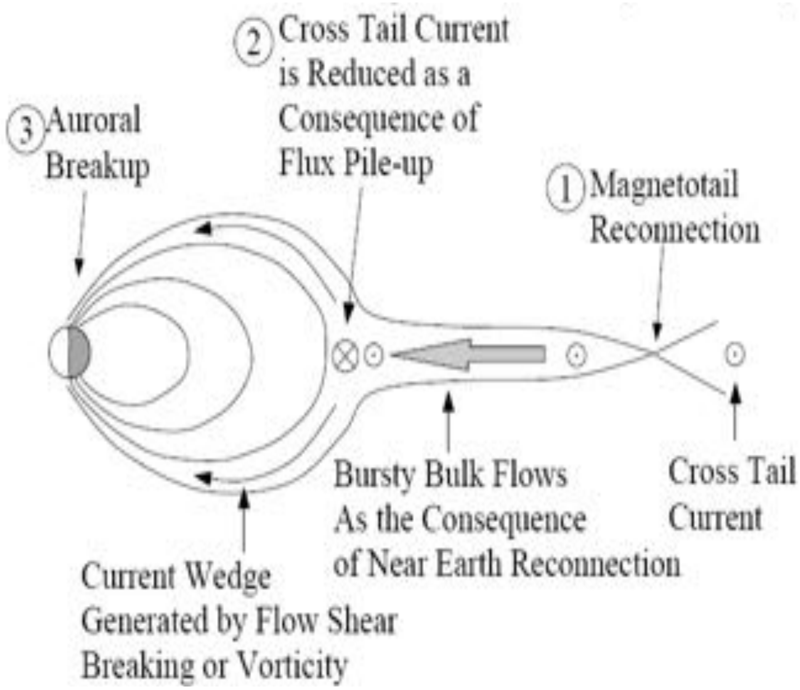


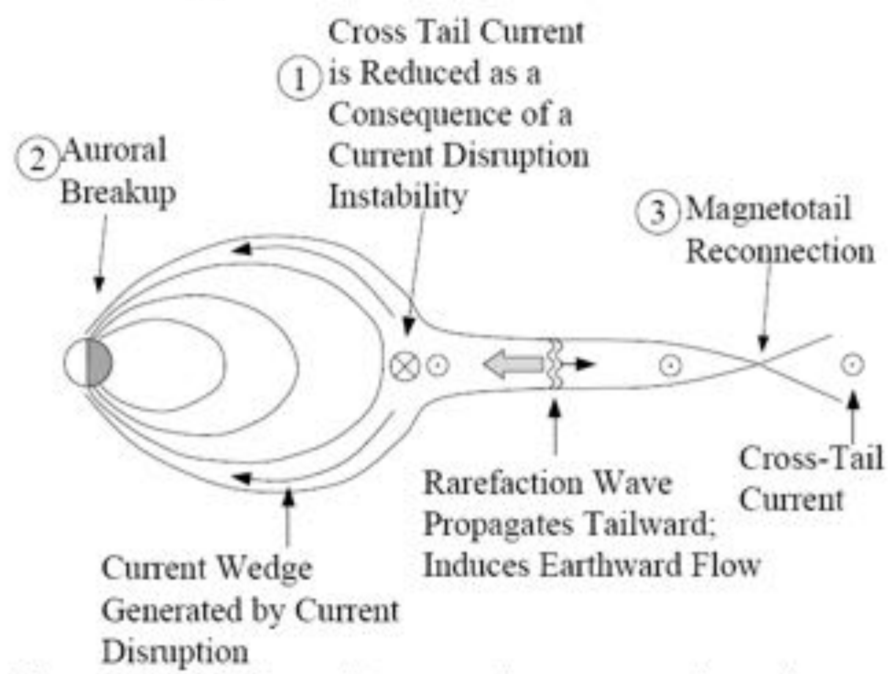
For this and many other reasons, we know the "onset" originates in a pre-midnight region between ~7 and ~20 Re downtail



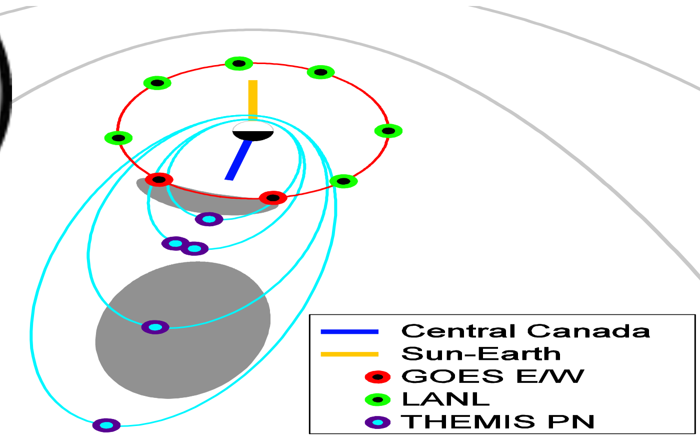
MLT and MLat distribution of ~800 onsets identified in the IMAGE WIC data (see paper by *Frey et al.*, *JGR*, 2004).

What causes substorm expansion phase onset?





Near-Earth Neutral Line (NENL)	↔	***Current Disruption***
"Outside-In"	↔	***"Inside-Out"***
Thin Current Sheet (TCS)	↔	***On the edge of the TCS***



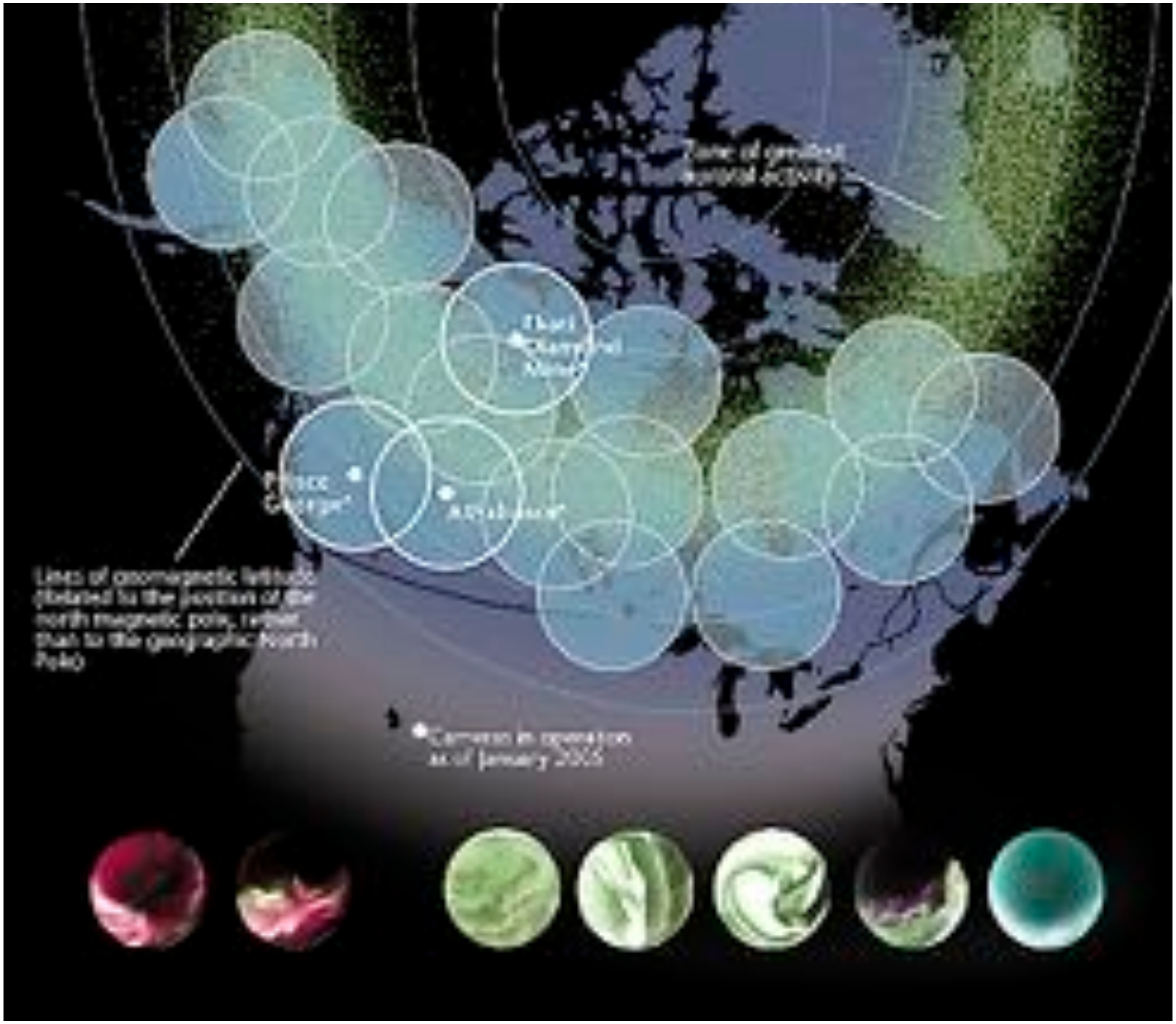
THEMIS and GOES – 7 satellites with 1, 2, and 4 sidereal day orbits.

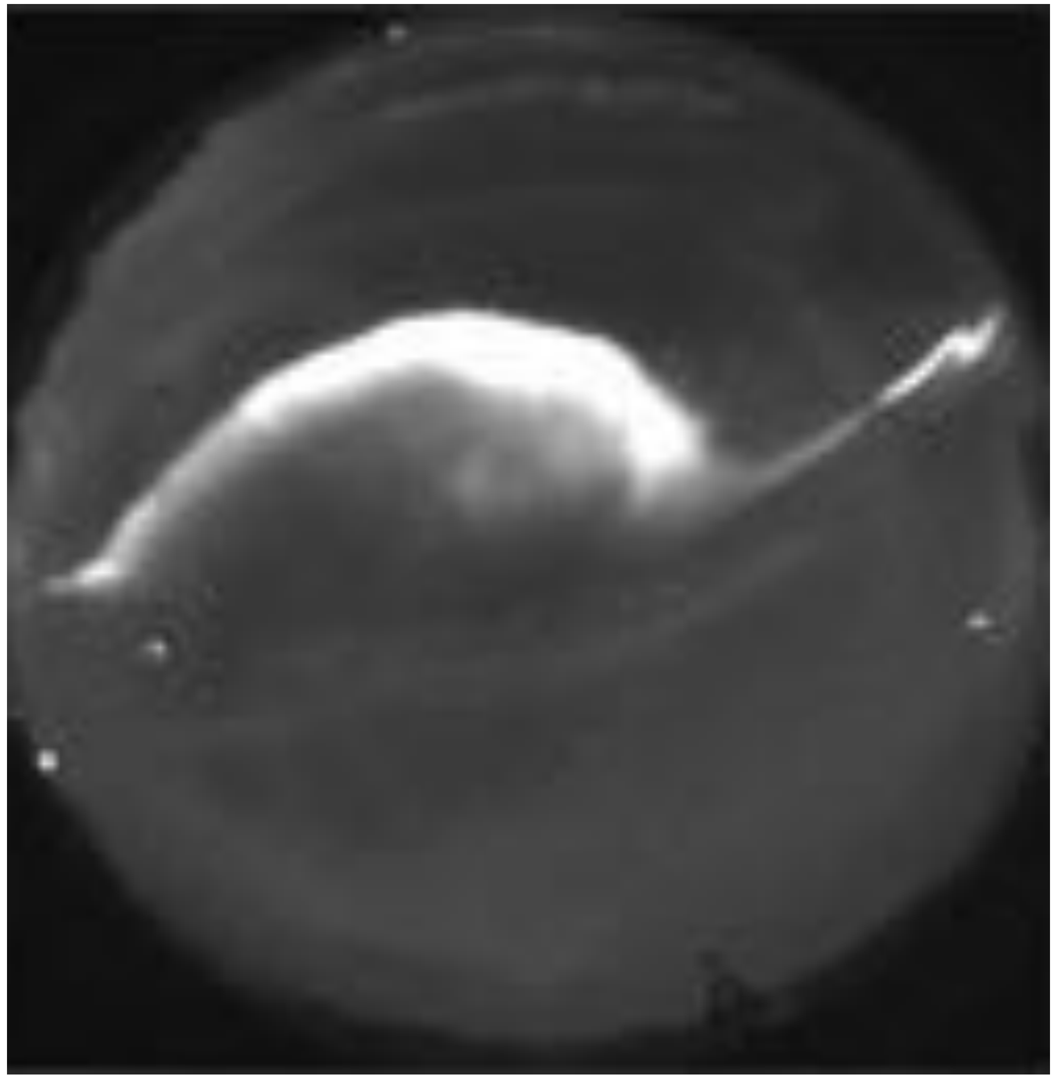
Every 4 sidereal days, all 7 are in "apogee conjunction".

