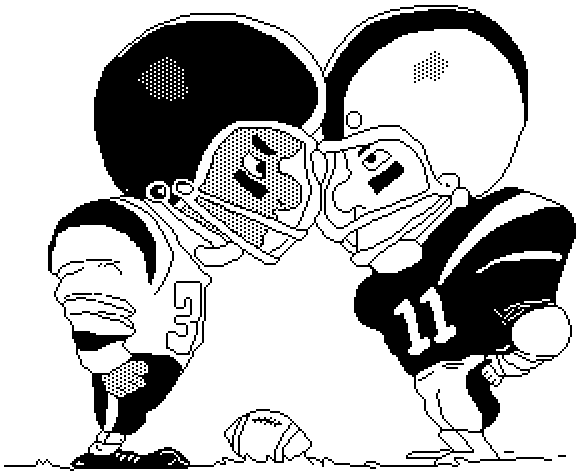

GEM WORKSHOP 1999 STUDENT COMMISIONED TUTORIAL:

“What are they arguing about?” SUBSTORMS!

A Presentation at the GEM Workshop

June 24, 1999 - Snowmass, CO

by

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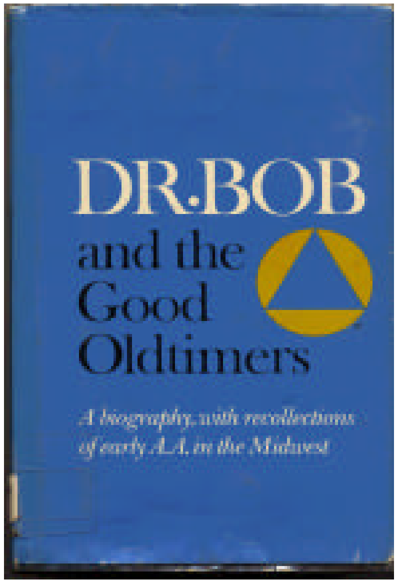


THE CHARGE

- "graduate student commissioned" tutorial
- A polling of the students at the Fall AGU, and later through email, elicited a consistent topic of confusion: substorms.
- Specifically, while students are familiar with the models and the general concept of a substorm, they do not understand the current debates. A frequent response was, "What are they arguing about?" While established researchers understand the controversies, they have not been clearly delineated for the students.
- "here are the observations";
  "here is how the models explain them";
  "here are the outstanding questions".

QUESTIONS TO BE ADDRESSED

- What is the time sequence of the CD model? The revised NENL model? A quantitative timeline is preferred. (e.g., for the rNENL model, reconnection occurs for x minutes on closed field lines before onset, etc.). What is the *observational* evidence that agrees/disagrees with each of the model timelines.
- What are the objections of the CD group to the rNENL model, in terms of observations? How does the rNENL model address those concerns? What are the objections of the rNENL group to the CD model? How does the CD model address these concerns. Of particular importance is the concept of braking, and how it rNENL model relates that to the most equatorward arc brightening at onset. You should also present objections to the braking theory.
- What are the *observational* differences between substorms and pseudo-breakups? Given these observations, how do both models account for the differences, if any. A related questions is, can small substorms occur without reconnecting lobe flux?
- What are the unanswered questions that neither model adequately addresses?

A PARTIAL HISTORY OF PAST AND PRESENT ARGUMENTS

- Substorms do not have a growth phase they are directly driven by solar wind
- Magnetic reconnection does not occur because no one has been able to work out a theory or because there is no such thing as field lines
- Southward fields in tail are not reversals of Earth field by reconnection, but are waves, tilts or vacuum field of field-aligned currents
- Flows in the plasma sheet are not real flows, they are field-aligned streaming in boundary layers or instrumental distortion of complex particle distributions
- Plasma sheet flows are generated at the distant x-line not a near-Earth x-line
- Plasma sheet flows are sucked in by a tail cusp instability (current disruption) not pushed in by an x-line
- Auroral breakup does not map to the typical location of the NENL
- Flux ropes (plasmoids) are created late in the expansion phase or are not produced by every substorm
- Every intensification of the aurora or electrojet is a substorm
- All substorms are externally triggered
- Substorms are not a separate phenomenon. The term substorm is a good descriptive name for a class of dynamic phenomena

WHAT IS A SUBSTORM?
Two Different Views

- A time interval during which solar wind energy coupling to the magnetosphere is enhanced, and energy is stored and released to the atmosphere in a quasi-periodic manner
- A set of physical processes that produces a temporally and spatially organized display of aurora and magnetic activity
- A time interval that includes at least one sudden brightening, expansion and recovery of the aurora
- ++
- A substorm is not a separate phenomenon, but rather a realization of the magnetospheric dynamics distinguished by large-intensity energy dissipation combined with significant configurational changes.

DEFINITIONS OF A SUBSTORM

- “A magnetic storm consists of sporadic and intermittent polar disturbances, the lifetimes being usually one or more hours. These I call *polar substorms*.” [*Chapman*, 1962]
- “The sequence of auroral events over the entire polar region during the passage from auroral quiet through the various active phases to subsequent calm is called an *auroral substorm*: it coincides with a magnetic (DP) substorm, with which it has some close relationships.” [*Akasofu*, 1964].
- “To generalize the concept of the auroral substorm to include the worldwide disturbance characteristics and to emphasize the importance of the magnetosphere in auroral zone observations, we have suggested the term, *magnetospheric substorm*.” [*Coroniti, McPherron and Parks*, 1968]
- “A magnetospheric substorm is a transient process initiated on the night side of the Earth in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and magnetosphere.” [*Rostoker et al.*, 1980]

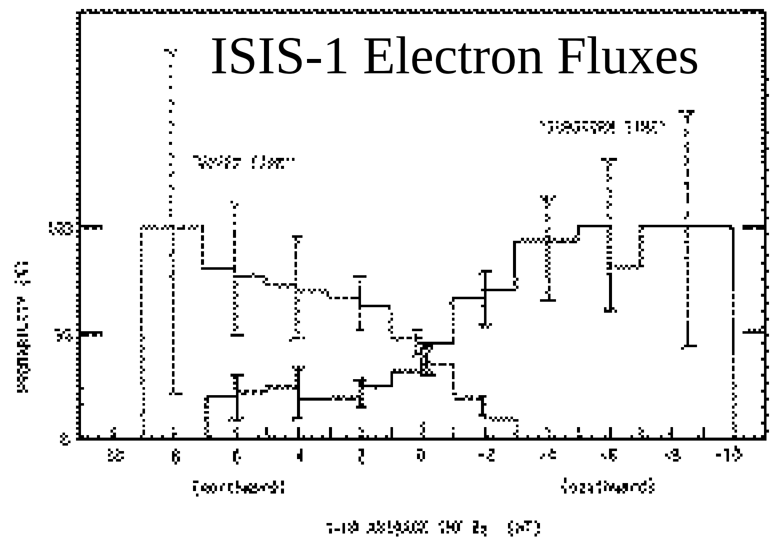
WHAT CAUSES A SUBSTORM?

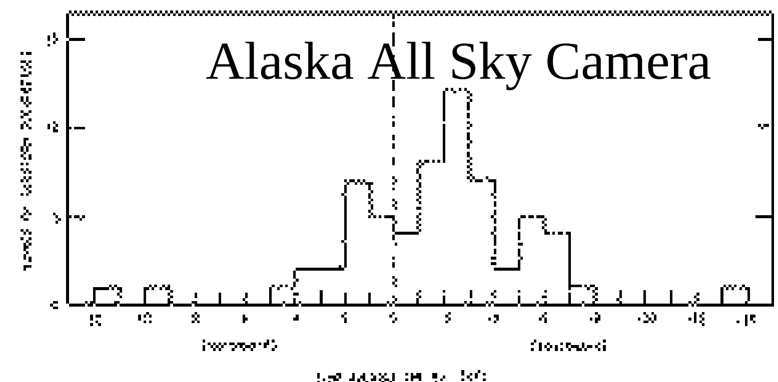
- A substorm is caused by a southward turning of the interplanetary magnetic field which initiates reconnection at the dayside magnetopause
- Dipole field lines connect with interplanetary magnetic field lines allowing a fraction of the interplanetary electric field to penetrate the magnetosphere and energy to be extracted from the solar wind
- This coupling drives an internal convection system and associated electrical currents which link the outer magnetosphere to the ionosphere.
- Time lags in flux and plasma transport lead to distortion of the magnetotail and the creation of a thin current sheet close to the Earth that becomes progressively more unstable
- The unstable current sheet becomes susceptible to triggered release of energy
- An instability begins releasing energy and allowing flux and plasma to return to the dayside
- Energy in converted to flux ropes, injection into the ring current and outer radiation belts, Joule heating of the ionosphere by steady currents, waves, and particle precipitation

SUBSTORM OCCURRENCE PROBABILITY

(Kamide et al, JGR, 82(35), 5521, 1977)

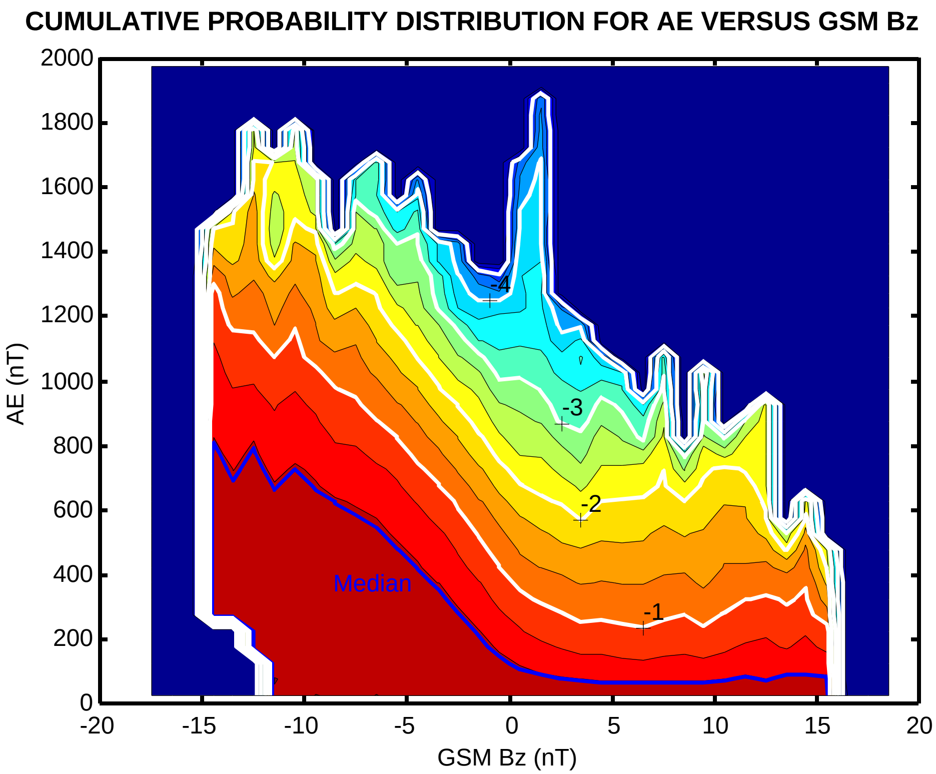
- Use ISIS-1 electron data, Alaska All Sky Camera data, ground magnetometers to identify substorm occurrence
- Correlate probability of substorm occurrence with IMF Bz in hour before
- Note probability of quiet conditions increases with Bz>0 and probability of substorm increases with Bz<0
- Number of all sky camera pictures with aurora substorms shows definite bias towards negative Bz
- Increasing probability of size of auroral oval and occurrence of substorms suggests that the substorm probability is related to the amount of energy in the tail