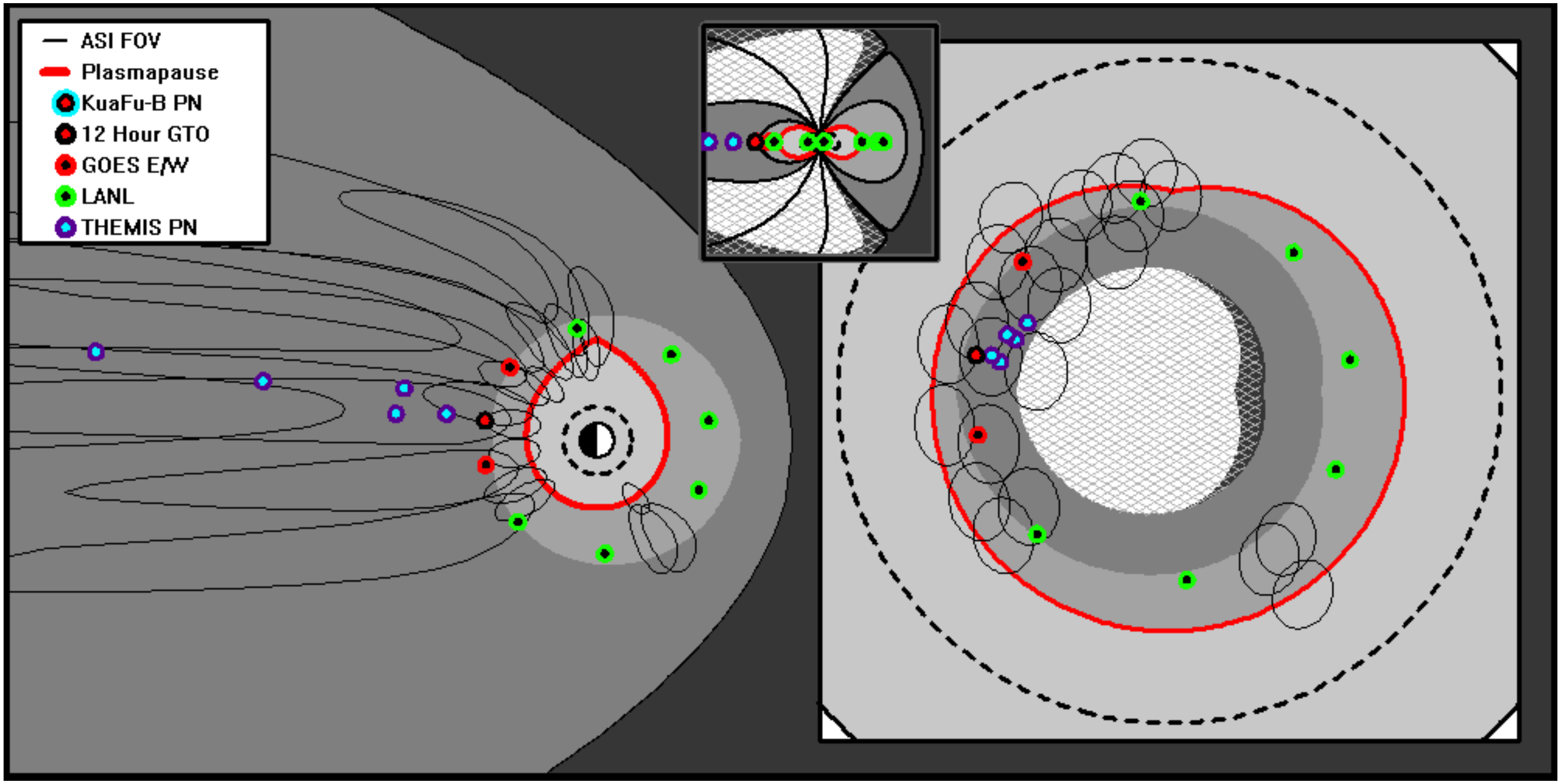
Every apogee conjunction occurs over central Canada.

At apogee conjunction, the constellation brackets the CD and NENL regions

The Substorm



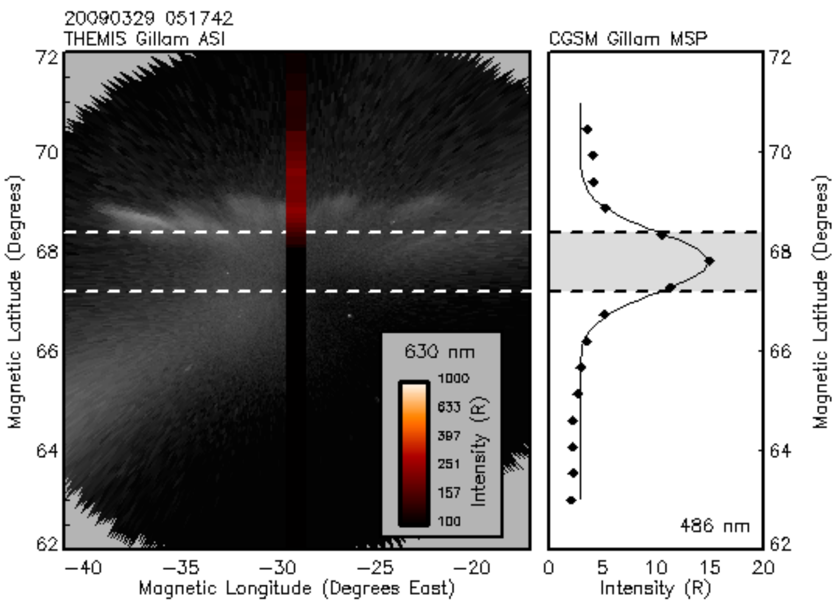


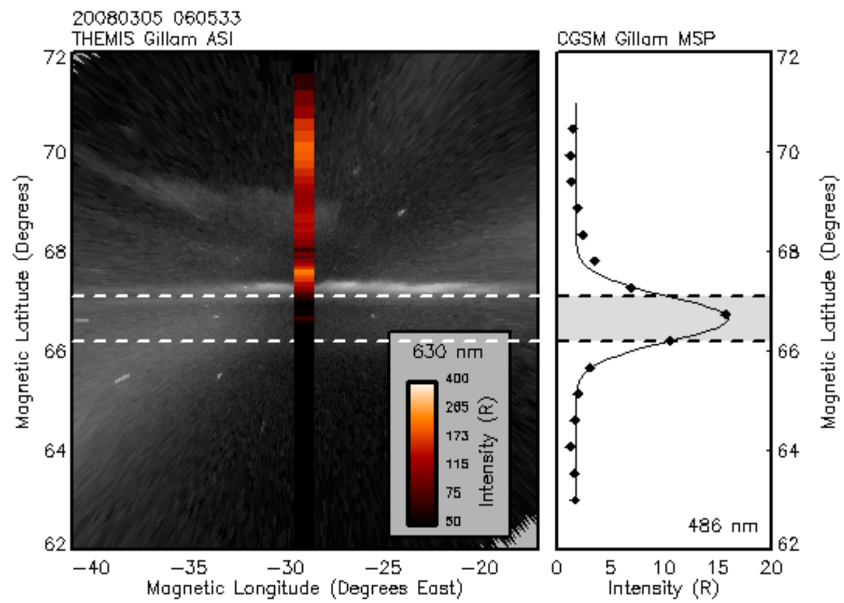


This figure shows the THEMIS idea. The apogee conjunctions in the nightside evening sector were to be over Canada, magnetically conjugate to the fields of view of 20 white light ASIs and numerous ground-based magnetometers. The ground-based instruments were to identify the onset time and meridian, while the satellites would track the radial evolution of the expansion phase. The mission acronym – Time History of Macroscale Interactions during Substorms – says it all. See *Angelopoulos* [*Space Science Reviews,* 2008]. See also *Donovan et al.* [*JASTP,* 2006], and *Mende et al.* [*Space Science Reviews,* 2008].

The Substorm

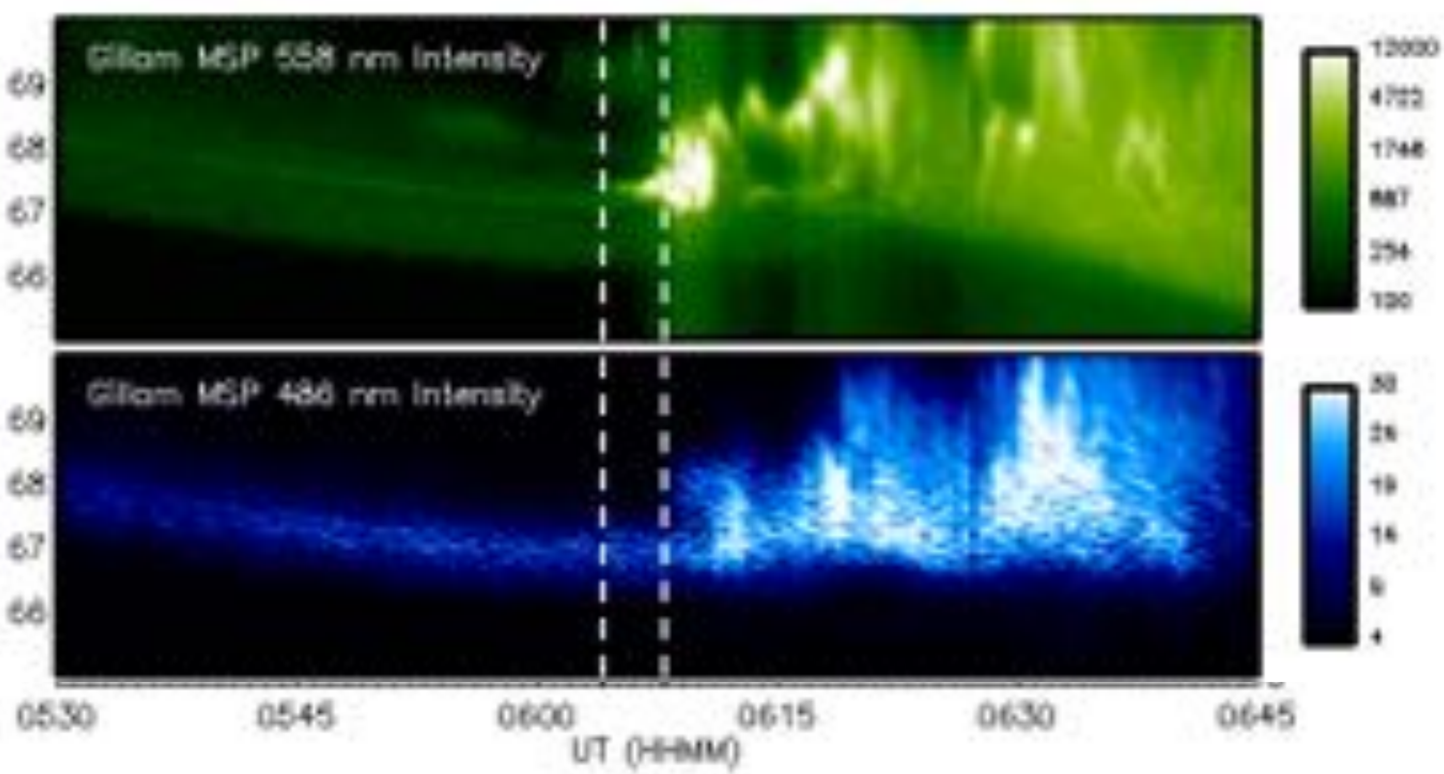
09-a



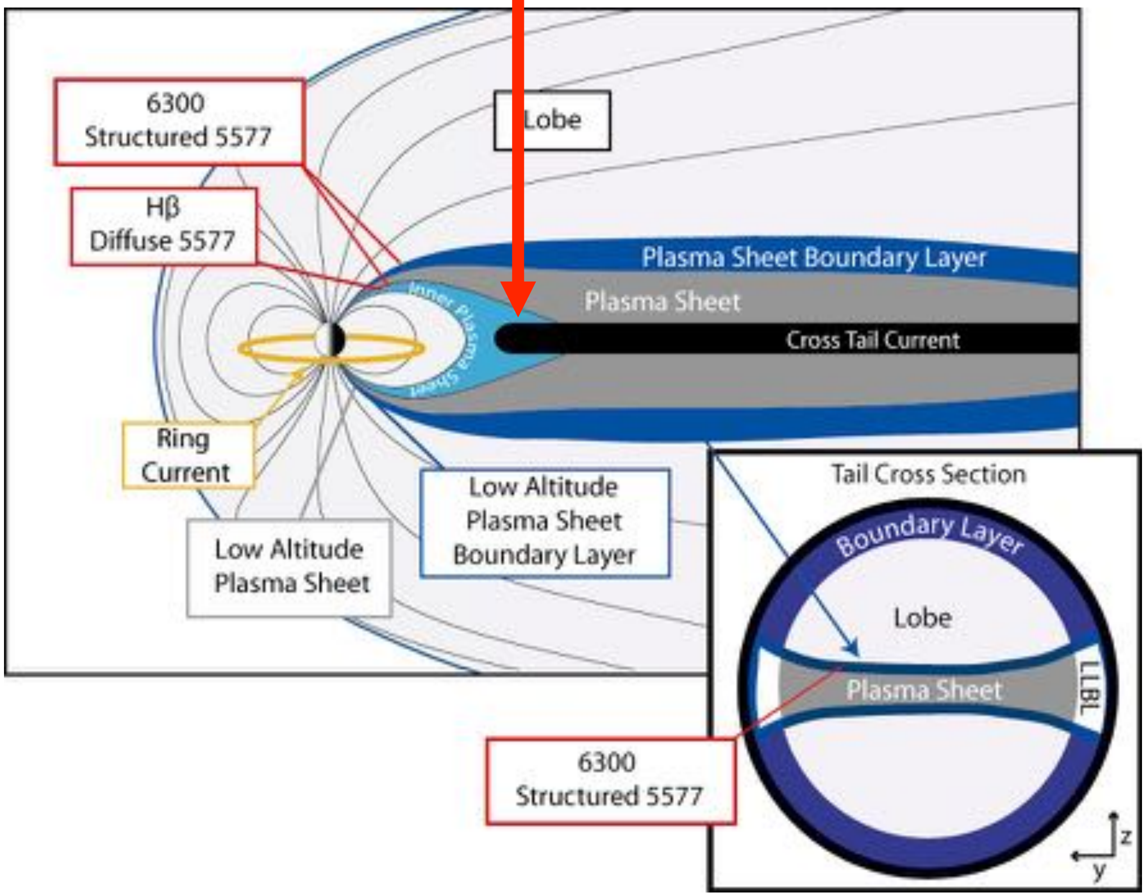


The Substorm

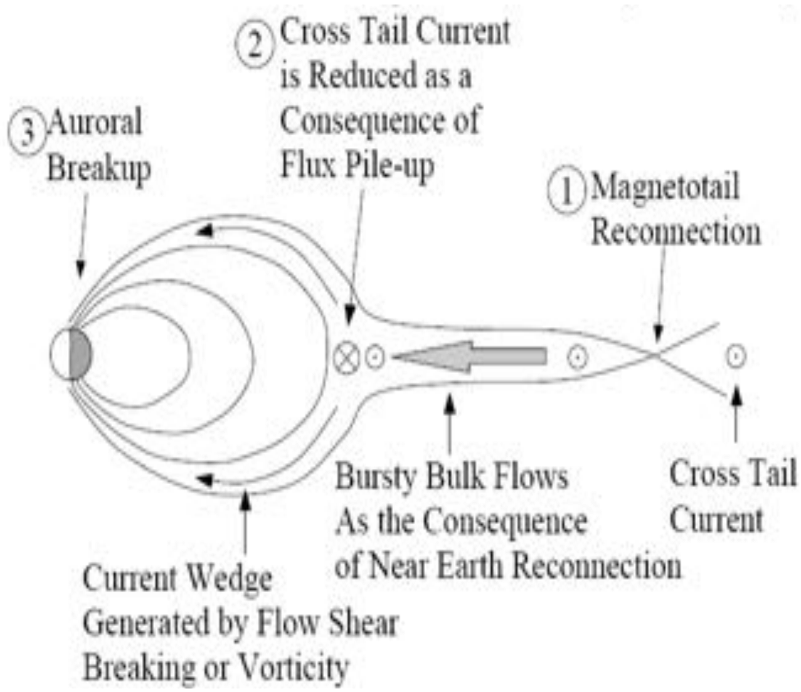
09-b

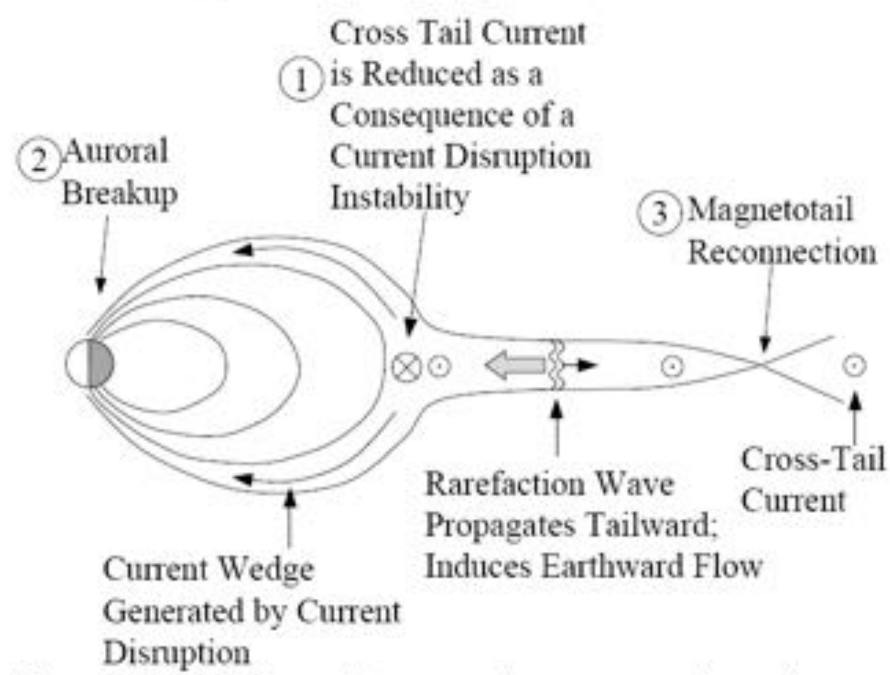


Onset Arc Maps Here



What causes substorm expansion phase onset?



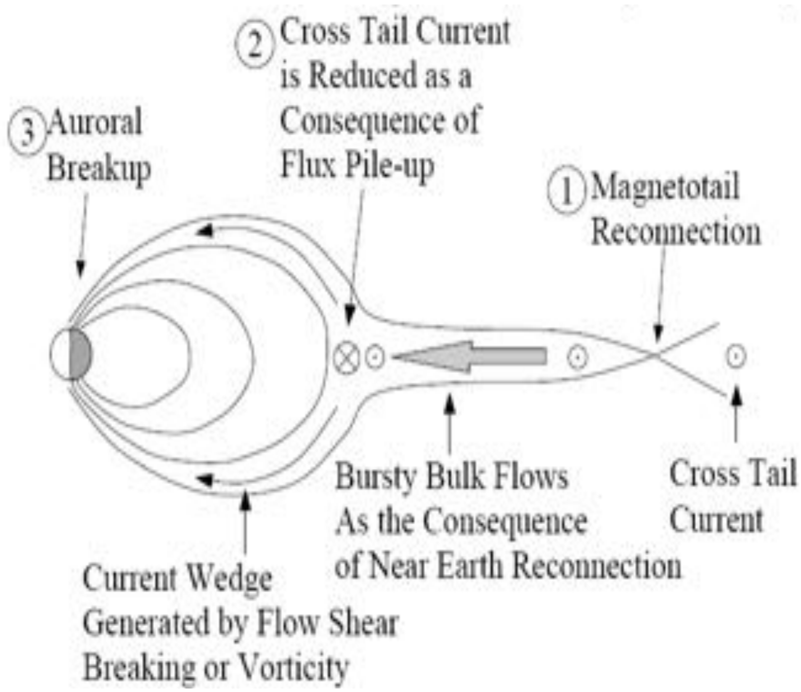


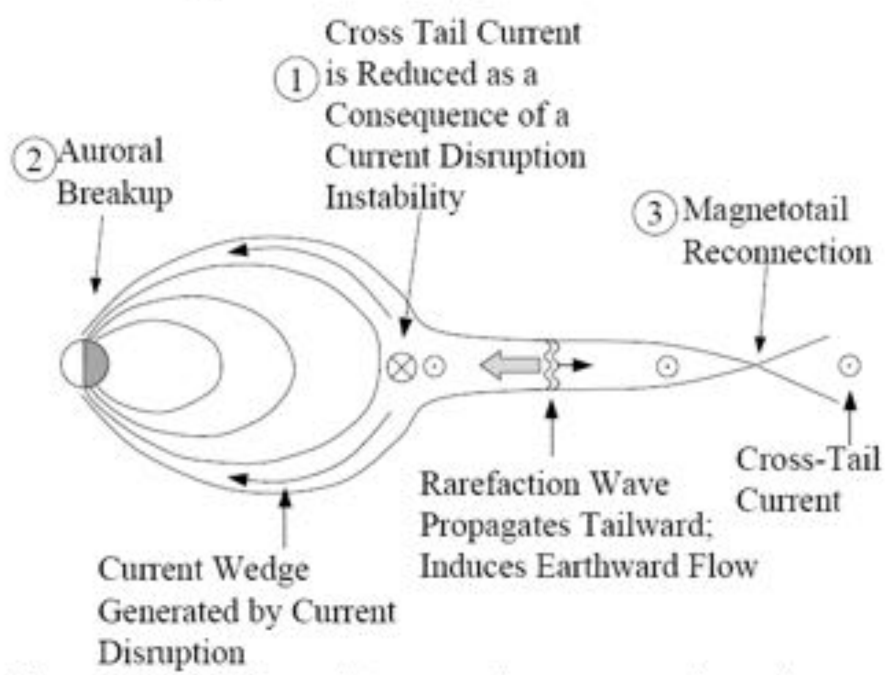
"Outside-In"

In the TCS away from the dipolar region… NENL

"Inside-Out"

In the transition between the TCS and the dipolar region… CD (CLI) or Ballooning

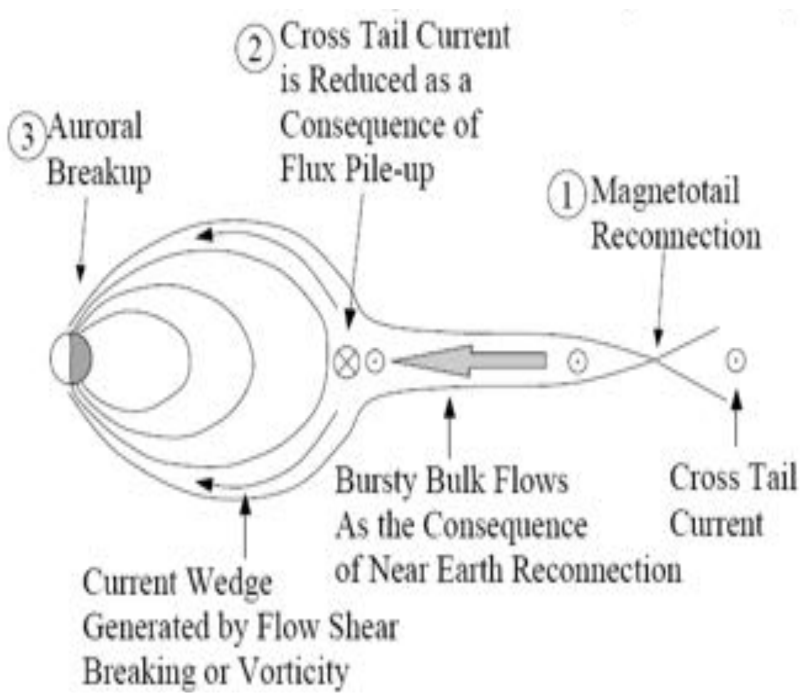




"Outside-In"

"Inside-Out"

For each scenario there is a story connecting instability (tail) evolution to that of the aurora.



"Outside-In"

NER at X<-12 Re launches narrow fast flows towards the inner edge of the TCS.

Fast flows pile up at the inner edge leading do dipolarization, injection, Pi2s, and the brightening of the onset arc (that is on field lines threading field lines near the inner edge of the TCS ("the transition region")).

A variation of this is that the onset arc actually maps to the NER or nearby it (though that seems to be disproven [*Sergeev et al., JGR*, 2012] (see also Question 1).

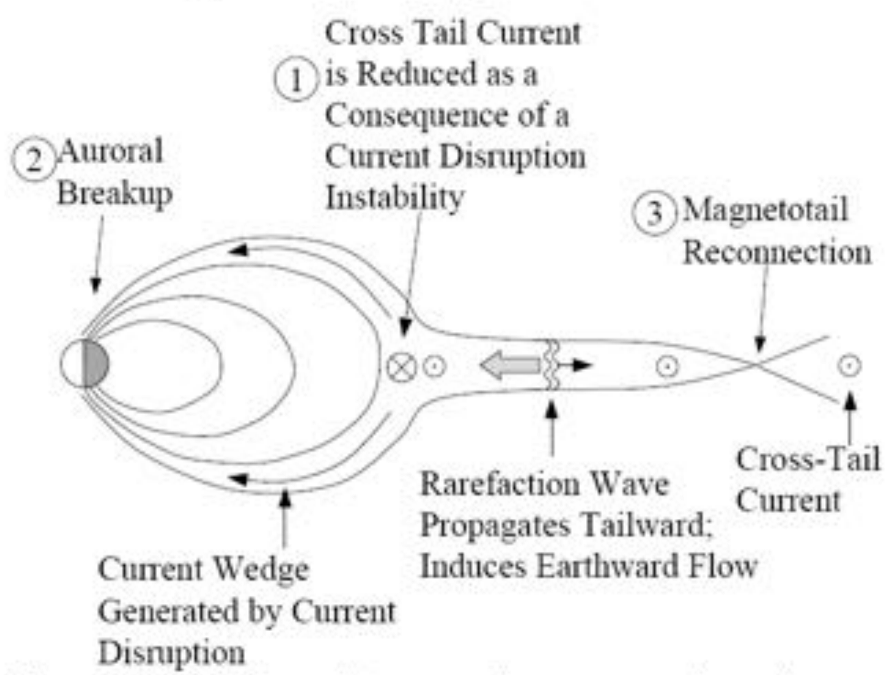
"Hence this model separates the source region of the wedge current from the NENL." Shiokawa et al. (page 4505)*, JGR, 1998.*

Instability arises at the transition region, leading to collapse/ disruption of the CTC near the inner edge.

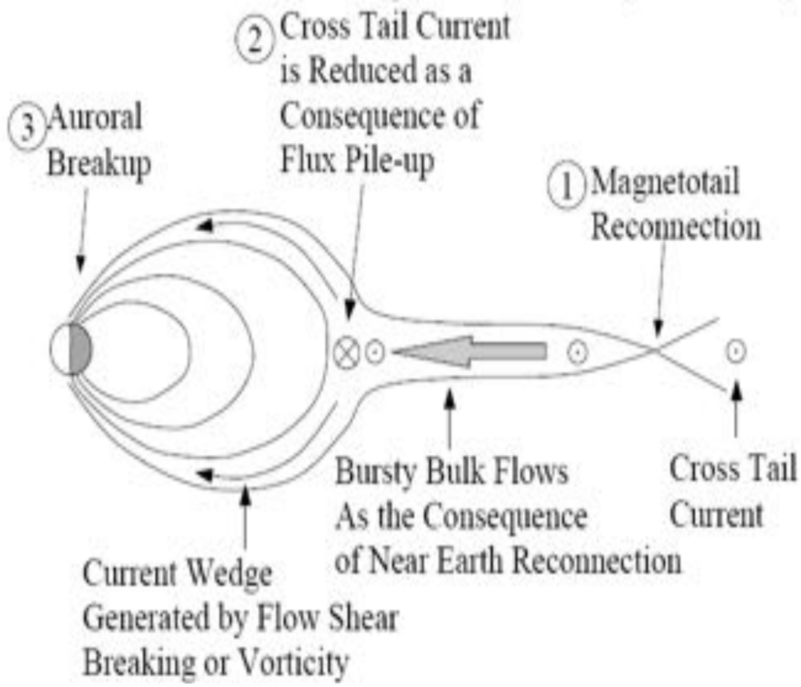
The brightening arc corresponds to the beginning of the instability (ballooning? Other?) at the inner edge of the TCS.

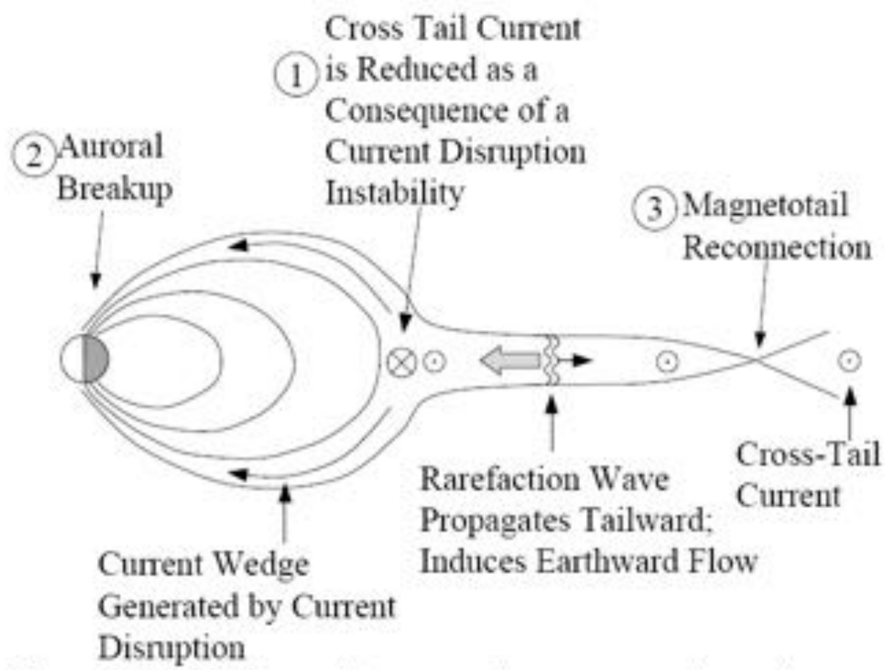
The NER comes later, caused by changes in the TCS communicating by a tailward propagating rarefaction wave which draws flux tubes in.