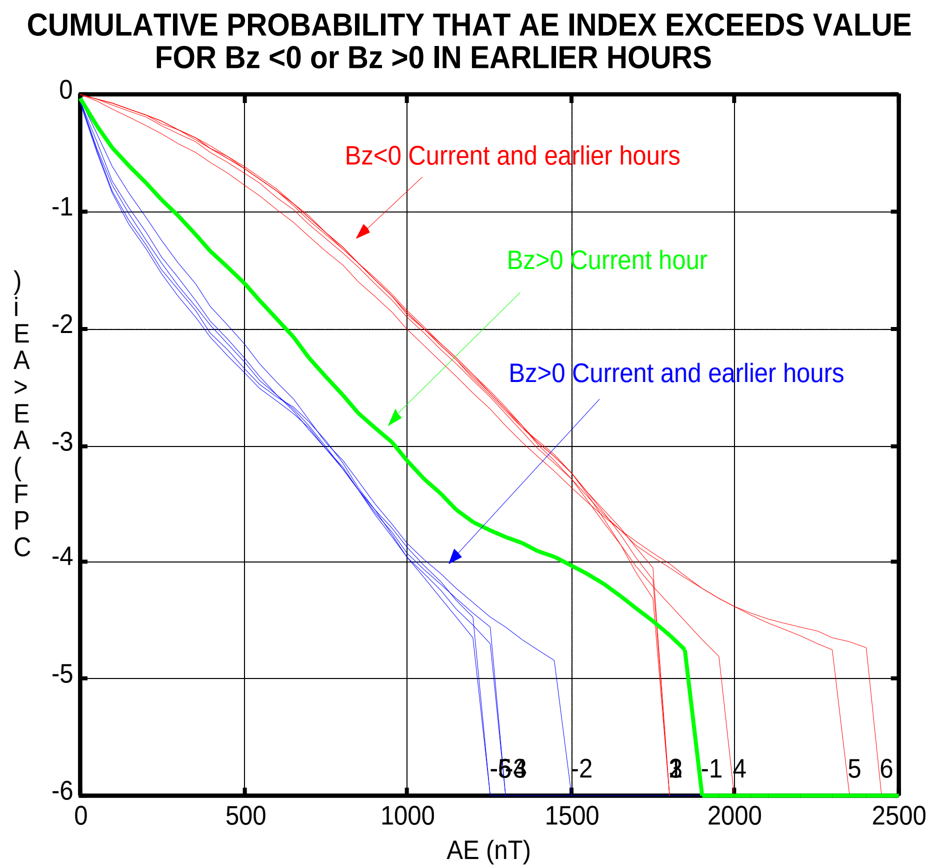
“WHAT CAUSES A SUBSTORM?” IMF - Bz and RECONNECTION!

- Use 30 years of hourly AE and IMF Bz
- For each 1 nT bin of Bz create the cumulative probability distribution for corresponding AE index
- Display contour map of the probability of observing AE exceeding a given value as a function of Bz
- The probability of observing large values of AE decreases very rapidly as Bz changes to positive values
- The median value of AE for Bz > 0 is less than 100, the background level of AE from Sq variations in measurements



DEPENDENCE OF ELECTROJET ACTIVITY ON NUMBER OF HOURS OF Bz>0 or Bz <0

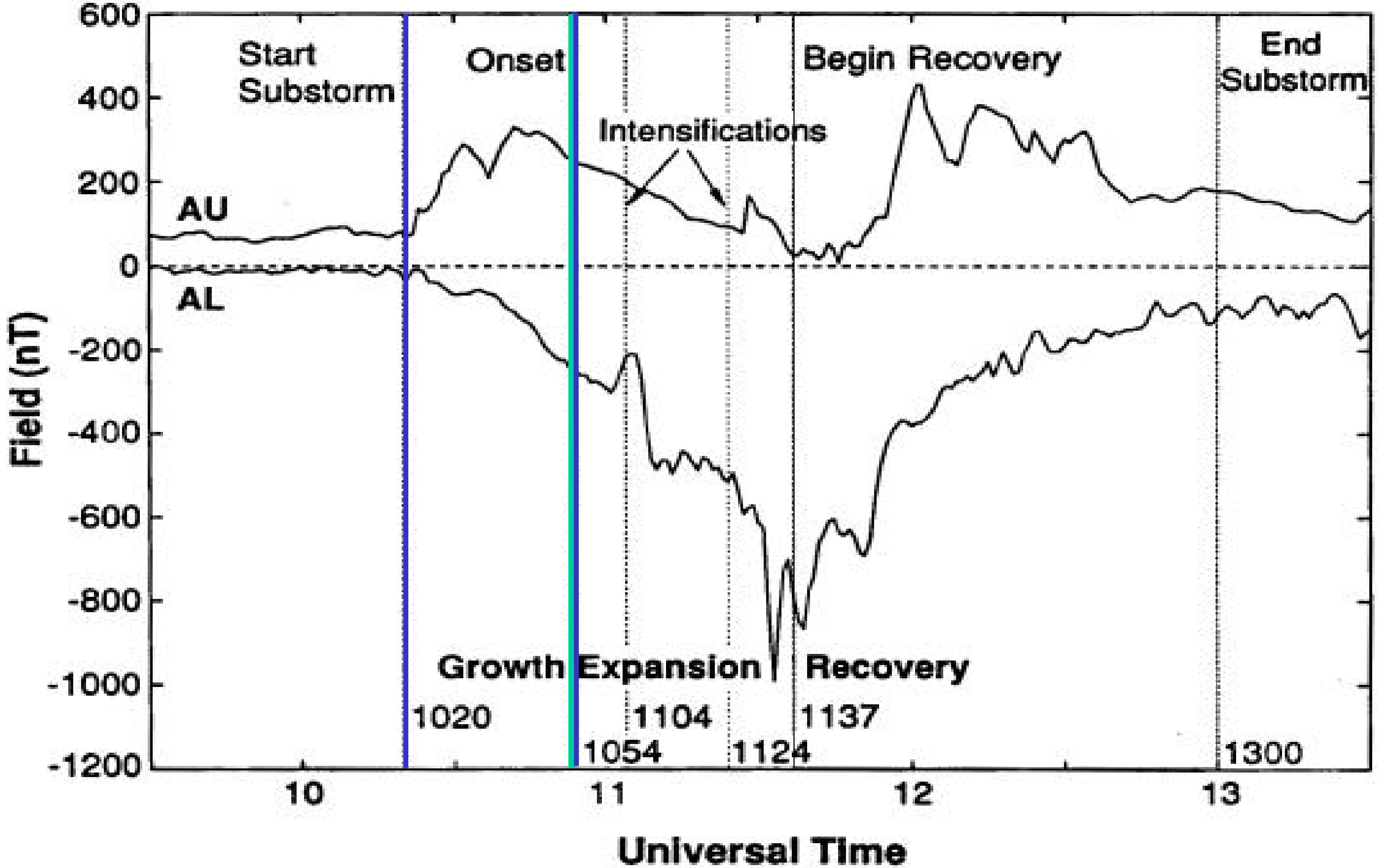
- Select data by number of hours prior to current hour that hourly Bz is continuously of one sign
- Create distribution showing probability that AE exceeds a give value for each situation
- All distributions for Bz<0 are identical indicating activity is created by Bz in a given hour
- All distributions for Bz>0 are the same except for the current hour indicating that typical activity takes at least two hours to decay
- Note the median probability for Bz>0 is ~50 nT while for Bz<0 it in ~250 nT
- Over most of the range probabilities for Bz>0 and Bz<0 differ by a factor of 100



WHAT ARE THE PHASES OF A SUBSTORM?

- Start of Substorm - Southward turning of the IMF at dayside magnetopause
- Growth Phase - Enhanced solar wind coupling and energy storage in tail with ionospheric manifestations of enhanced convection
- Pseudo Breakup - Release of small amount of stored energy
- Substorm Onset - Beginning of expansion phase
- Expansion Phase -Release of stored energy into radiation belts (ring current), particle precipitation (aurora), Joule heating (bay activity), plasmoids (magnetic bubble)
- Intensification - Renewal of substorm expansion that increases disturbed region and strength of disturbances
- Recovery Phase - Reestablishment of quiet conditions and regular structure after IMF has turned northward
- End of Substorm - Electrojet currents fade into background

SUBSTORM PHASES FROM CDAW-6



DEFINITION OF SUBSTORM ONSET

- A *substorm* is the organized response of the magnetosphere to a short interval of southward IMF
- *Isolated substorms* have three obvious phases
- The transition from growth phase to expansion phase is called the *substorm onset*
- Substorm onsets are associated with *repeatable signatures*
- Onset signatures are often seen *multiple times* in substorms
- In the tail there is usually a clear transition in behavior associated with a typical onset signature. We call this the *main onset* of the substorm
- The main onset organizes the tail signatures into a *physically meaningful pattern*

WHAT TRIGGERS THE SUBSTORM ONSET?

- The expansion phase can occur with no evident external input.
- Substorms are also triggered by pressures pulses, by northward turnings of the IMF, or by changes in By
- Expansion begins in thin current sheets close to the Earth
- Expansions probably results from some type of plasma instability
- +++++++++++++++++QUESTIONS++++++++++++++++++++++
- Are the growth phase and recovery phases necessary to establish the conditions for instability of thin current sheets?
- Is only one physical process responsible for the onset?
- Is demagnetization of ions and subsequent ion tearing the cause?
- Is the steep pressure gradient that retards the flow unstable to ballooning instability?
- Are changes in ionospheric conductivity and currents the cause of the onset?

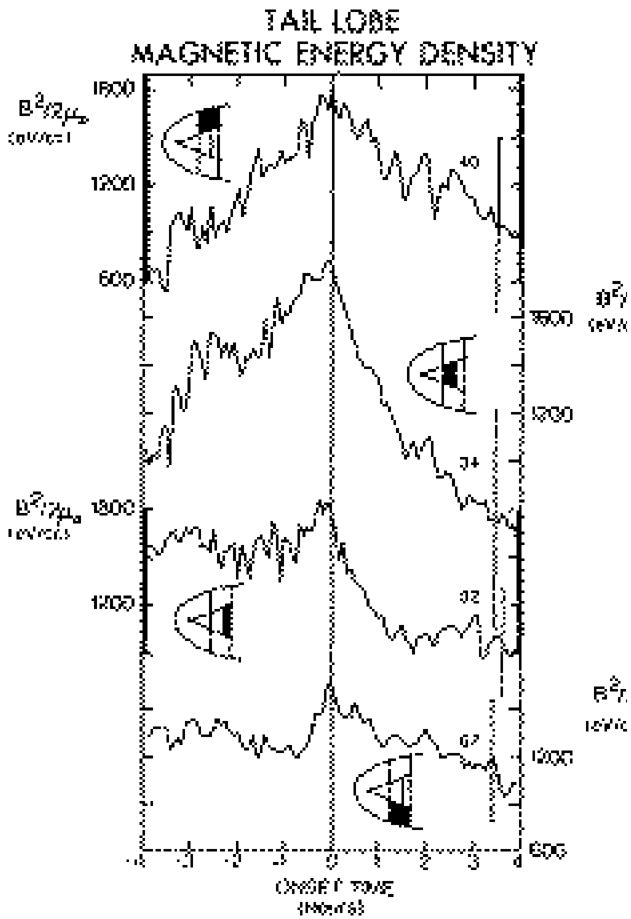
TYPICAL SUBSTORM DEVELOPMENT: *GROWTH PHASE (0 to 60 minutes)*