<u>The broad-strokes difference between this and "Out-In" in terms of the aurora is what the brightening signifies.</u>



"Inside-Out"



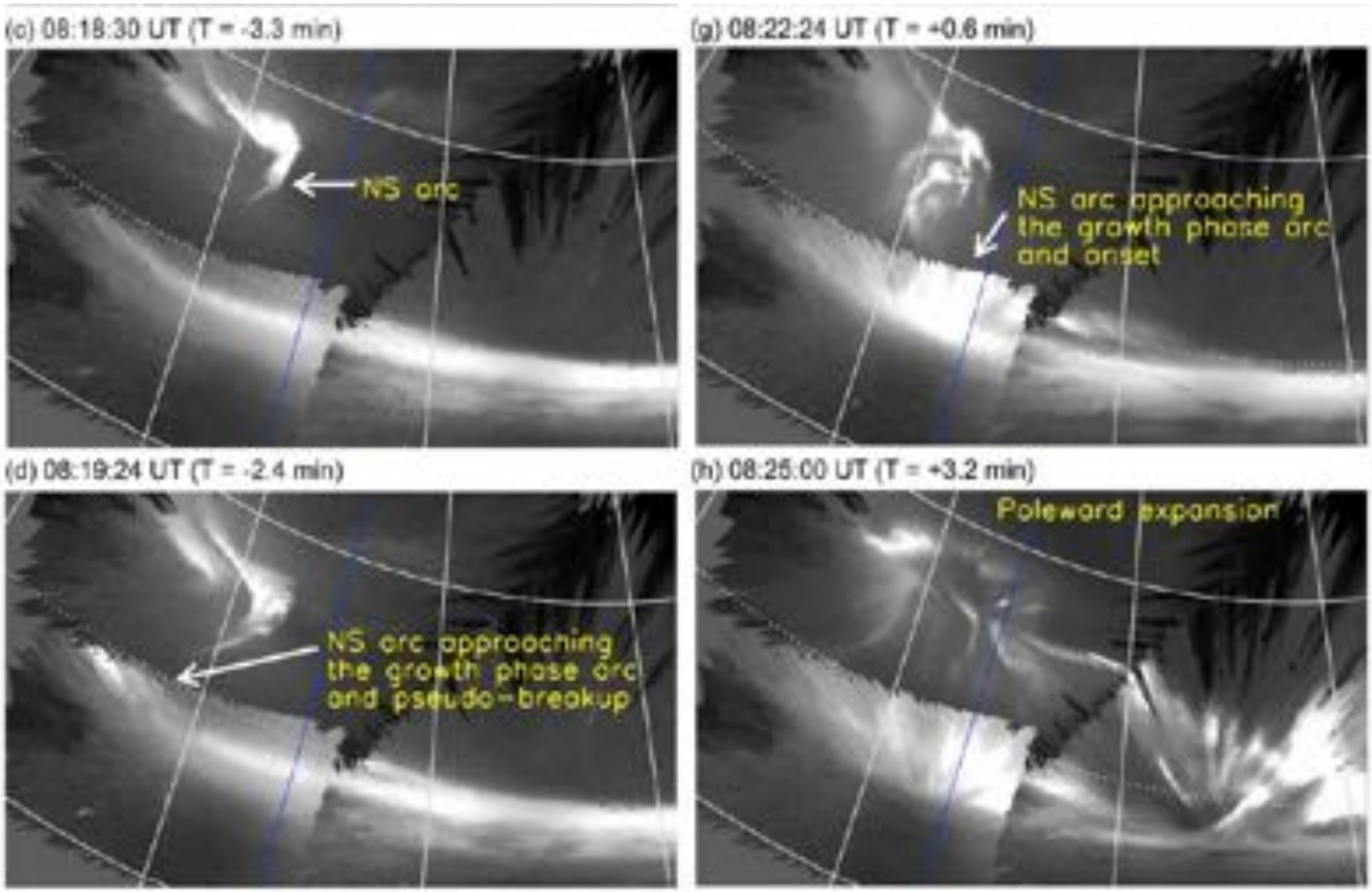


"Outside-In"

"Inside-Out"

Expansion phase onset marks the start of magnetotail instability ("Inside-Out"), or the start of something caused by the start of the magnetotail instability ("Outside-In").

The Substorm



Courtesy Toshi Nishimura.

"In-Out"

Instability at inner edge of TCS arises spontaneously. Rapidly changing topology at inner edge draws flux tubes in from TCS leading *subsequently* to NER.

Burst of reconnection at the DNL forms a low-entropy flux tube which meanders through CPS all the way to inner edge then moves azimuthally along inner edge… makes a marginally unstable inner edge unstable (necessary for onset in this scenario).

"Out-In"

Instability in TCS drives NER… BBFs to inner edge leading *subsequently* to flux pileup (dipolarization).

Instability in TCS drives NER… fast mode waves propagate to PSBL then ionosphere… in this variant PBI, then streamer, then auroral brightening is via the path NER ►► PSBL ►► Ionosphere.

I believe every substorm researcher's "world view" fits under one of these umbrellas.

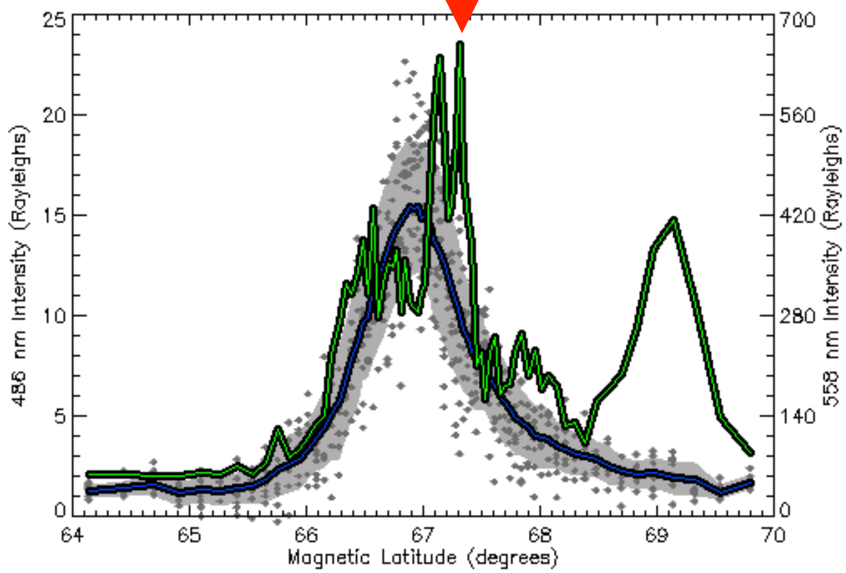
The Substorm

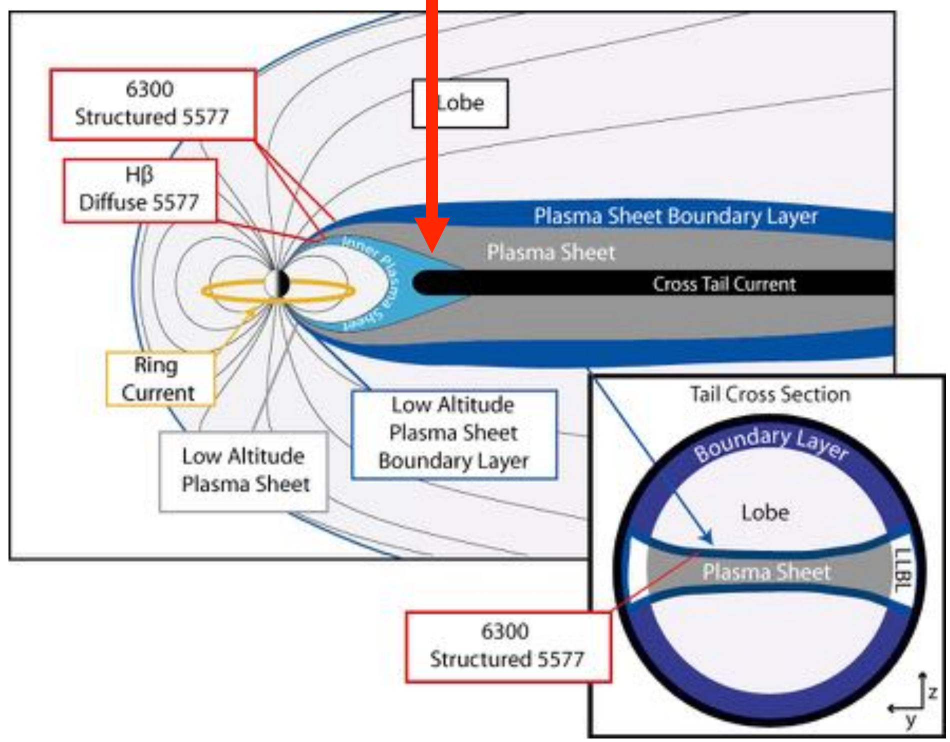
11-a

Why do some of us think it is traditional Inside-Out?