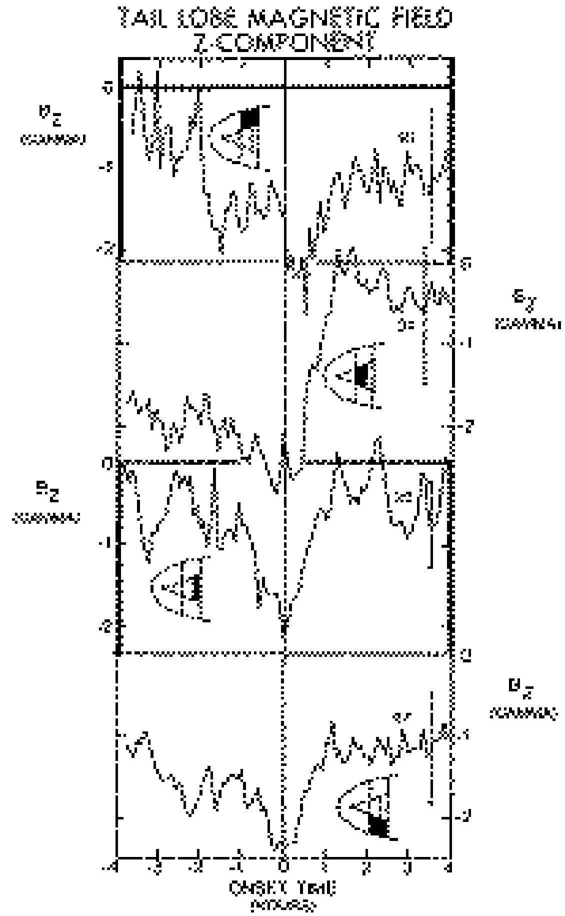
• T = 0	IMF turns southward at bow shock
• T = 8 min	Dayside ground disturbances begin
• T = 20 min	Tail lobe increase and rotation begins
• T = ?	Nightside ground disturbances begin
• T = ?	Obvious thinning of plasma sheet
• T = 40 min	Pseudo breakup likely also flow bursts at poleward boundary of the oval
• T = 60 min	Minimum distance to subsolar point
	Maximum in Blobe, and minimum in tail Bz
	Maximum expansion of polar cap Strong, thin tail current close to Earth
	Well developed DP-2 current system

CHANGES IN TAIL LOBE

(Caan et al., PSS, 26, 269, 1978)

- Computer detection of time of ~1800 midlatitude positive bay substorm onsets
- Superposed epoch analysis of 30-60 tail lobe field events in various sectors
- Increase of lobe field and decrease of Bz prior to onset
- Decrease of lobe field and increase of Bz after onset
- Interpretation is energy storage and release





TYPICAL SUBSTORM DEVELOPMENT: *ONSET (± 2 minutes)*

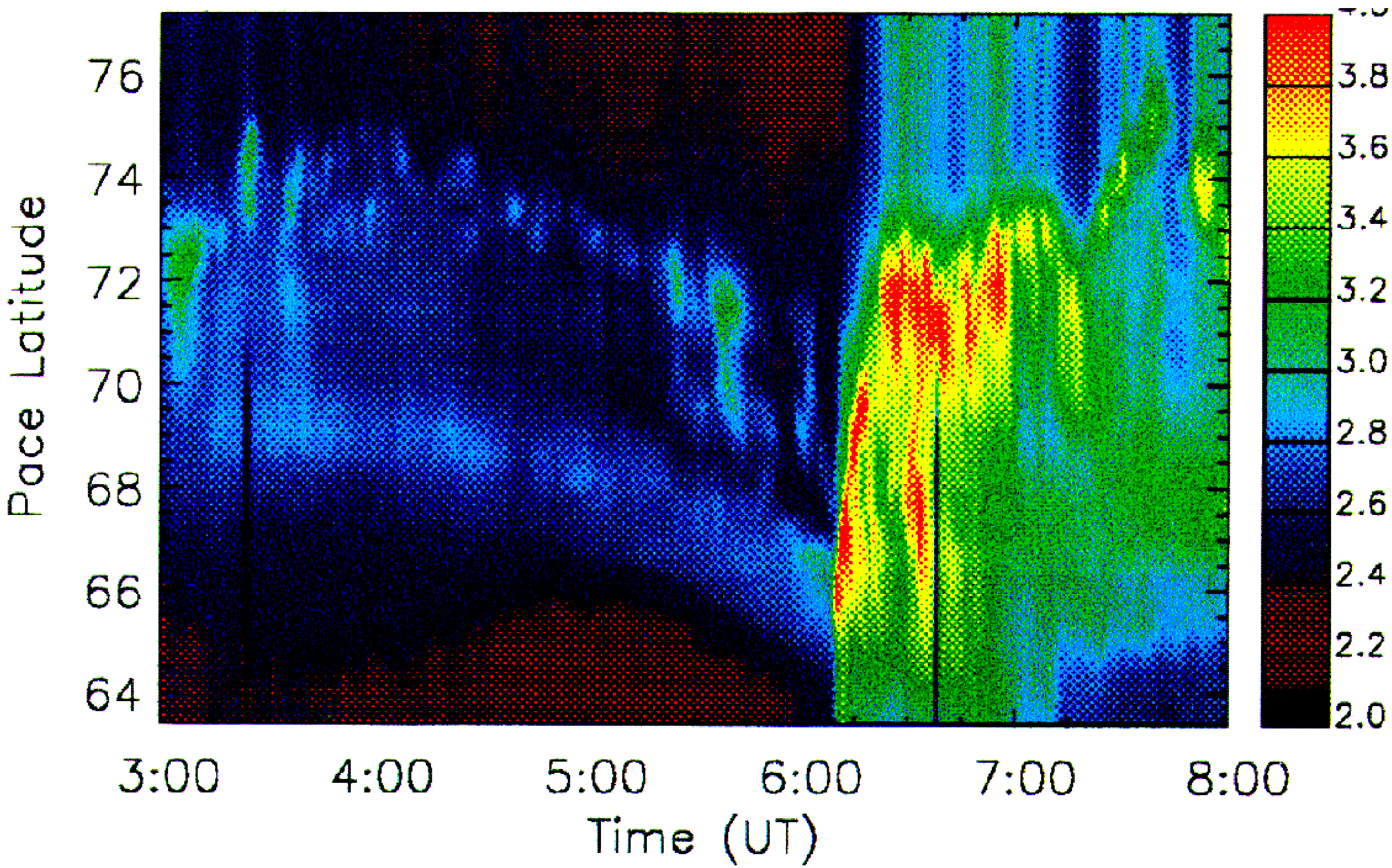
- Tailward flow with southward Bz in premidnight near Earth plasma sheet
- Earthward flow with northward Bz in near Earth plasma sheet
- Bt in near Earth lobe begins decrease
- Bz in near Earth lobe begins increase
- Earthward flow approaches synchronous orbit
- Magnetic turbulence seen near synchronous orbit
- Auroral breakup begins on equatorward discrete arc just premidnight
- Sudden onset of westward electrojet in midnight sector
- Pi 2 burst seen in auroral zone with Pi 1b rider
- Sudden intensification of AKR
- Synchronous field begins to dipolarize at midnight
- Dispersionless injection of electrons and ions at synchronous orbit
- Midlatitude Pi 2 burst and positive H bay begin
- Low latitude Pi 2 burst

TAIL OBSERVTION OF $B_z<0$ PRIOR TO MIDLATITUDE Pi 2

TYPICAL SUBSTORM DEVELOPMENT: *EXPANSION PHASE*

- Poleward expansion of auroral bulge
- Growth of westward electrojet
- Formation of westward surge
- Decrease of tail lobe field and dipolarization
- Magnetic turbulence at inner edge of plasma sheet
- Dipolarization of synchronous magnetic field
- Injection and energization of synchronous particles
- Drop out of outer plasma sheet
- Tailward motion of flux ropes (plasmoids)
- Pulsating patches of drifting electrons in morning sector
- Intensification of westward electrojet and formation of new surge frequently to west of preceding event
- Reversal of plasma flow direction in near-earth plasma sheet
- Asymmetric development of ring current
- Omega bands form in morning sector

CANOPUS OBSERVATIONS OF GROWTH AND EXPANSION PHASE



TYPICAL SUBSTORM DEVELOPMENT: *RECOVERY PHASE*

- Aurora reaches maximum poleward expansion and quiet structures reform (?)
- Electrojets attain maximum strength and die away
- Substorm current wedge fades
- Injected particles drift around Earth
- Plasma sheet reappears in middle tail and thickens
- Near-Earth X-line moves downtail
- All plasma sheet flows are Earthward
- Plasmoids pass beyond the usual location of distant x-line

SUBSTORM MODELS

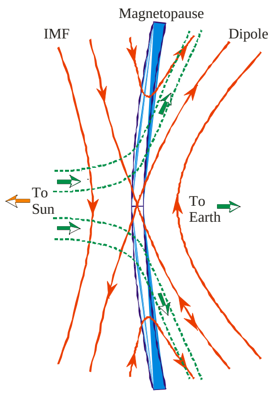
- NENL: Updated Near Earth Neutral Line Model
- CD: Current Disruption Models
  - Cross tail current instabilities
  - Pressure gradient instabilities
- M-I Coupling: Magnetosphere-Ionosphere Coupling
  - Feedback instability
  - Wave induced particle precipitation
- Solar Wind Triggering: Reduction of convection
- Boundary Layer Dynamics:
  - Kelvin-Helmholtz in dusk low latitude boundary layer
  - Thermal catastrophe

THE NENL SUBSTORM SEQUENCE
Growth Phase

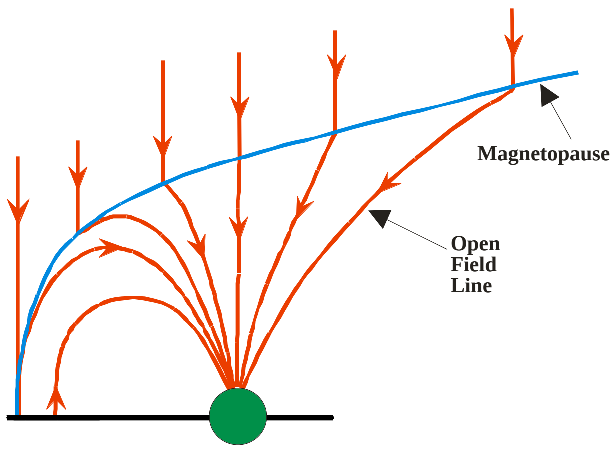
- IMF turns southward at magnetopause initiating dayside reconnection
- Solar wind transports open flux to tail lobe
- Open flux is added to tail lobe increasing B near-tail and increasing tail radius far-tail
- Polar cap area increases moving auroral oval to lower latitudes
- Plasma sheet thins from lobe squeezing and flux transport to dayside decreasing width of oval
- Tail current moves earthward to balance force on tail and strengthens to produce the increased lobe field. Tail cusp moves Earthward.
- Magnetopause is eroded increasing flair and dynamic pressure on tail lobe
- Region 1 currents increase due to solar wind drag. Region 2 currents increase due to increased shielding. Electrojets strengthen from enhanced E and σ
- Sporadic bursts of reconnection at distant x-line generate boundary layer ion beams and aurora
- Plasma sheet ions become demagnetized
- Pseudo breakups indicate localized transient reconnection is occurring
- Significant reconnection begins in near-Earth plasma sheet (~25 Re) on closed field lines

SUBSTORM GROWTH PHASE

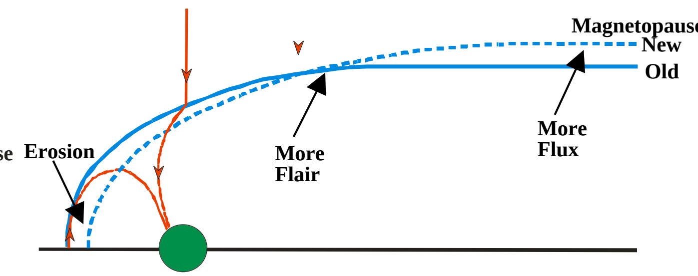
Dayside Reconnection



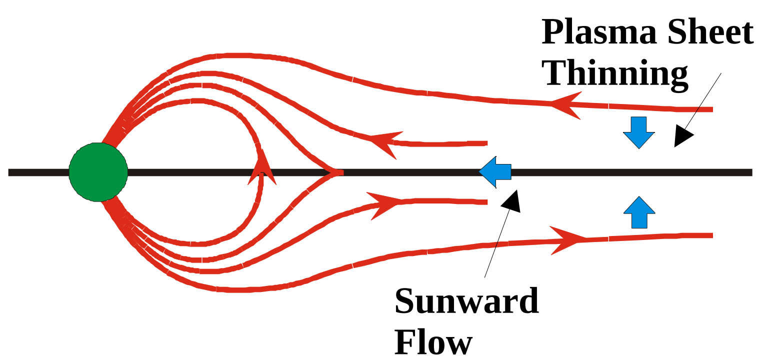
Transpolar Flux Transport



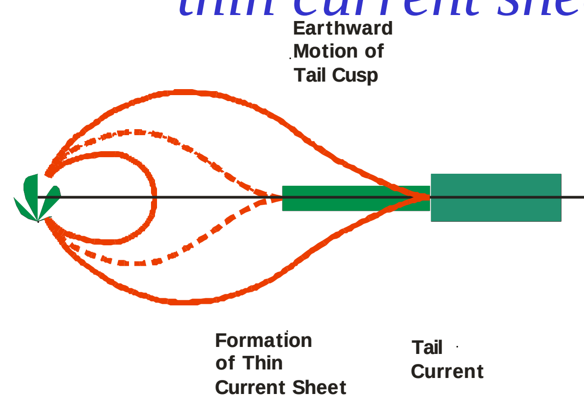
Erosion and Flairing



Thinning of plasma sheet



Creation of thin current sheet

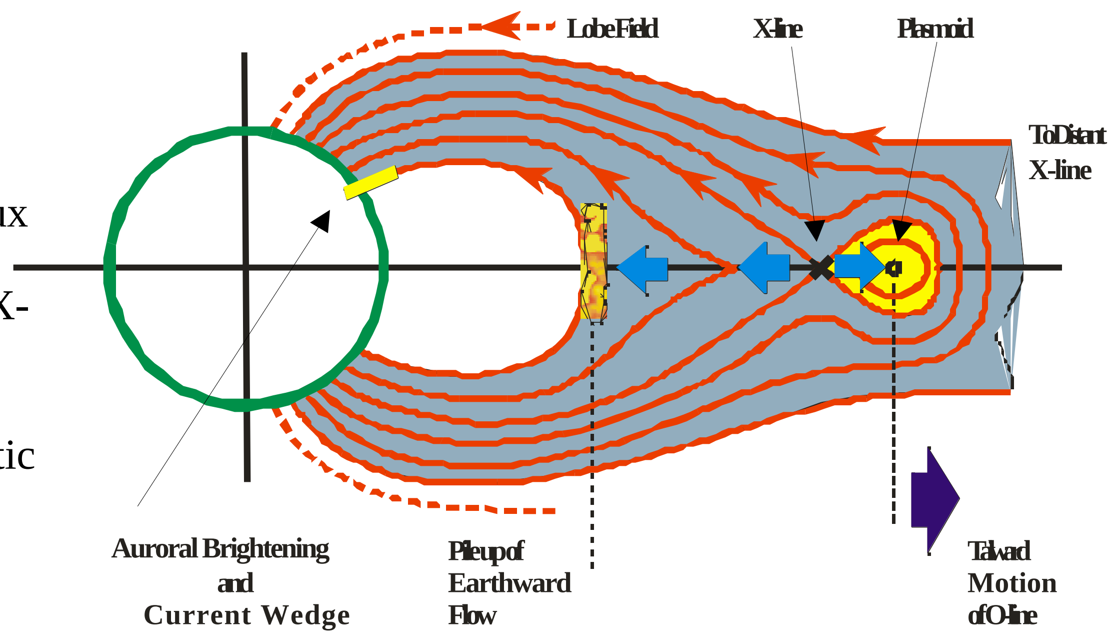


THE NENL SUBSTORM SEQUENCE
Expansion Onset

- Localized reconnection accelerates strong convective flows and initiates growth of flux rope
- Axis of flux rope begins moving tailward
- A narrow channel of flow surges Earthward
- Alfven waves are launched towards auroral zone by enhanced electric field within flow channel (Pi 2)
- Flow reaches tail cusp and is erratically braked by pressure gradient creating wave activity, possibly through wave instability (CD)
- Flow stagnates and flux piles up near midnight outside of synchronous orbit dipolarizing B
- Electron precipitation begins in region of stagnation
- Field-aligned currents of the initial substorm current wedge (swc) are generated at edges of channel in braking region
- Inductive electric field is created by rapid increase in magnetic field
- Particles are energized and guided into the stagnation region by the inductive electric field
- Compressional waves generate midlatitude Pi 2

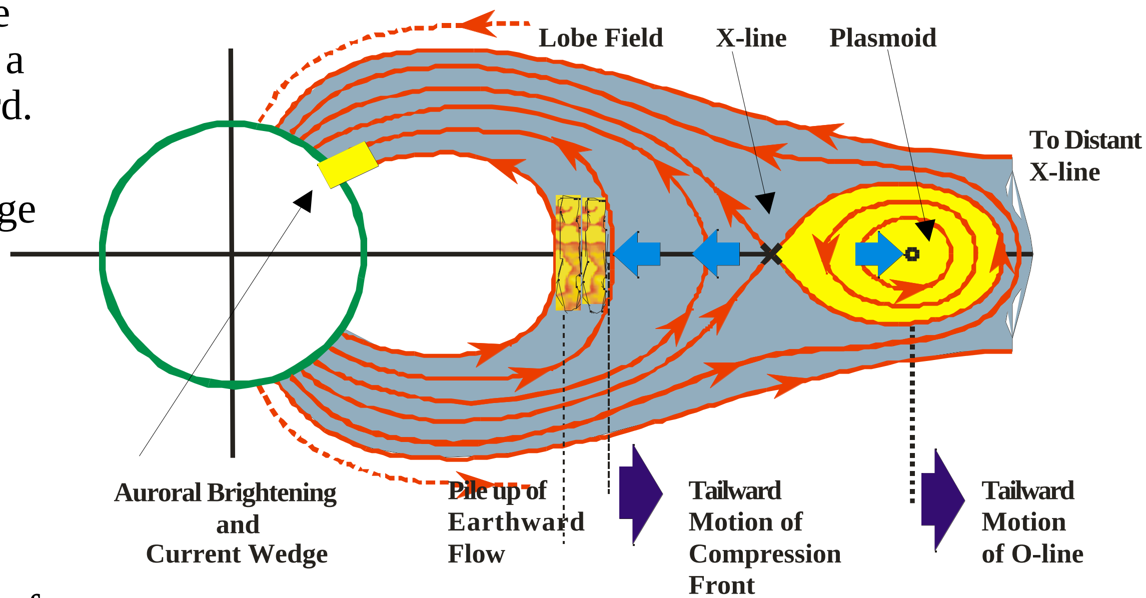
FORMATION OF NENL EXPANSION ONSET

- Substorm onset begins with the formation of a localized pair of X- and O-lines on closed field lines at center of near-Earth plasma sheet
- Reconnection creates a flux rope centered around the O-line. The flux rope moves tailward due to momentum provided by forces in X-line
- Earthward flow is decelerated as it runs into rigid dipole field. Magnetic flux piles up creating a turbulent region that maps to the auroral breakup region.
- The substorm current wedge is created by the inertial current of the flow deceleration.



FORMATION OF NENL
EARLY EXPANSION PHASE

- Continued reconnection adds to flux rope moving its center further tailward.
- Reconnection also adds flux to the Earthward pile up region creating a compression front moving tailward.
- The front maps to the poleward edge of the expanding auroral bulge
- Closed field lines are present between poleward edge of aurora and X-line
- Closed field lines are also present poleward of projected X-line
- The last closed field lines moves equatorward at the speed of the convective flow (no reconnection of open field lines)

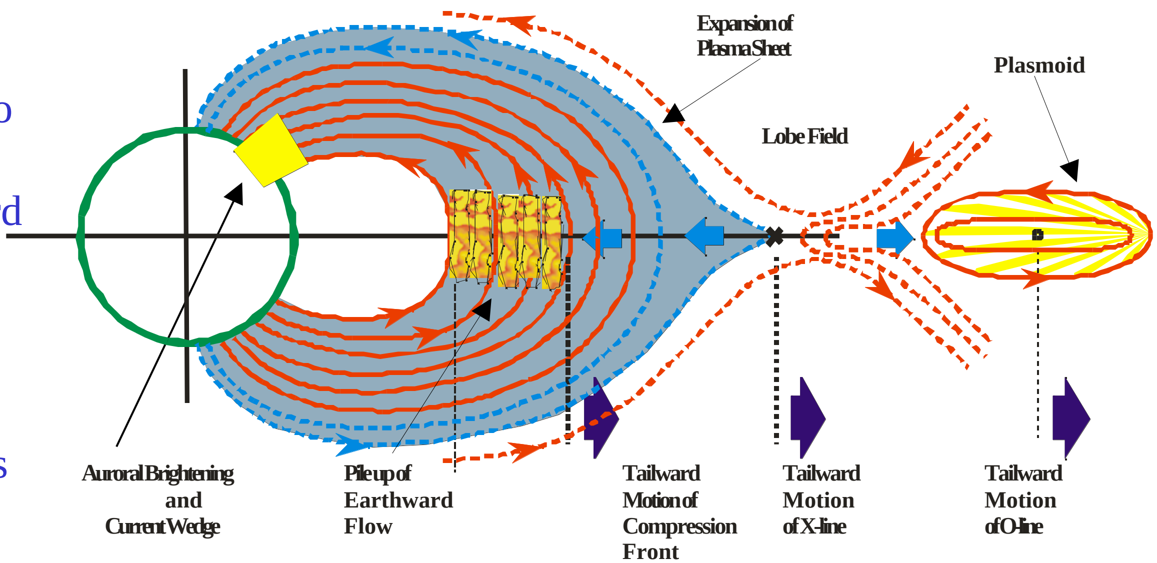


THE NENL SUBSTORM SEQUENCE
Expansion Phase - Earthward Side

- Subsequent flow bursts are decelerated further from the Earth creating a tailward moving compression front
- They are also diverted around the Earth creating vorticity, magnetic shears, and vertical pressure gradients
- The above generate strong and persistent currents of the substorm current wedge
- Outward field-aligned current of scw become unstable and creates aurora of westward surge
- Nightside reconnection is transient producing multiple intervals of flow and flux transport typically separated by 20 minutes (bbf's)
- Successive reconnection events may occur at different azimuths and radial distances
- Each burst consists of multiple, short-duration high speed flow bursts typically two minutes apart (Impulsive Dissipation Events)
- The individual IDE's drive pulses of Pi 2 pulsations
- The integrated effect of Earthward bbf's is a sustained current wedge with step-like increases and a compression front that moves tailward
- The compression front maps to poleward edge of auroral expansion
- The near-earth x-line extends azimuthally but is probably not reconnecting along full length
- This creates additional narrow flow channels at ends of flux rope that expand the current wedge and move the compression front tailward