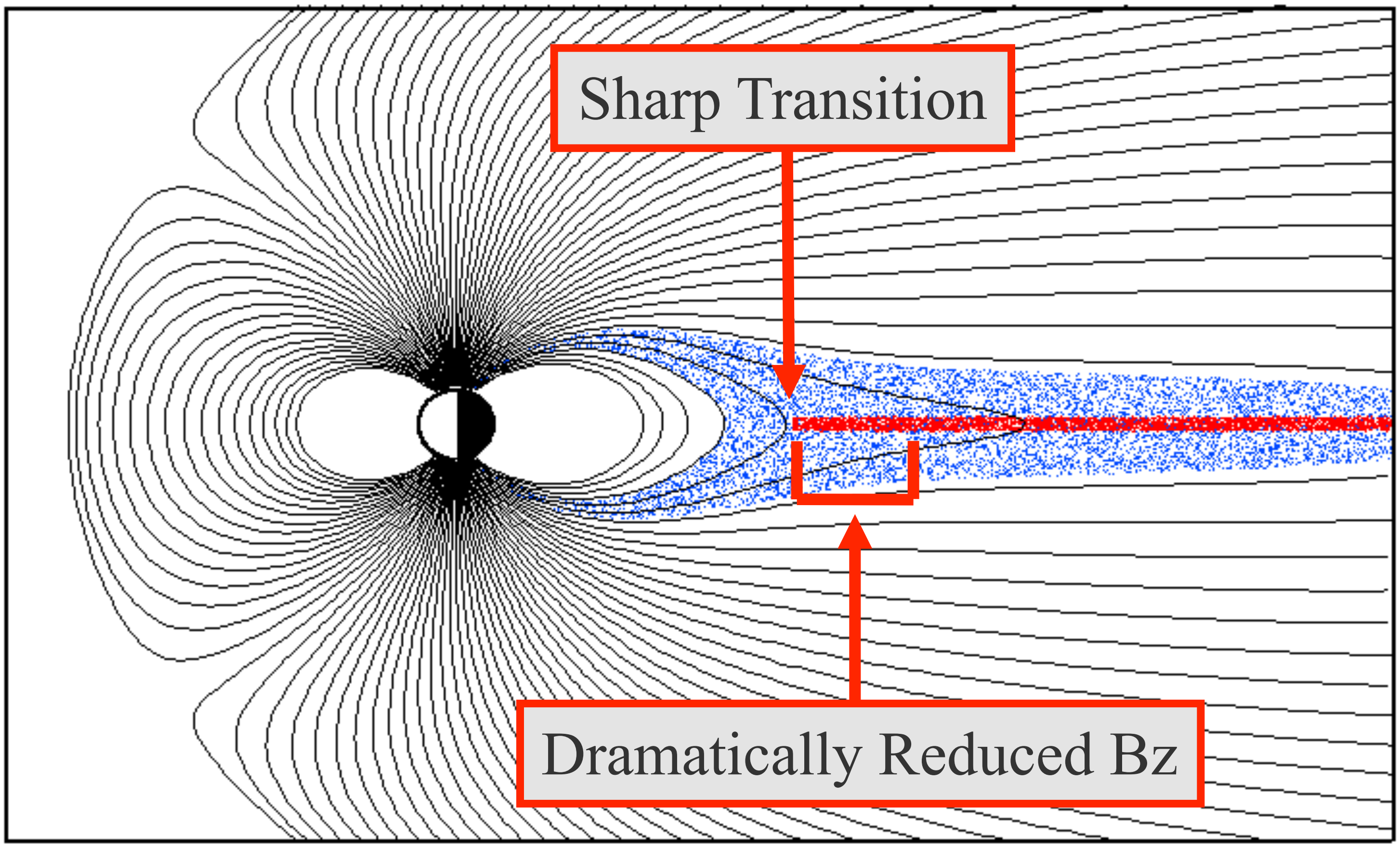
Onset Arc

Onset Arc Maps Here

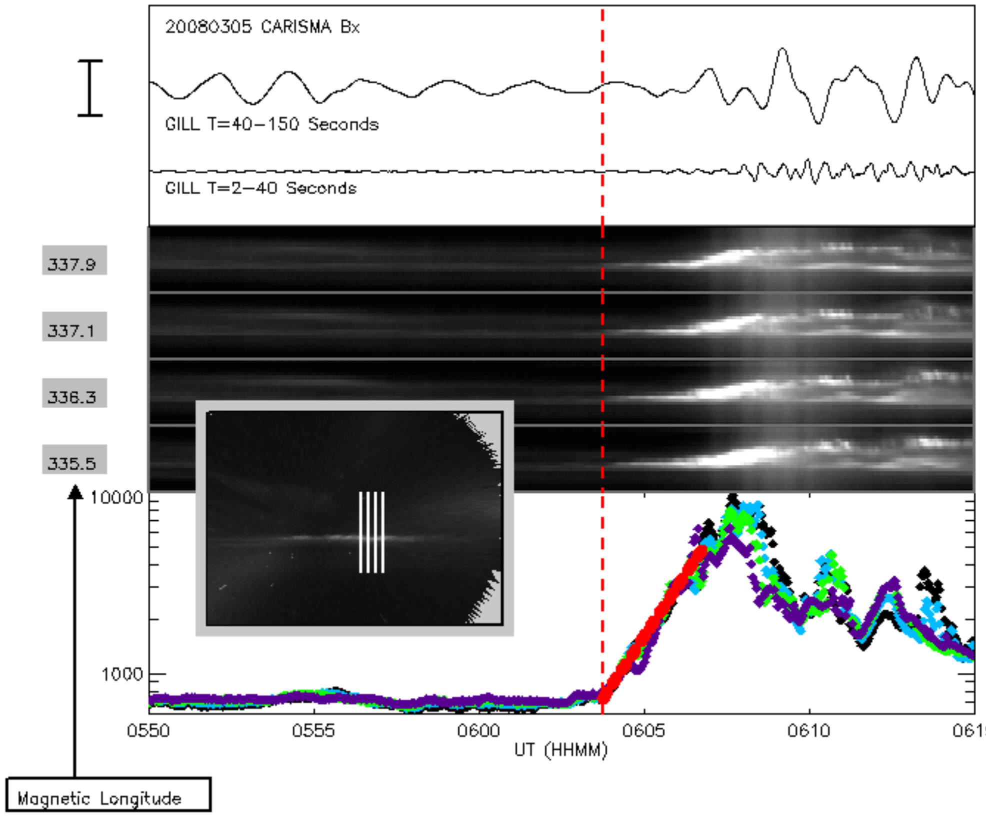




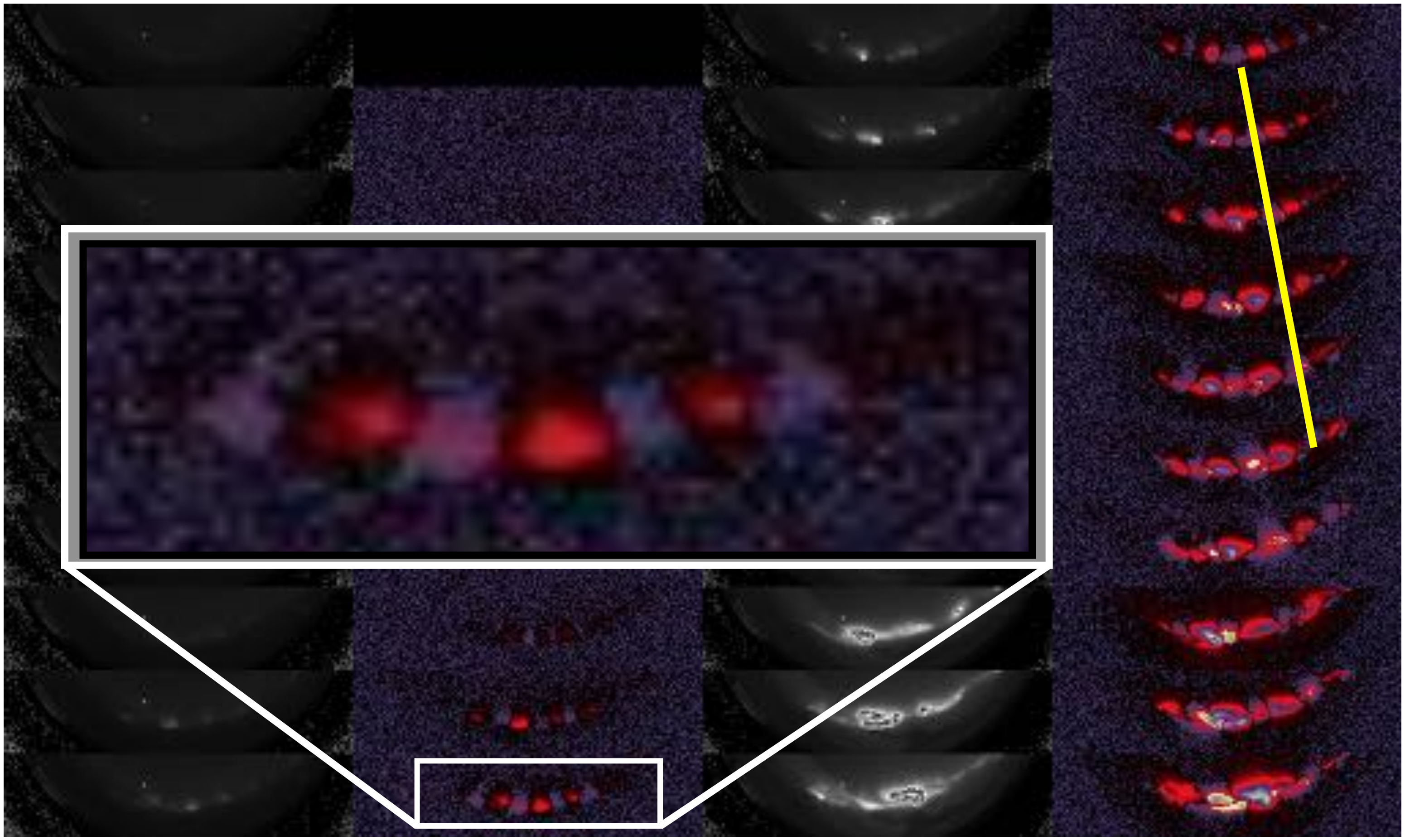
We know where the arc is relative to the H+ aurora, and we have a very good idea what the H+ aurora corresponds to in the magnetotail, but we do not know <u>where</u> that is on a case by case basis.



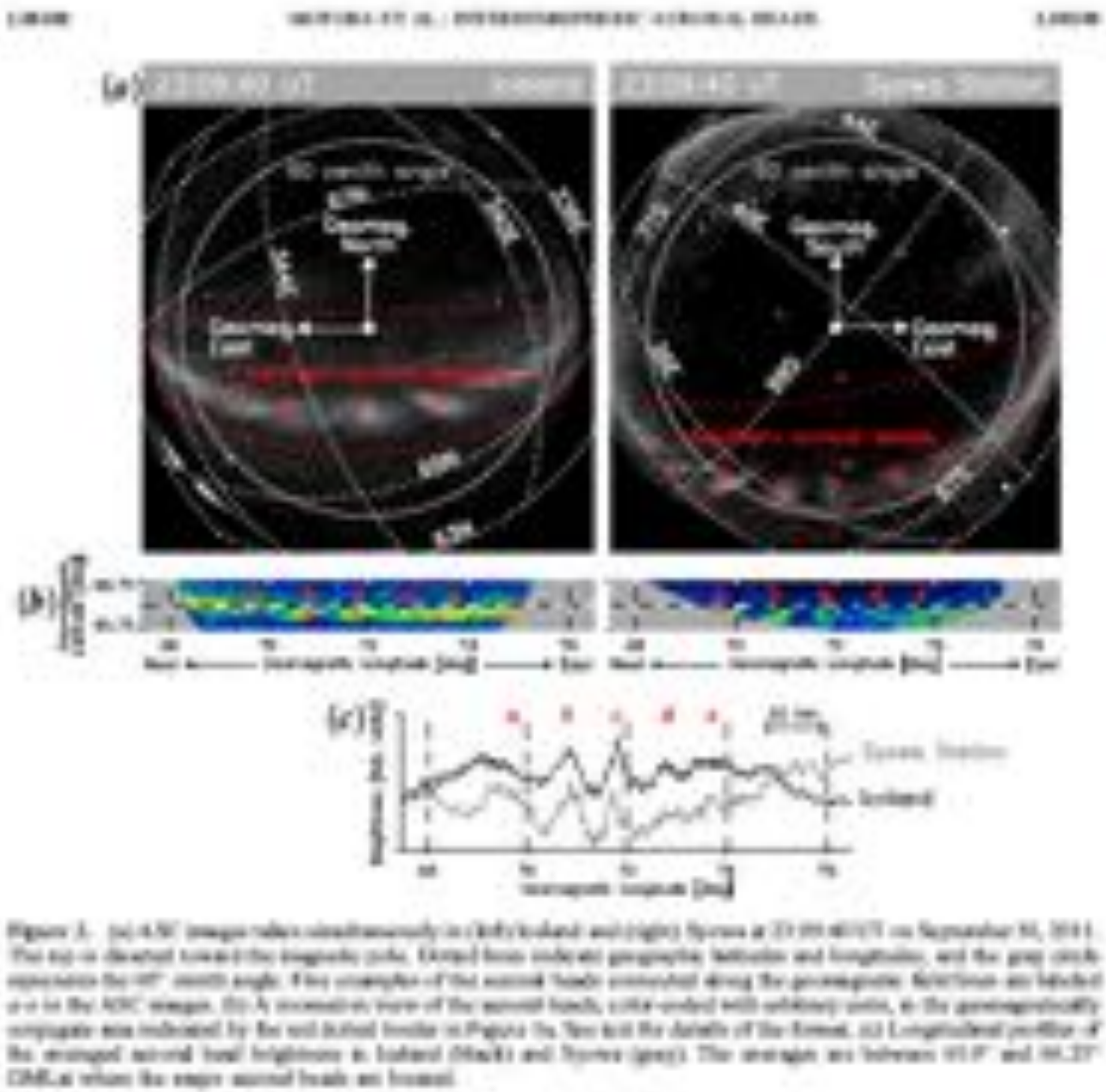
There is increasing evidence that in the late growth phase the transition between "tail-like" and "quasi-dipolar" is radially sharp. This corresponds to anomalously low |B| near the "inner edge".



The arc brightens in a way that looks like a parameter describing an instability…. More or less always it starts on an azimuthally extended stretch of the arc essentially simultaneously (unstable azimuthally extended region in the tail), more or less always brightens like e^(t/Tau) for 3Tau or so, then saturates (again as one expects from an instability at the inner edge). [*by the way – a challenge here for the BBF leading to flux pileup would be to show through simulation or other that flux pileup would lead to this e^t/ tau growth of brightness of the arc.*

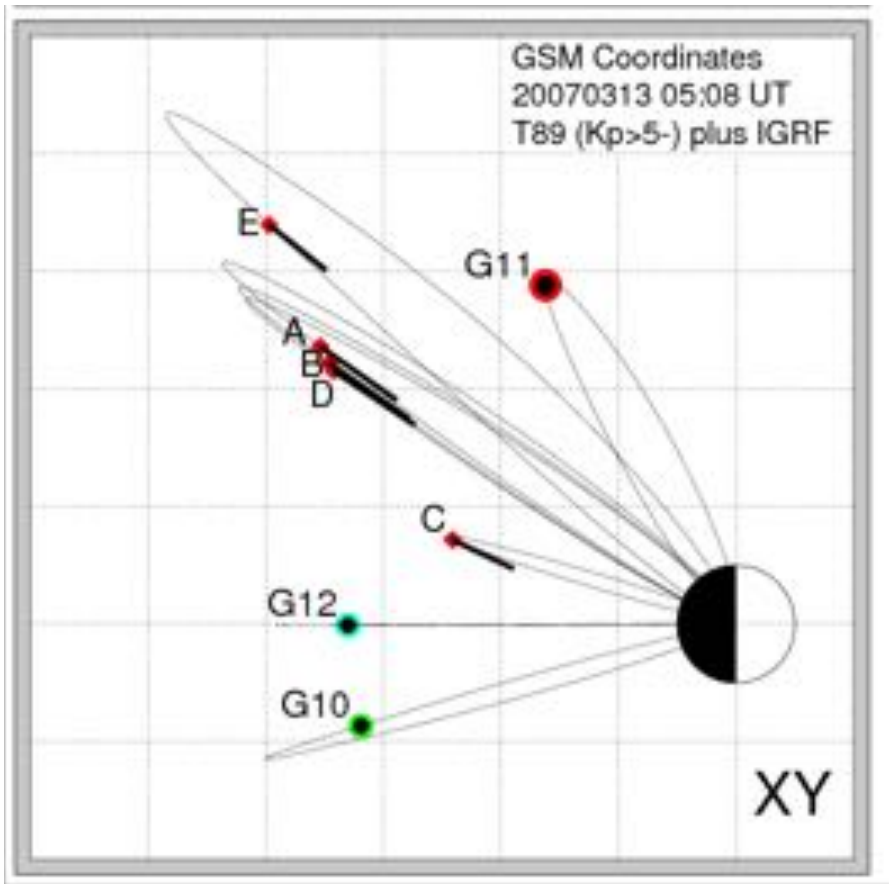


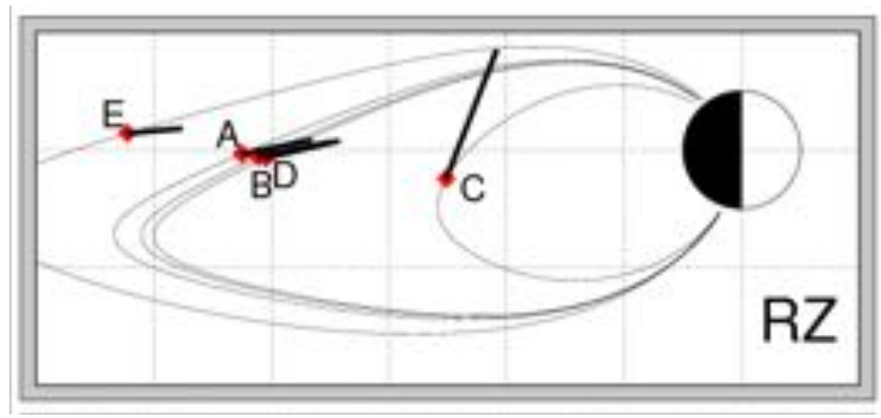
Partial images (and difference frames) from THEMIS ASI at Athabasca
The talk I initially conceived would have been entirely around this point.