FORMATION OF NENL
LATE EXPANSION PHASE

- Reconnection moves into open field lines of lobe
- The x-line moves tailward in discrete jumps
- Earthward flows are slowed and diverted around the Earth
- The plasma sheet expands close to Earth
- A thin current sheet forms tailward of X-line
- Open field lines help propel a macroscopic plasmoid downtail
- Note compression front may still be on previously closed field lines
- Both old and new closed field lines are still poleward of poleward edge of auroral bulge



THE NENL SUBSTORM SEQUENCE
Expansion Phase - Tailward Side

- The start of reconnection prior to onset produces a small flux rope moving tailward held in by closed field lines
- The “ends” of a growing flux rope are connected to the Earth in opposite hemispheres
- Momentum is added to flux rope by reconnection at x-line
- Further reconnection adds additional loops to the flux rope effectively moving its leading edge down the tail and adding new plasma with tailward momentum
- Substorm onset is observed
- Reconnection site moves down the tail as closer to the Earth the flux pileup boundary also moves tailward
- Reconnection breaks through into the lobe connecting near-Earth and distant x-lines
- Open field lines accelerate central part of flux rope tailward through curvature force and dynamic pressure of tailward flow on back side
- Compression front mapping to poleward edge of auroral bulge has not yet reached x-line location so there are closed field lines poleward of the bulge
- Within this closed field line region is a boundary corresponding to the first lobe line closed by reconnection
- The separatrix remains poleward of the auroral bulge

THE NENL SUBSTORM SEQUENCE
Recovery Phase

- The x-line moves tailward out of the near-earth region
- Earthward flows are observed in the near-earth region
- The plasma sheet expands
- The auroral electrojet moves to its highest latitude
- Bursts of reconnection occur at the x-line causing flows that appear at the open-closed field line separatrix
- Electrojet currents die away as the flows no longer reach the inner magnetosphere
- Reconnection eventually ceases as the x-line reaches a stable location

TAILWARD RETREAT OF THE NEAR-EARTH X-LINE

SOME OBJECTIONS TO THE NENL MODEL OF SUBSTORMS

- Magnetic reconnection does not occur
- Proposed NENL signatures do not occur often enough
- Signatures do not occur at the proposed times or places
- Tail flows are reflected ion beams or cold ionospheric oxygen
- $B_z < 0$ is due to waves in plasma sheet or FA current signatures
- There is no bifurcation of tail response at a fixed distance
- Reconnection is triggered late in substorm expansion by other processes
- The auroral breakup does not map to the known location of the NENL
- There is no evidence in aurora for the Earthward flows from a NENL
- Earthward flows do not dipolarize the local field at some observation points
- Earthward flows do not reach the current disruption region

CD OBJECTIONS TO NENL MODEL

(Lui, JGR, 101(A6), 12,955,1996)

Assertions:

- Auroral breakup is on closed field lines and continues there for 5-15 min
- Expansion takes 5-15 min to reach open field line boundary
- Midtail observations in breakup meridian show some substorms have no flow towards inner magnetosphere
- Energization of ions is local to the inner magnetosphere
- The current sheet before disruption has thickness comparable to ion gyroradius
- Some dipolarizations are a non MHD process

Objections:

- NENL says open field line reconnection begins at expansion onset so that plasmoid can be released at this time
- Plasmoid release timed with onset so inferred location of release is wrong
- CD can't be caused by reconnection if not connected to a flow from x-line
- In the NENL model energization should occur near the x-line and particles must be transported to inner region
- MHD assumes larger scales so therefore conclusions of MHD models (that are theory basis for NENL) are inappropriate
- Observation of a dipolarization is not support for an MHD theory of substorms

THE SUBSTORM ONSET IN CURRENT DISRUPTION MODELS

CROSS-FIELD CURRENT INSTABILITY

- A standard growth phase creates a strong current in a thin plasma sheet close to the Earth
- +++++++++ONSET+++++++++++++
- The current sheet becomes unstable and produces intense waves that lead to a break down of frozen-in condition
- If global conditions are correct an expansion phase begins. Otherwise a pseudo breakup.
- In an expansion stretched field lines relax by diffusing Earthward through the instability region, Fermi accelerating particles in a convective surge
- The cross-tail current is redirected to the ionosphere
- The reduction in J as B dipolarizes typically increases the field curvature force accelerating plasma Earthward
- A rarefaction wave propagates tailward further thinning the plasma sheet and expanding the unstable region diverting more current into the ionosphere
- The rarefaction wave reduces plasma sheet Bz and triggers reconnection
- Reconnection works through the plasma sheet and releases a plasmoid
- ++++++++EXPANSION++++++++++
- Continue as in the NENL model but with a start of reconnection and release of plasmoid later than expansion onset

OBJECTIONS TO NENL MODEL BY CONVECTION REDUCTION MODEL

(Lyons, personal communication, 1999)

Assertions:

- There is strong evidence that the magnetosphere generally accumulates energy in the tail lobes during periods of enhanced convection and does not go unstable
- Obvious substorms show no effects in tail at appropriate spacecraft for about half of all substorms
- Flow channels in substorm expansion must have scale size comparable to bursty bulk flows which occur all the time regardless of substorm phase to account for infrequent observation of flows in expansion
- MHD models based on sudden onset of resitivity are unphysical and hence inappropriate support for NENL
- The NENL model can not explain substorm triggering by northward turns

Objections:

- The NENL model states that continuous solar wind stress causes internal strain leading inevitably to an internal instability
- If the NENL model were correct a spacecraft should see flows and field changes for every substorm
- It seems impossible for a few, narrow flow channels to dipolarize the near-Earth magnetic field and return lobe flux
- The plasma sheet is always resistive
- A model must explain triggering to be correct

THE SUBSTORM ONSET IN CONVECTION REDUCTION MODEL

- IMF drives convection E-field and loads energy into tail lobe
- Energy accumulates continuously until externally triggered by solar wind
- In the inner magnetosphere particle drifts include E-field, grad B, curvature B
- +++++++++ONSET+++++++++++++
- A sudden reduction in IMF caused by a northward turning or reduction in |By| reduces or eliminates E-field drift (*triggering*)
- Particles are suddenly on azimuthal paths drifting away from midnight
- An azimuthal pressure gradient develops with a minimum at midnight
- The pressure gradient drives a substorm current wedge
- The current wedge diverts the tail current causing an inward collapse
- The inward collapse creates a rarefaction wave that travels downtail and triggers near-earth reconnection
- +++++++++EXPANSION+++++++++
- ???? I landed in Denver leaving his paper on the air plane

THE SUBSTORM IN BOUNDARY LAYER MODEL

(Rostoker, JGR, 101(A6), 12,955,1996)

- A standard growth phase creates a strong current in a thin plasma sheet close to the Earth
- +++++++++ONSET+++++++++++++
- At the end of the growth phase there is strong shielding of the inner magnetosphere by Region 2 currents out to equatorial plane post midnight closing through the inner edge of the tail current down to ionosphere premidnight
- The tail current is disrupted by some instability (CD) and diverted into the atmosphere as a substorm current wedge
- The addition of the Region 2 and scw corresponds to a cancellation of the Region 2 and hence a "*breakdown of shielding*"
- The CD launches a rarefaction wave down the tail that travels to the distant (50-80 Re) x-line starting reconnection
- An Earthward flow travels up the plasma sheet across its full width
- This flow creates a strong shear at the inner edge of the dusk low latitude boundary layer
- This shear goes Kelvin-Helmholtz unstable producing outward field-aligned current lines from the ionosphere
- Each K-H FAC line corresponds to a westward traveling surge
- ++++++++RECOVERY++++++++++
- Reconnect lobe flux at distant x-line and return it to dayside with flows in the recovery phase

DO SUBSTORMS HAVE MULTIPLE ONSETS OR ARE THESE MULTIPLE SUBSTORMS?

- Most disturbed intervals contain *multiple* occurrences of the phenomena characteristic of onset
- This substructure is *quasi-periodic* with a period of 15-20 minutes
- Many researchers *call* each such event a "substorm" although they do not include all the characteristics originally used to define a substorm
- The *question* is whether these events are separate and unrelated, or they are organized by a larger phenomenon (*the original substorm*)
- If they are part of something larger, which member of the sequence is *most important* and can be used as a time reference (*main onset*)?

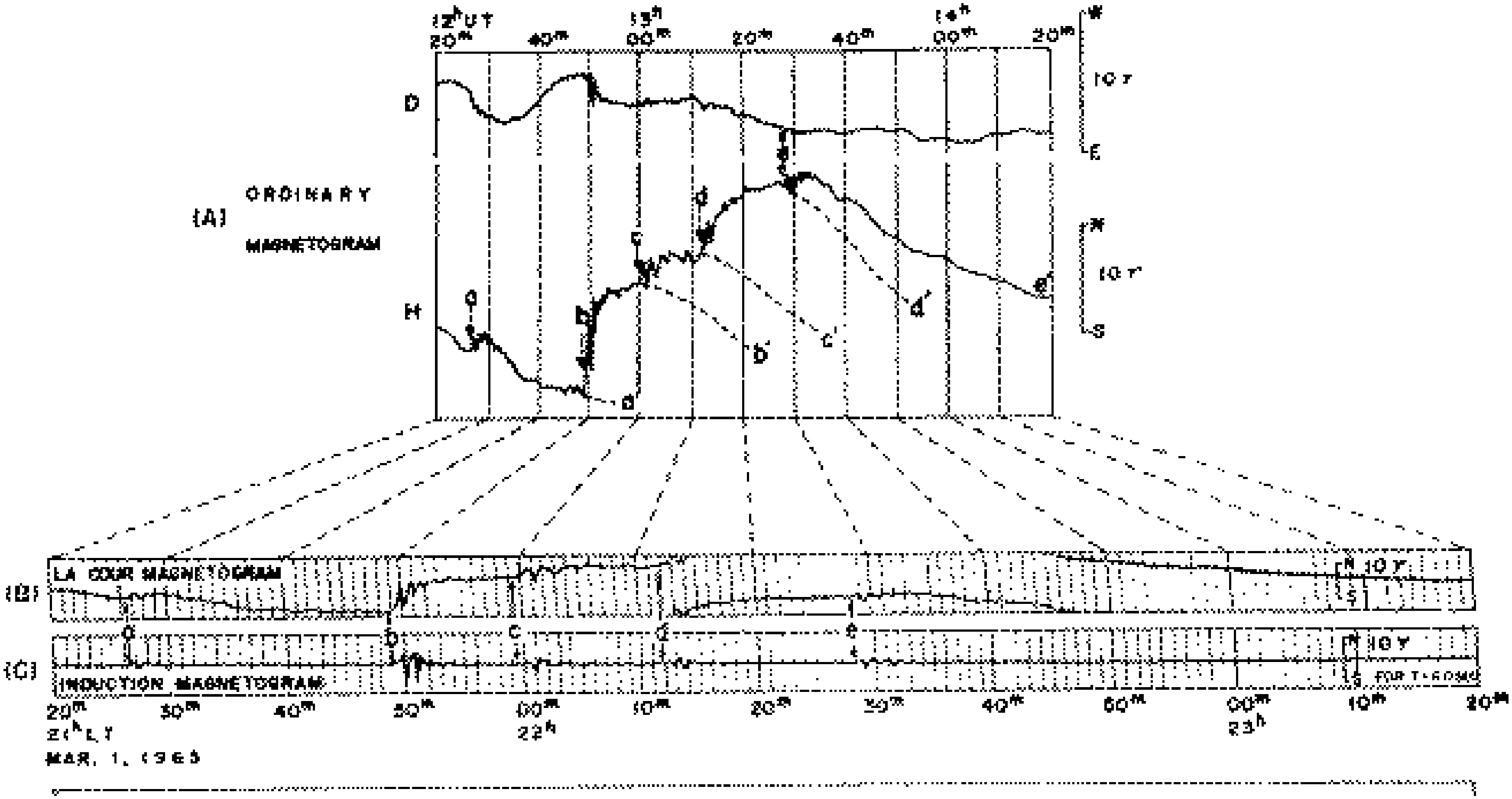
IS EVERY AURORAL INTENSIFICATION A SUBSTORM?

- Many investigators use the term “substorm” for the substorm expansion alone.
- How big does an auroral intensification have to be to be called an expansion and hence a substorm?
- Are there signatures in the magnetosphere that distinguish an auroral intensification from a substorm?

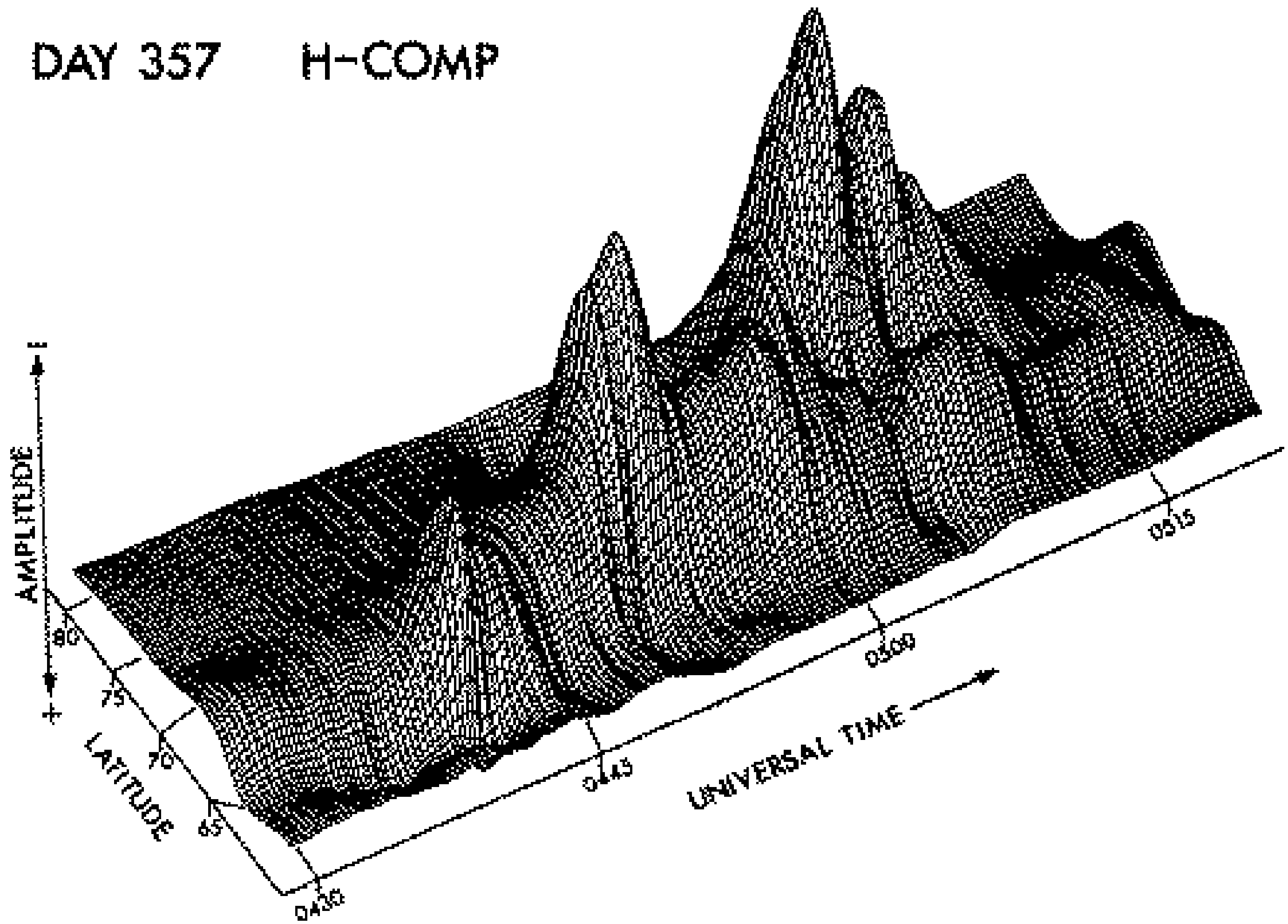
SIGNATURES OF SUBSTORM ONSET

- AURORAL ZONE
  - Brightening of most equatorial arc near midnight
  - Precipitation of energetic electrons
  - Onset of broad band Pi 2 pulsation burst with Pi b
  - Formation of a short segment of westward electrojet
- MIDLATITUDE
  - Quasi monochromatic Pi 2 pulsation burst
  - Beginning of positive bay in H and positive (premidnight) or negative (post midnight) bay in D component
- SYNCHRONOUS ORBIT
  - Start of D perturbation
  - Onset of dipolarization
  - Dispersionless particle injection
- TAIL LOBE
  - Peak of lobe field strength
  - Minimum in Bz component
  - Intensification of AKR
  - Arrival of a TCR
- PLASMA SHEET
  - Fast bursty flow with northward Bz in near-Earth plasma sheet
  - Tailward flow with southward Bz
- DISTANT TAIL
  - Passage of plasmoid extrapolated back to release at onset

RELATION OF MULTIPLE Pi 2 BURSTS TO SUBSTORM EXPANSION (Saito and Sakurai, 1970)



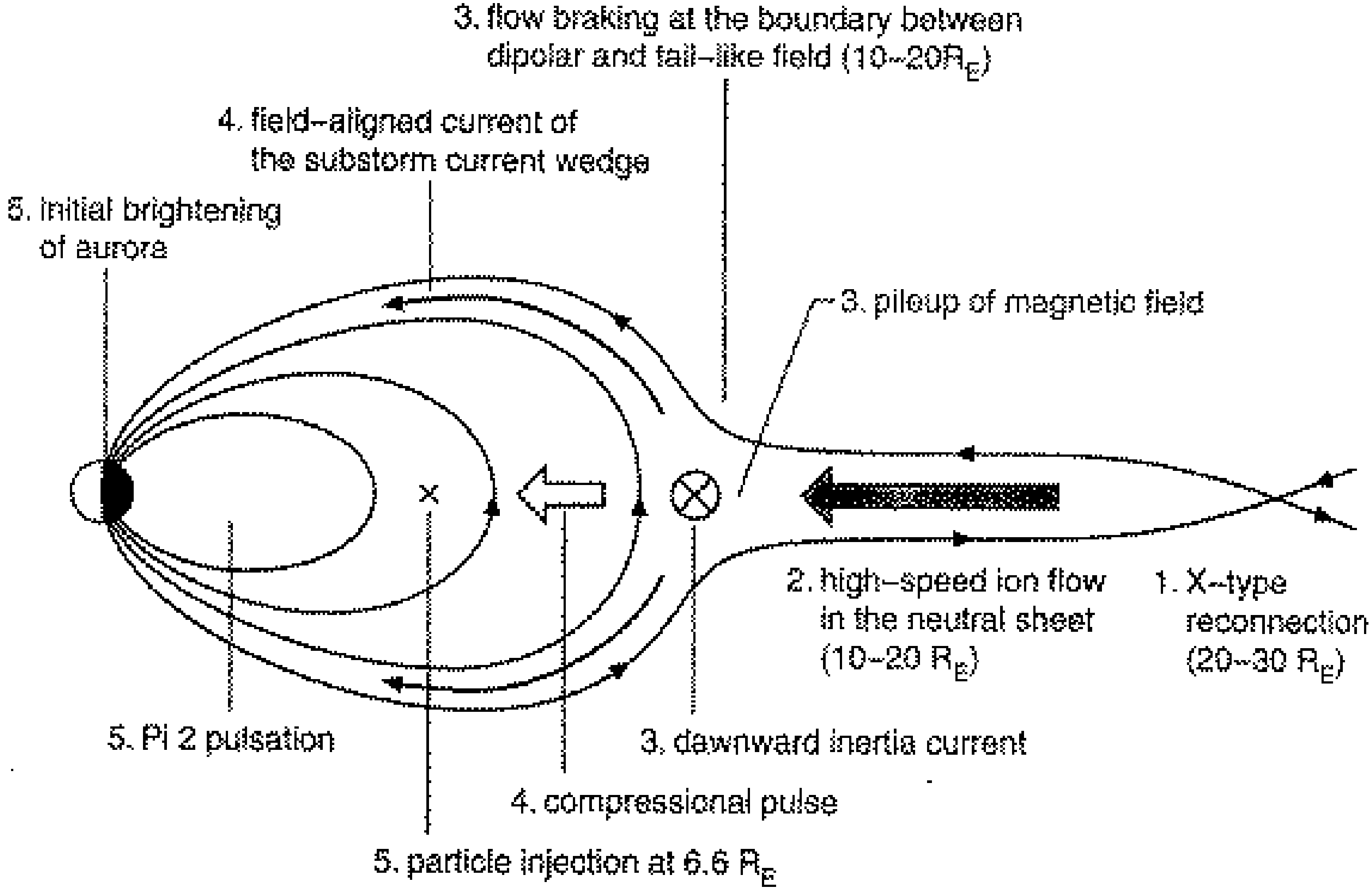
AURORAL ZONE VIEW OF MULTIPLE ONSET SUBSTORM
(Kisabeth and Rostoker, 1972)



WHAT PROCESS LINKS SIGNATURES OF SUBSTORM ONSET?

- High speed plasma flow (*bursty bulk flow*) occurs in localized channel transporting magnetic flux earthward
- The leading edge of the flow burst excites Alfven waves that resonate between magnetosphere and ionosphere (*auroral zone Pi 2 burst*)
- Flow is slowed by adverse pressure gradient (*inertial current from braking)* creating initial substorm current wedge and beginning of auroral bulge
- Flow is diverted azimuthally as it approaches the earth (*main driver of substorm current wedge*)
- Closure of wedge currents through ionosphere (*segment of westward electrojet*)
- Outward current of wedge becomes unstable accelerating electrons into premidnight arc (*brightening*)
- Field-aligned currents of substorm current wedge create positive perturbations (*midlatitude positive bay and synchronous field changes*)
- Pile up of magnetic flux induces electric field through which particle drift gaining energy (*dispersionless injection*)
- Cavity resonance excited by compressional waves from pile up (*midlatitude Pi 2*)

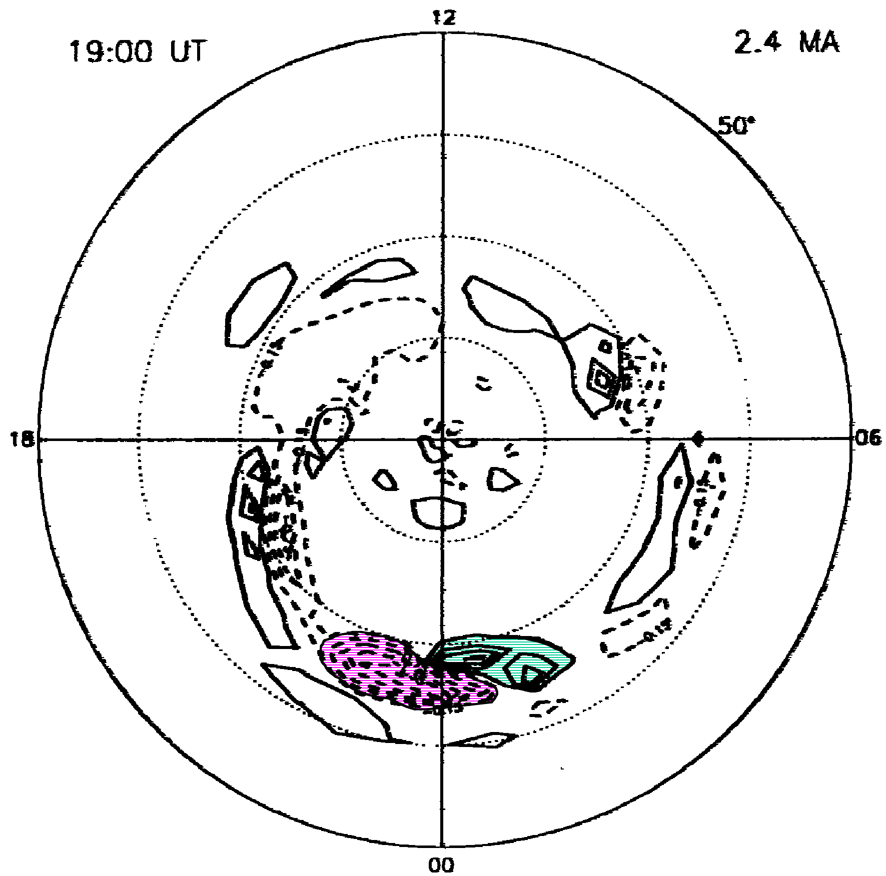
A SCHEMATIC SUMMARY OF THE Pi 2 GENERATION MECHANISM (Shiokawa et al., 1998)