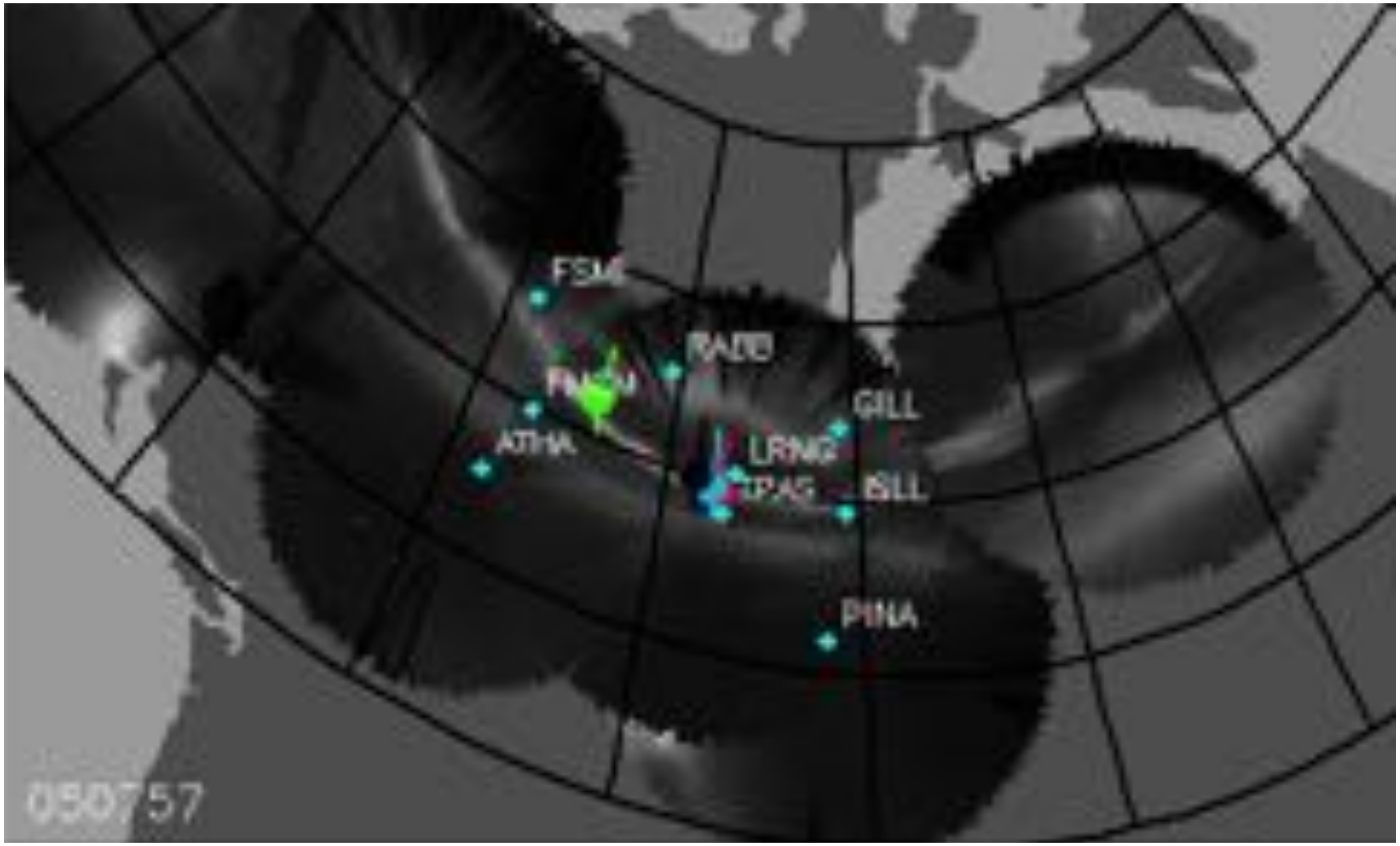


This is Figure 2 from *Motoba et al*. [*GRL*, 2012]. I believe this will be recognized as a turning point in substorm research. *Motoba et al*. used simultaneous magnetically conjugate observations to show that the beading that occurs at onset is a magnetically conjugate phenomena. They conclude that this is proof that the beading originates in the magnetosphere (as opposed to the ionospheric end where for example current limiting or JXB instabilities (see e.g., *Hallinan* [*JGR*, 1976]) could be responsible. This means that the optical evolution around onset that looks like an instability (exponential growth, wave structure, inverse cascade, etc).

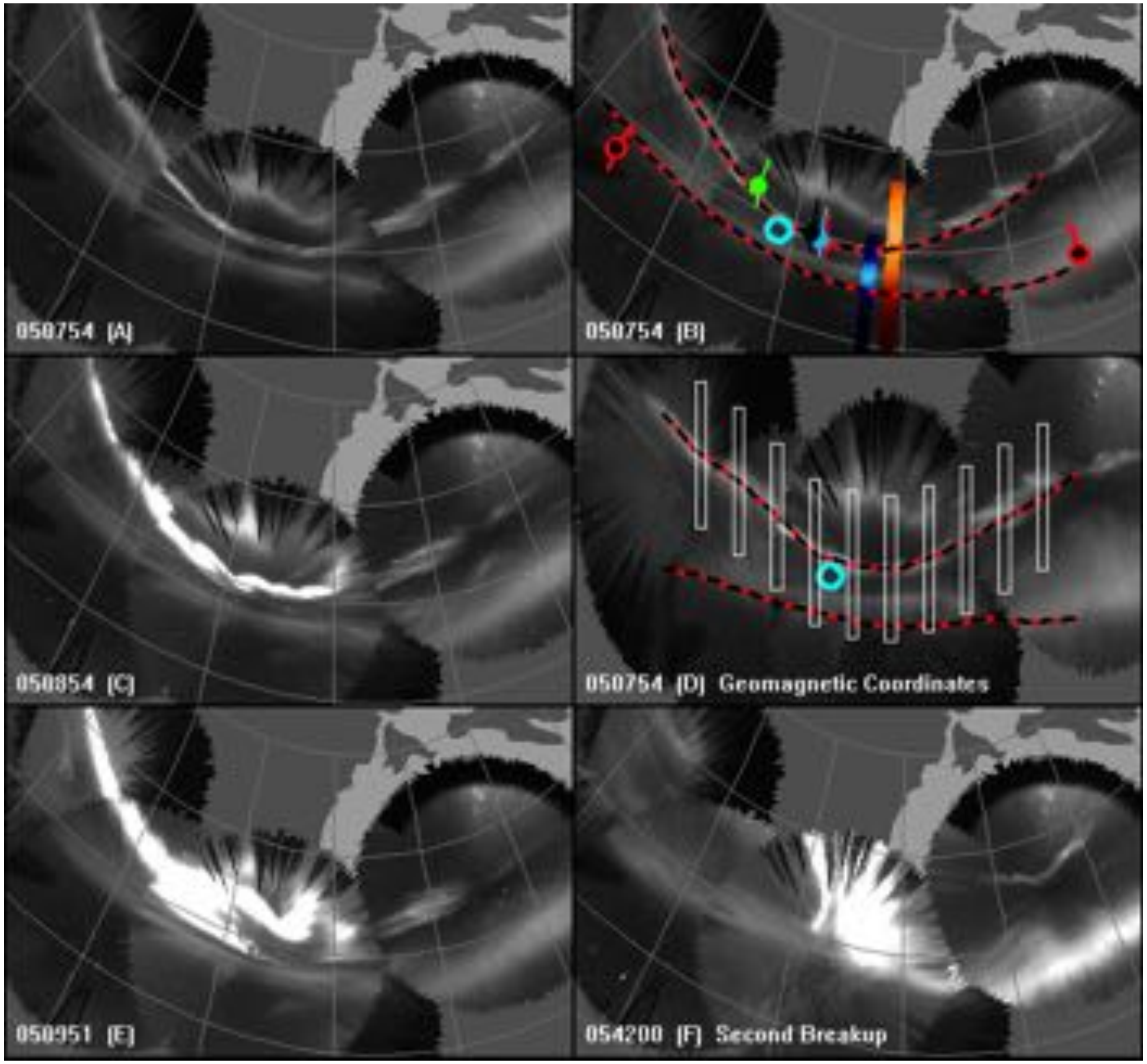
The Substorm

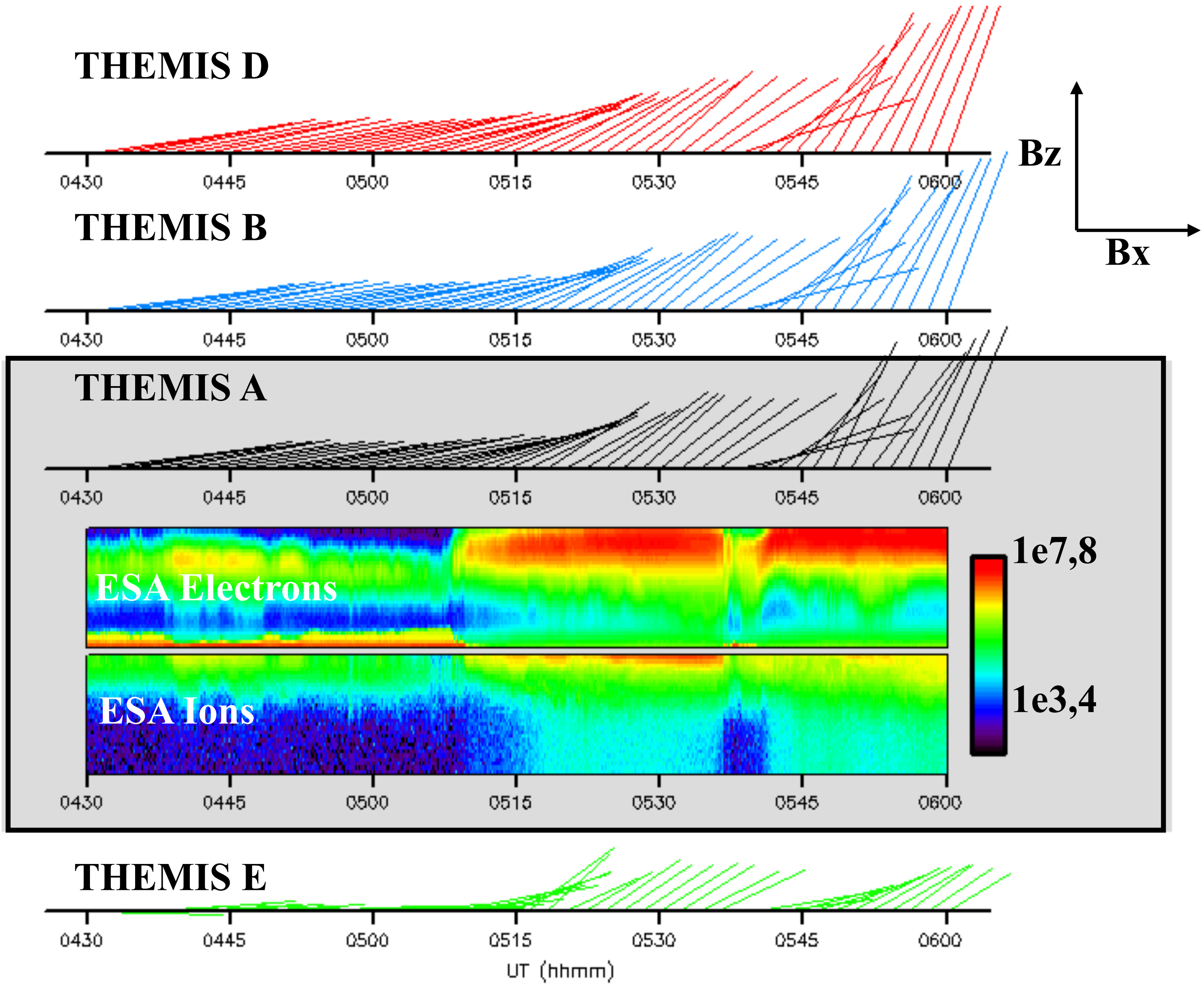




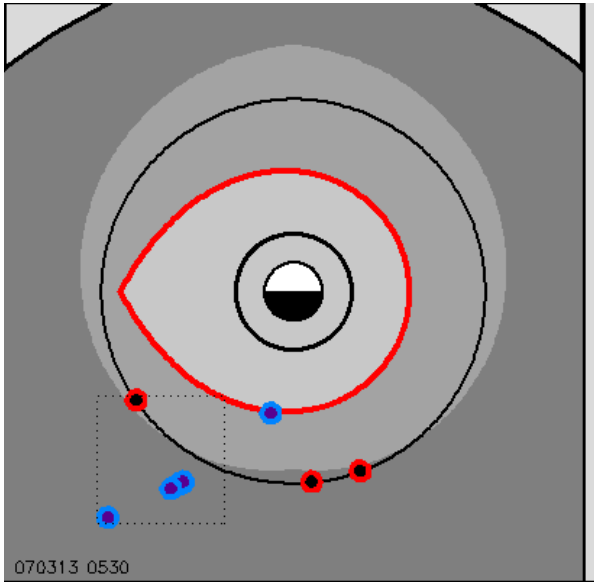


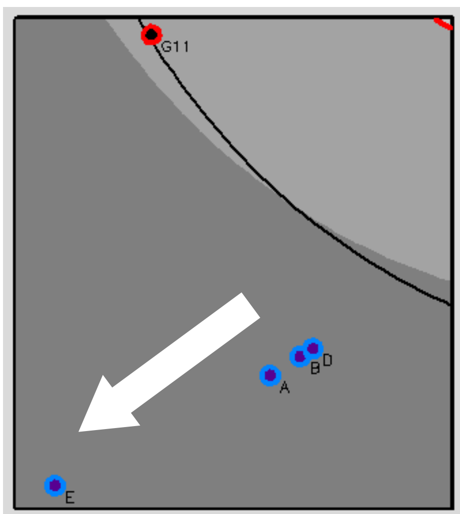
I want you to think about this figure when you are working through question 1.