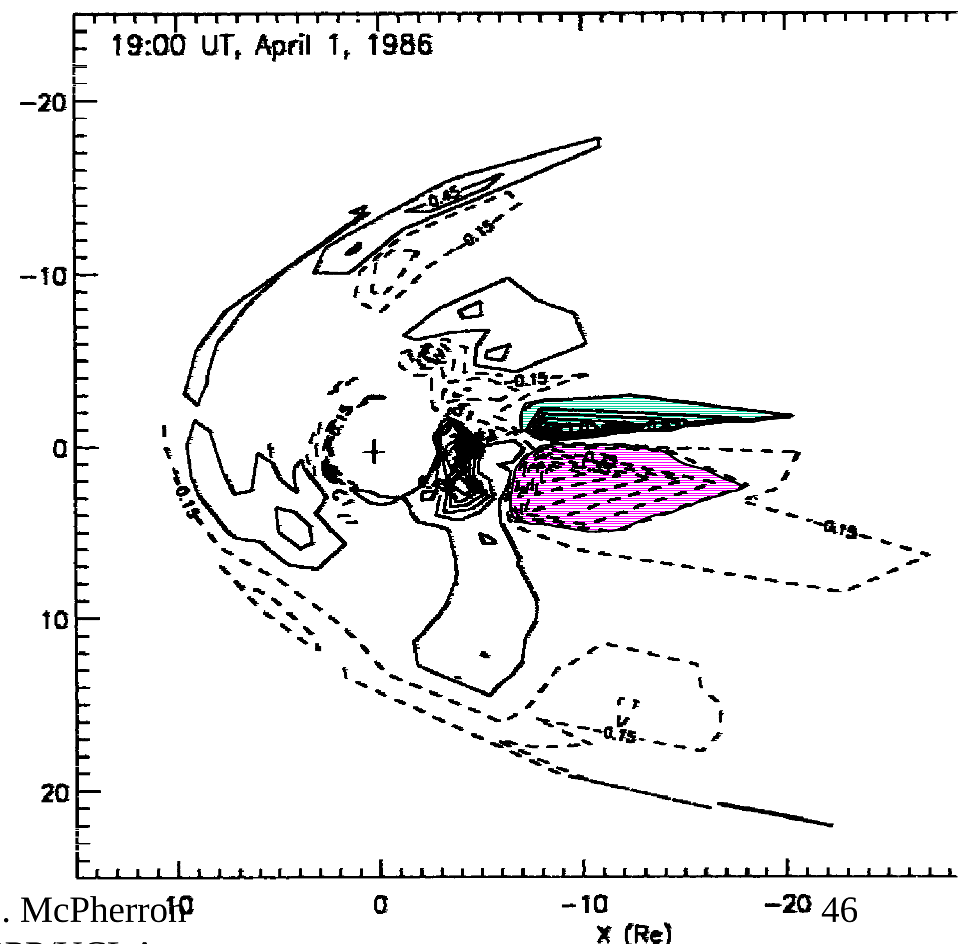
SUBSTORM CURRENT WEDGE IN IONOSPHERE AND MAGNETOSPHERE

Lu et. Al., JGR, 102(A7), 14,467, 1997

Ionosphere



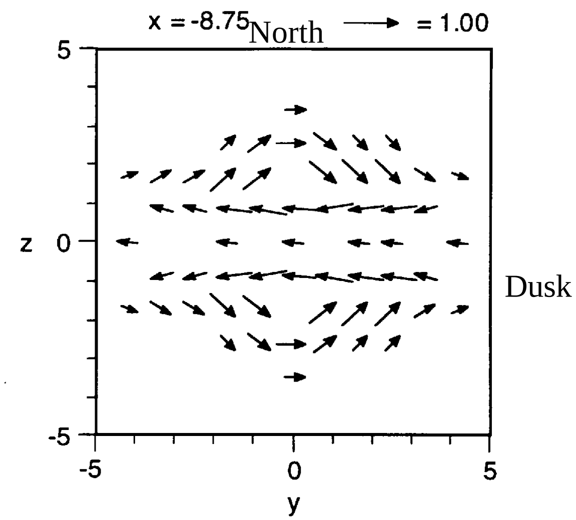
Magnetosphere

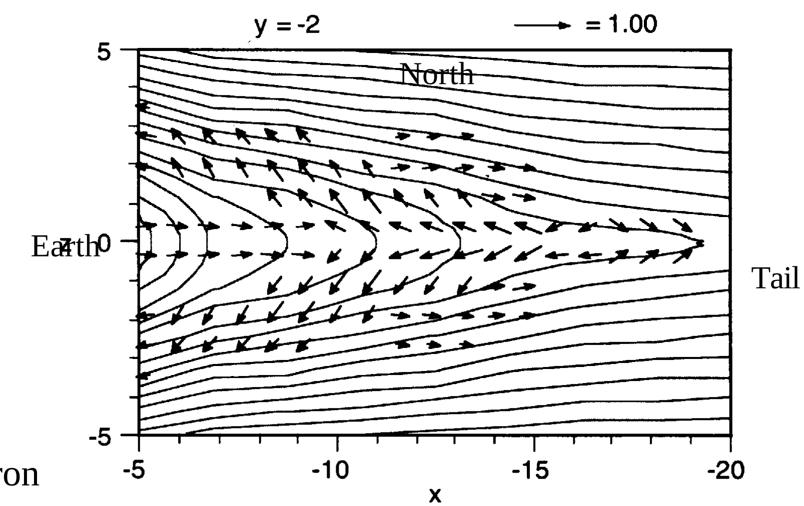


CURRENT PERTURBATIONS DUE TO SUBSTORM CURRENT WEDGE

(Birn et al., Preprint, 1999)

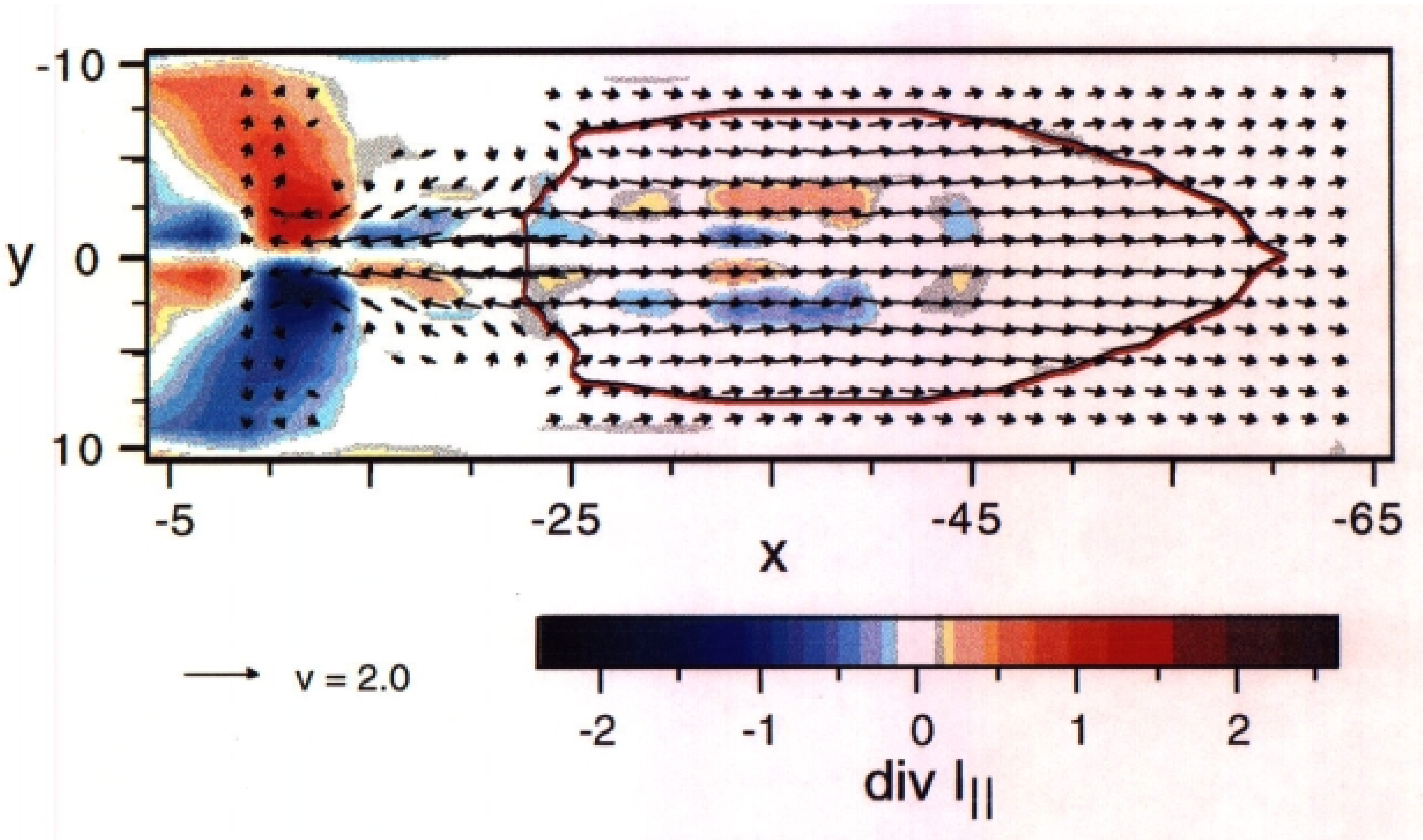
- X-line located at X = - 22 Re
- Top panel shows current changes (0-9 min after onset) in a plane orthogonal to tail axis at -8.75 Re
- An eastward current in the plasma sheet indicates reduction in cross tail current
- Dawn to dusk currents in what appears to be the lobe are flowing on plasma in an expanding plasma sheet in the region being dipolarized by the Earthward flow
- Bottom panel shows a north-south plane 2 Re towards dawn from the center of the tail
- Radial currents begin to flow in plasma sheet and are diverted into field-aligned currents