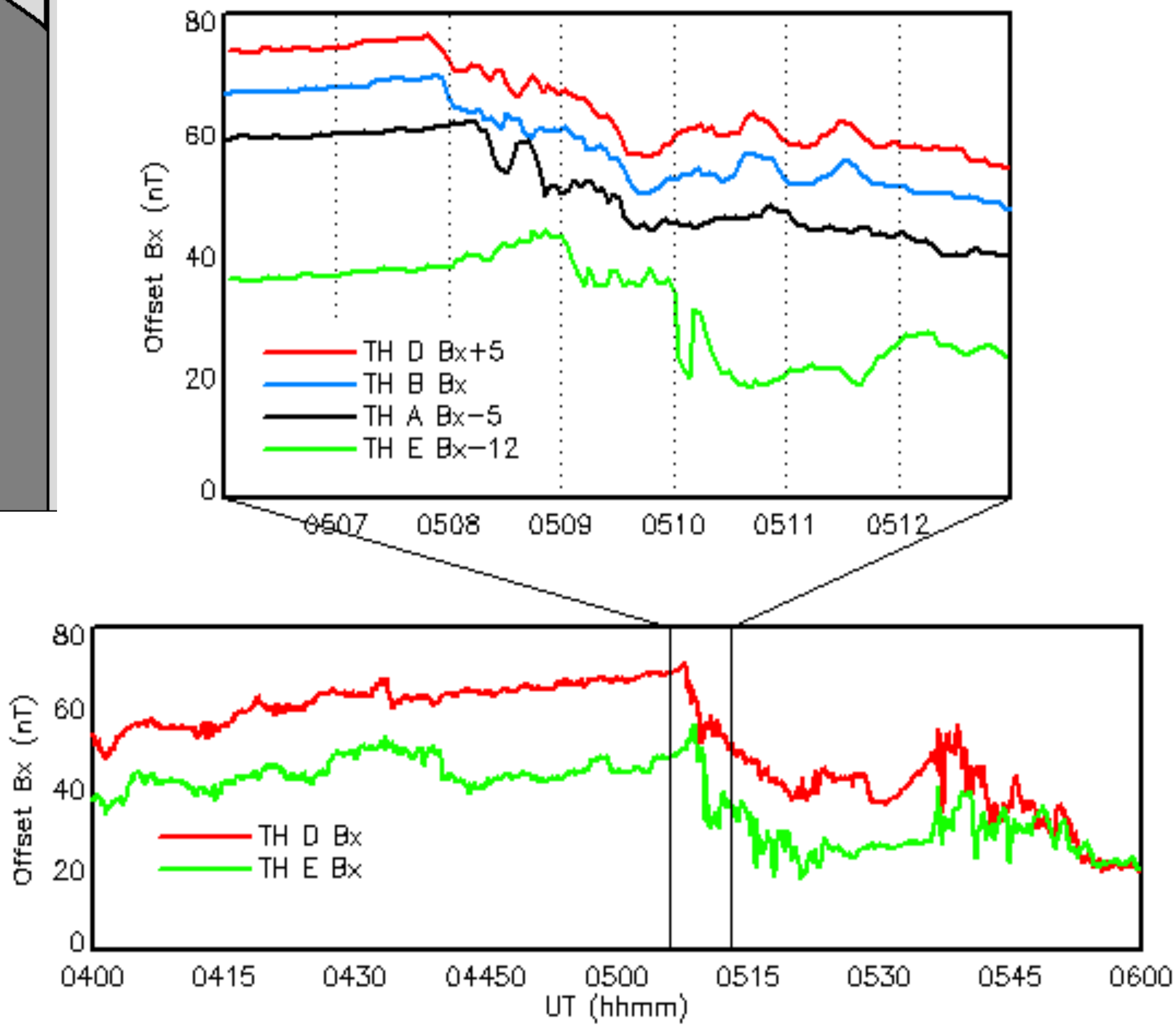

050754 [A]
050754 [B]
050854 [C]
050754 [D] Geomagnetic Coordinates
050951 [E]
054200 [F] Second Breakup

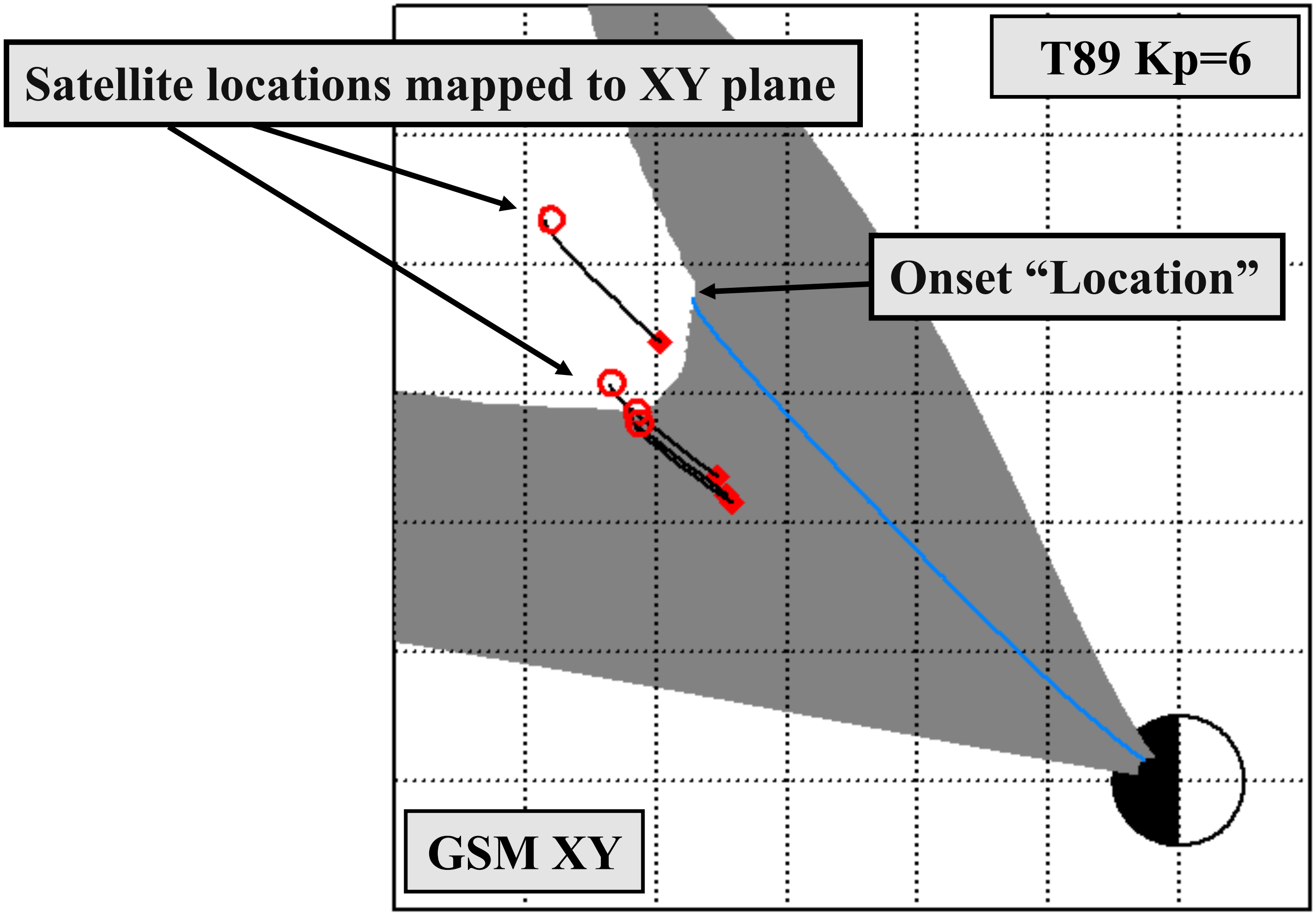

THEMIS D
Bz
Bx
0430
0445
0500
0515
0530
0545
0600
THEMIS B
THEMIS A
ESA Electrons
ESA Ions
1e7,8
1e3,4
THEMIS E
UT (hhmm)

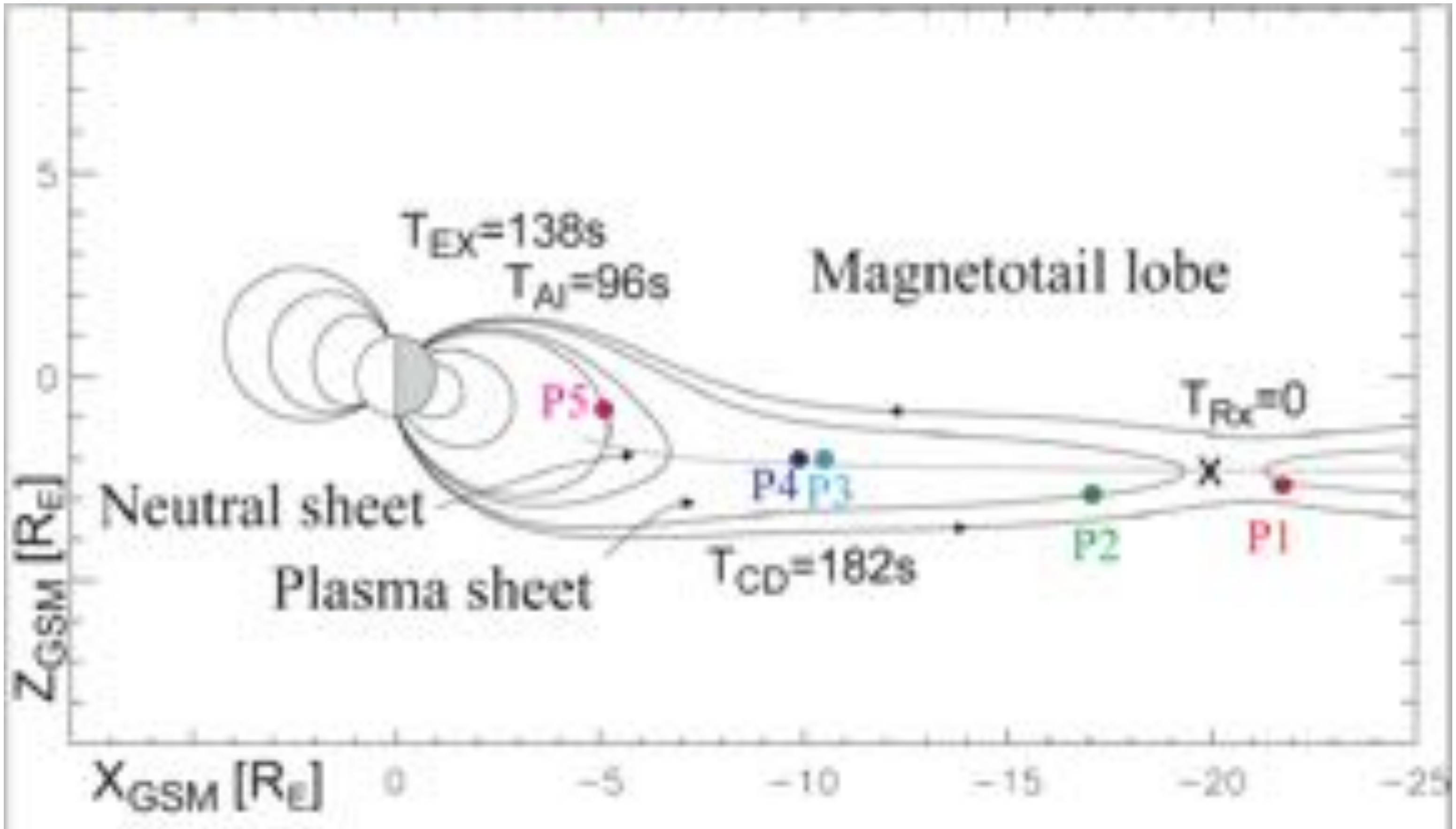
The Substorm








Satellite locations mapped to XY plane
T89 Kp=6
Onset "Location"
GSM XY



Satellite	Color	X	Y	Z	Neutral Sheet
THEMIS-A (P5)		-5.483	5.326	-0.623	0.6
THEMIS-B (P1)		-21.475	3.927	-2.806	-0.5
THEMIS-C (P2)		-17.165	4.573	-3.046	-0.8
THEMIS-D (P3)		-10.881	3.759	-2.086	0.2
THEMIS-E (P4)		-10.194	4.506	-1.913	0.2

Angelopoulos et al., Science, 2008.

Table 1. Summary of timing results during the 26 Feb 2008 04:53:45 UT substorm onset, in order of time sequence. The last column is the time delay assuming reconnection onset at 04:50:03 UT, at 20 R_E, which was arrived at based on our interpretation of data and an estimate of an average Alfvén speed in the plasma sheet of 500 km/s.

Event	Observed Time (UT)	Inferred delay (seconds since 04:50:03 UT)
Reconnection onset	04:50:03 (inferred)	T_{Rx}=0
Reconnection effects at P1	04:50:28	25
Reconnection effects at P2	04:50:38	35
Auroral intensification	04:51:39	T_{AI}=96
High latitude Pi2 onset	04:52:00	117
Substorm expansion onset	04:52:21	T_{EX}=138
Earthward flow onset at P3	04:52:27	144
Mid-latitude Pi2 onset	04:53:05	182
Dipolarization at P3	04:53:05	T_{CD} =182
Auroral Electroject Increase	04:54:00	237

I want you to think about this figure when you are working through question 3.

Angelopoulos et al., Science, 2008.

What should be done next?

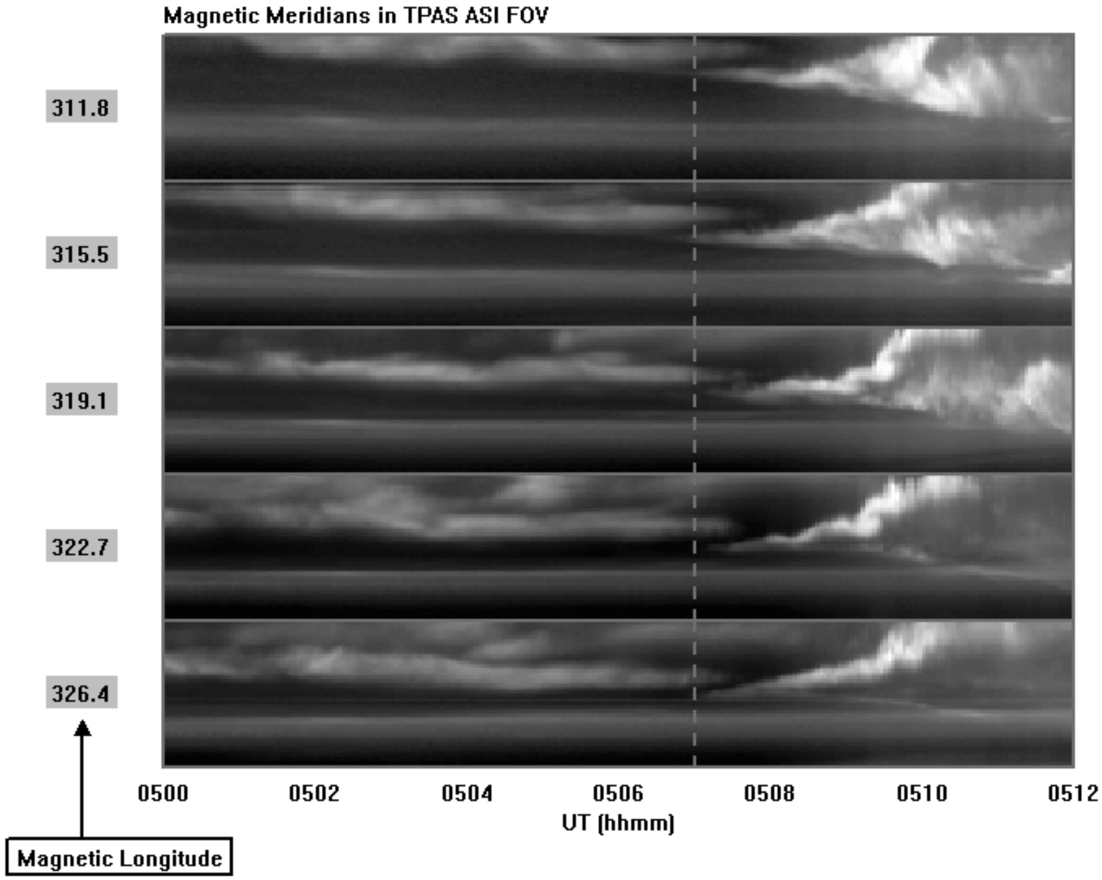
Auroral onset occurs on a new (in this case) or pre-existing quiet arc at the equatorward edge of the redline and poleward slope of the proton aurora. It is widely agreed that this statement is true.

In fact, since this is embedded in Akasofu's original definition of the phenomena, it is irrefutable.

However, we do not know what causes the onset arc (late growth phase). Therefore, we cannot say why, for example, the arc got brighter, or why the arc beads (we can infer… but we can't say).

<u>The single most agreed-upon substorm observation is of limited use in terms of assessing theories</u>.

Recent work by *Jiang et al.* [*JGR,* 2012], *Nishimura et al.* [*JGR,* 2012], *Liang et al.* [*JGR,* 2012], and others gives me hope on this front, but it is all fairly preliminary.



What causes the onset arc?

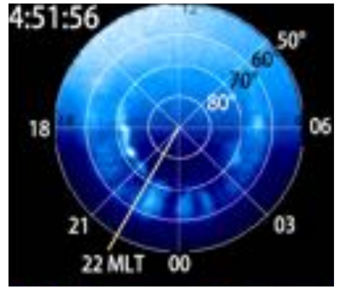
What should be done next?

The substorm is a dynamic process that arises from the competition between day and nightside reconnection.

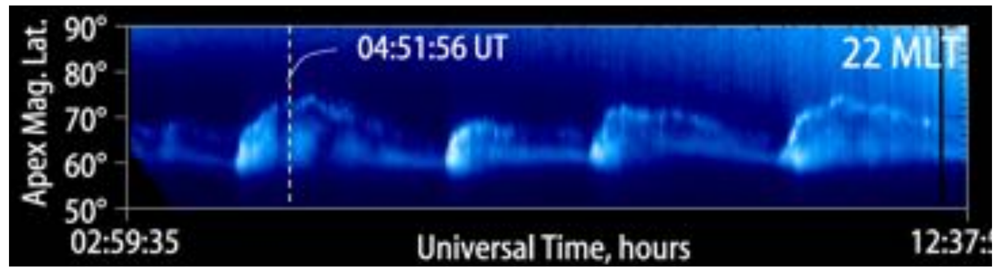
It might surprise you to know that we have never measured time series of these quantities, so the driver of the substorm (and for that matter storms, sawtooth events, steady magnetospheric convection events, etc. has never been observed.

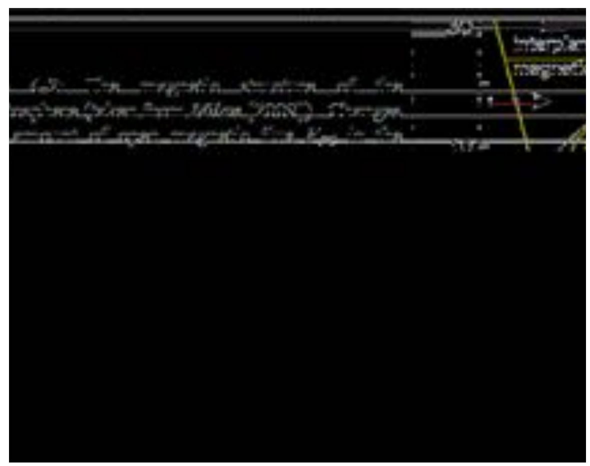
It would be important to do so – what would that require? 24/7 global (hemispheric) auroral imaging with daylight suppression and sensitivity to allow identification of the OCB.

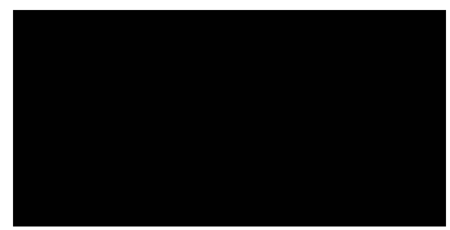
Observation of the day- and night-side reconnection rates.



The time series of dayside and nightside reconnection rates would be delivered by ESA's Kaufu B mission.

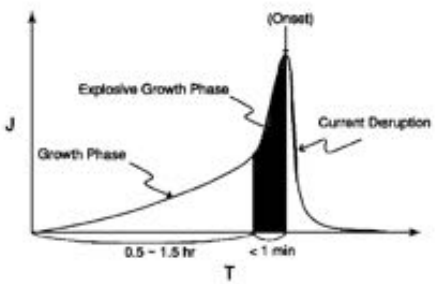




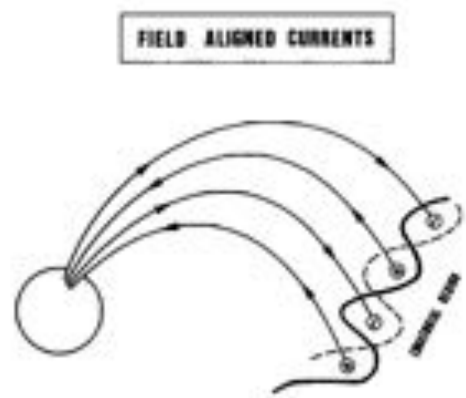


What should be done next?

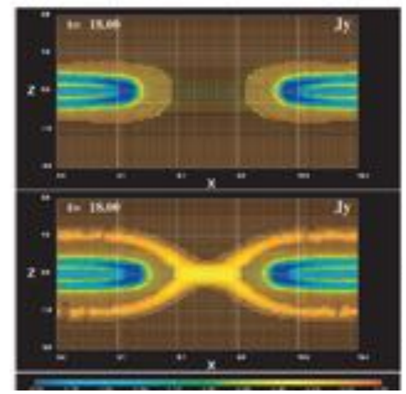
What is the instability?



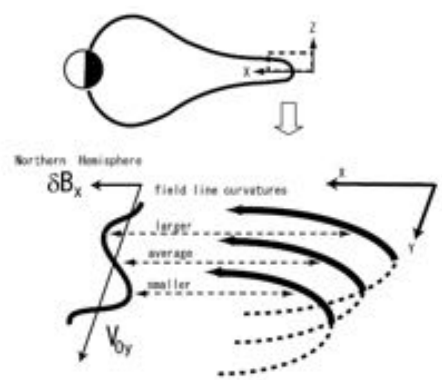
***Ohtani et al., Chapman Conf.*, 1990; *JGR*, 1992.**



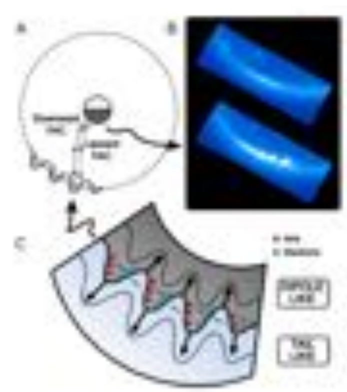
***Roux et al., JGR.*, 1991.**



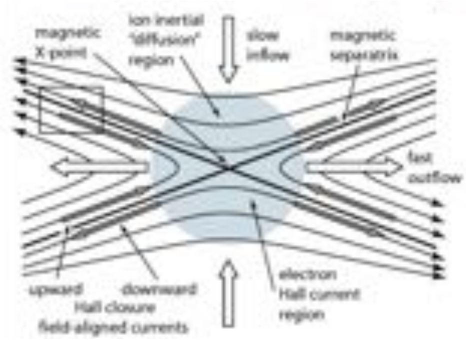
***Fujimoto et al., Comp Phys*, 2008.**



***Saito et al., GRL*, 2008**

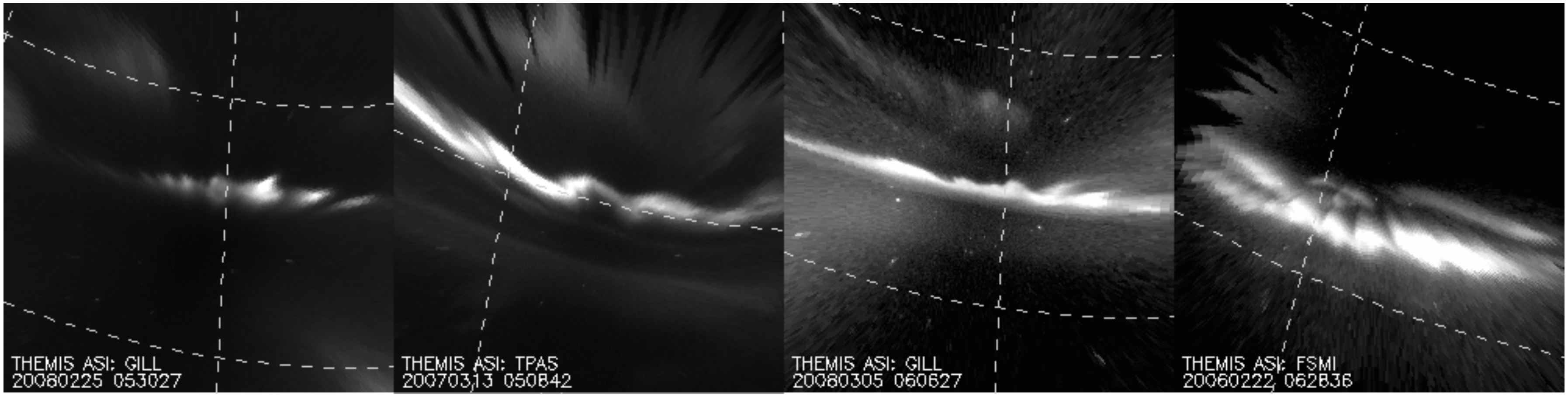


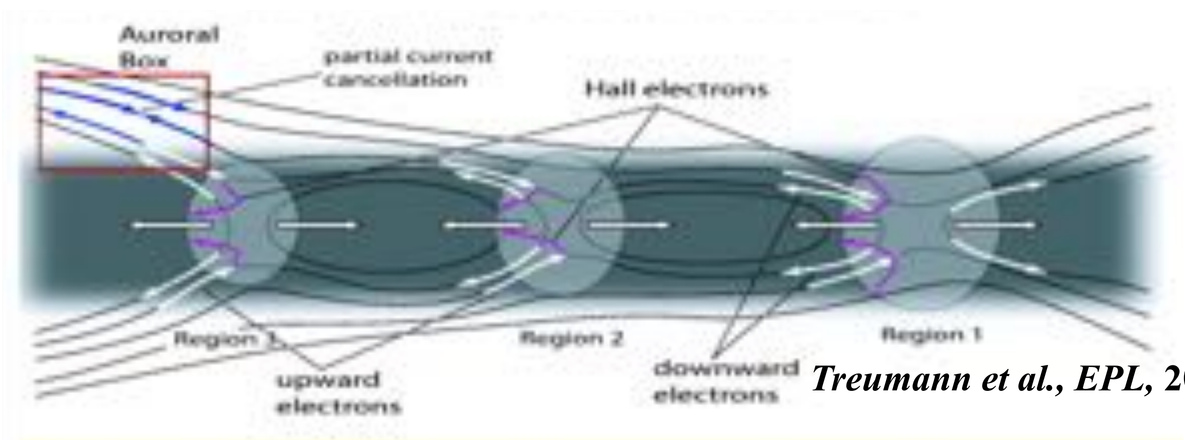
***Henderson, Ann. Geo.*, 2009.**



***Treumann et al., EPL*, 2009**

What should be done next?





***Treumann et al., EPL*, 2009**

Ionospheric signatures of near-Earth reconnection and other processes?

Summary

By definition, onset begins with the brightening of a new or pre-existing arc. It is almost universally agreed upon that the onset arc is on field lines threading the inner edge of the TCS (the so-called "transition region").

"Inside-Out" and "Outside-In" differ in order and what the brightening arc signifies. Whether there are events that are truly "Inside-Out" is not agreed on (based largely on the optical data, I believe most first-onsets are "Inside-Out").

We need to be sure when discussing new scenarios that there is clarity of the implication. Nishimura's is "triggered Inside-Out" (and not a variant of "Outside-In").

There are significant unresolved issues which need to be addressed: 1) what causes the onset arc? 2) where does the proton aurora map to (and how robust are the conclusions about the onset arc mapping? 3) do Nishimura's streamers/ BBFs cause onsets? 4) can we find more comprehensive evidence of NER/ BBFs in the optical data (e.g.,.. Do more work like Kepko's)?

The substorm problem is difficult
- **there are a lot of necessary details**
- **we all bring biases to interpretation of inadequate data**
- **substorm may encompass more than one phenomena**

New GB & in situ (THEMIS) observations are paying off…
- **verification of both substorm scenarios**
- **tests of models of the onset physics**

Clearly, exciting challenges remain…
- **what is (or is there an) ionospheric signature of MR**
- **auroral electrodynamics (what is an arc?)**
- **mapping**
- **ionospheric signatures of magnetospheric dynamics**