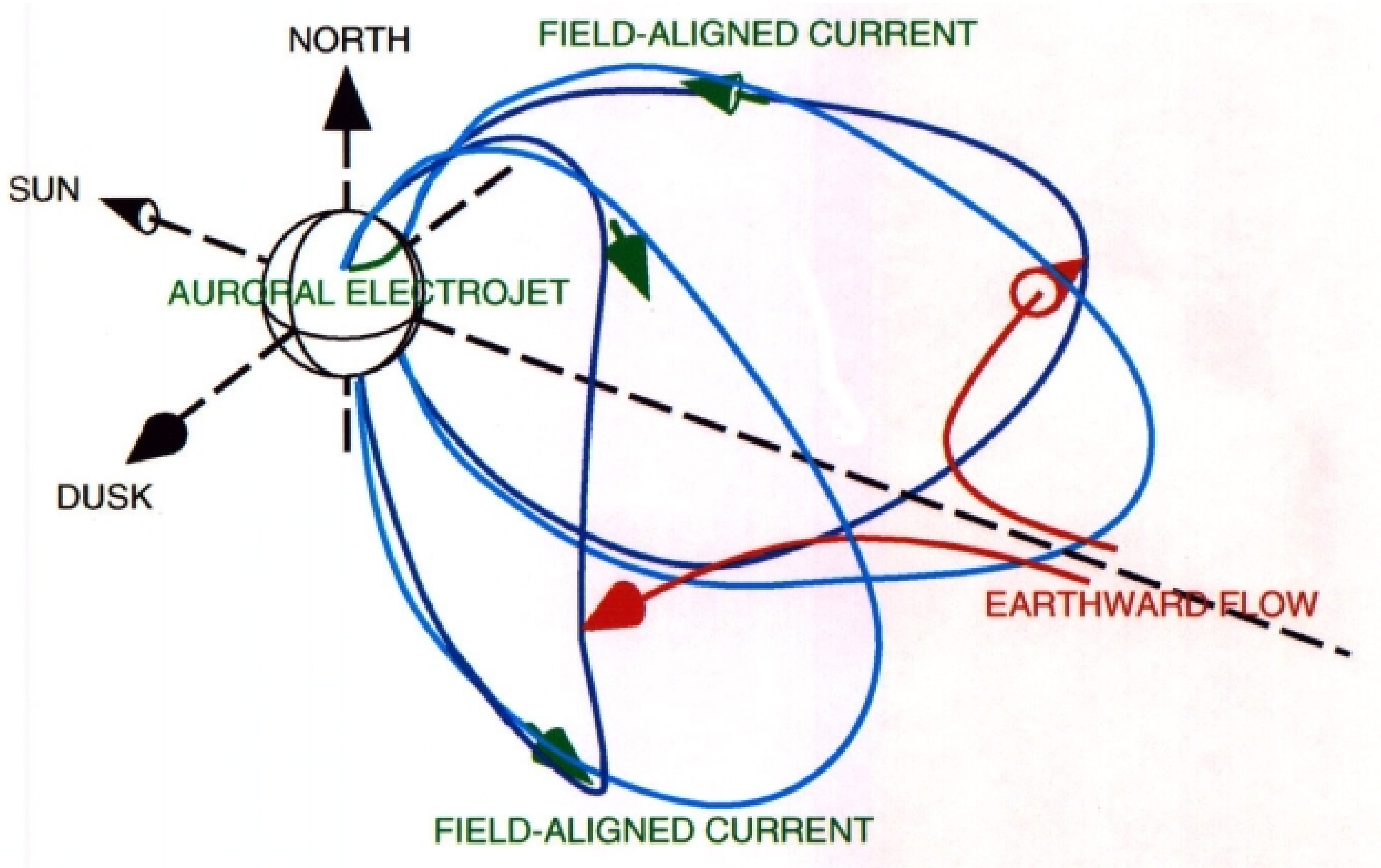


CURRENT DIVERSION INTEGRATED OVER Z

(Birn et al., Preprint, 1999)

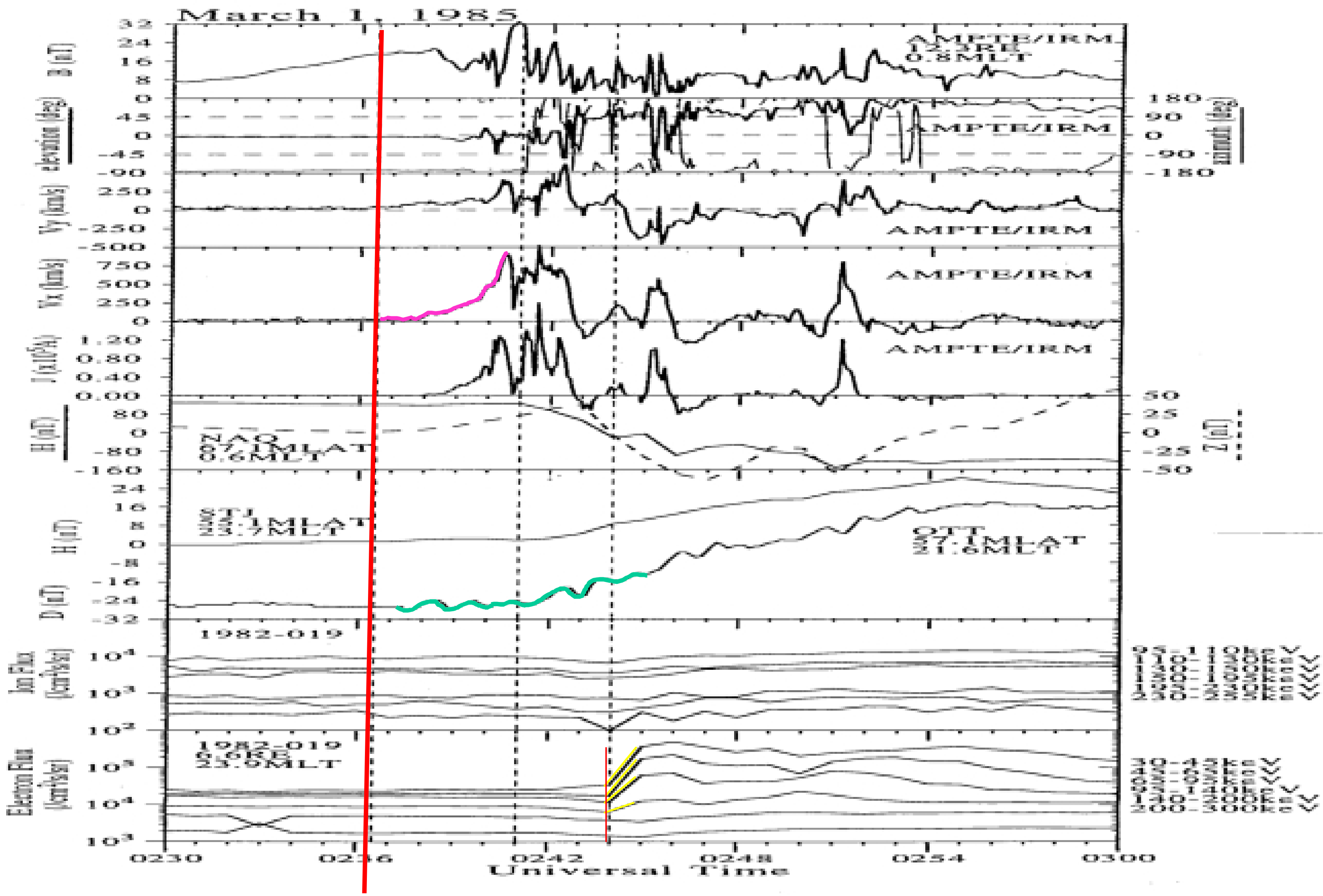


ASSOCIATION BETWEEN FLOW BURSTS AND SUBSTORM CURRENT WEDGE



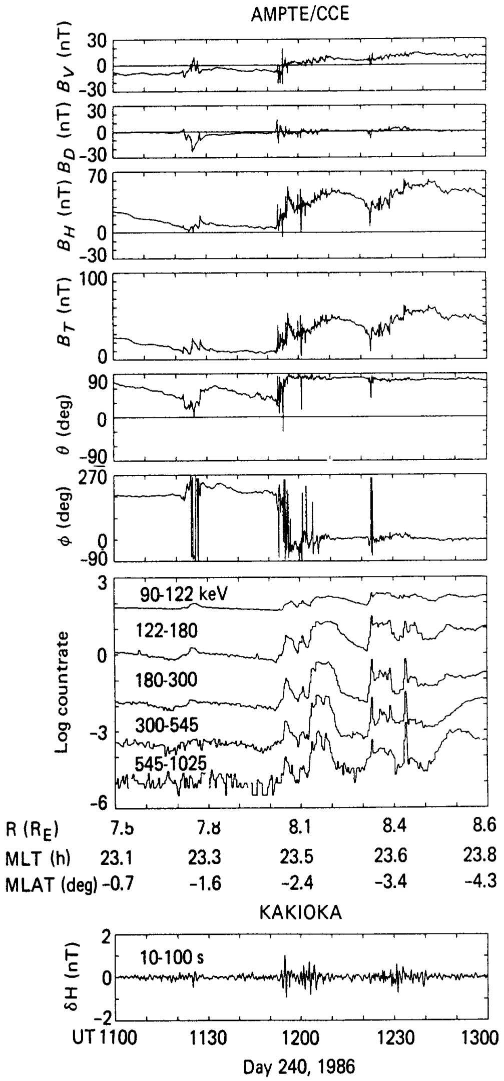
RELATION OF EARTHWARD FLOW AND INJECTION TO Pi 2 ONSET

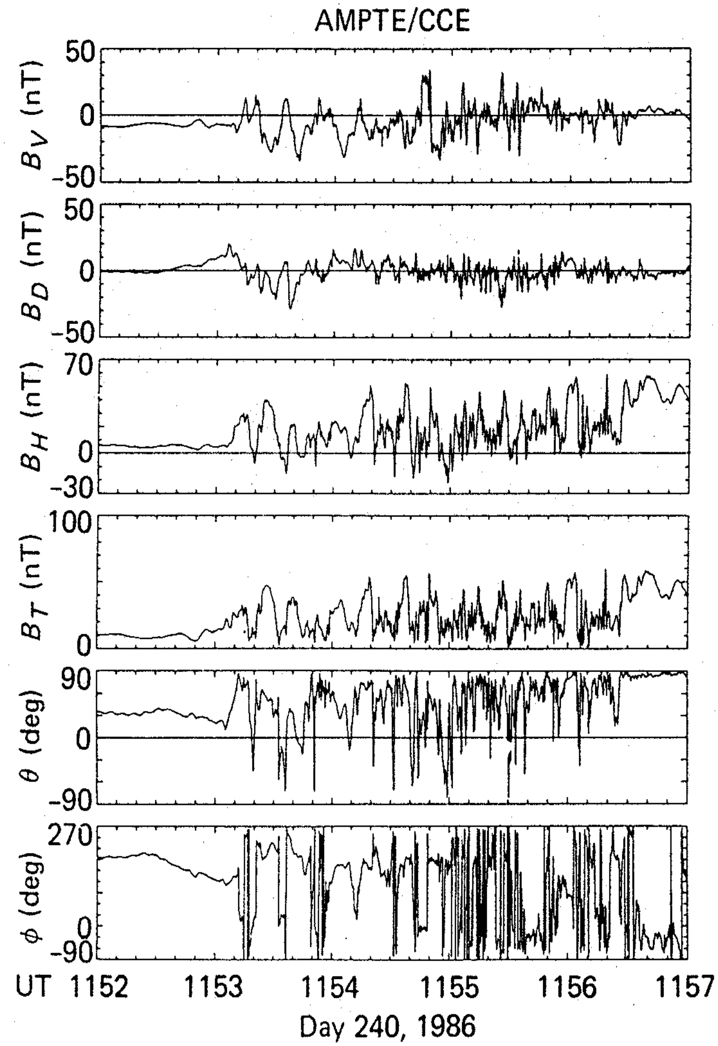
(Shiokawa et. al., JGR, 103(A3), 4491, 1998)



DISRUPTION OF THE CURRENT SHEET

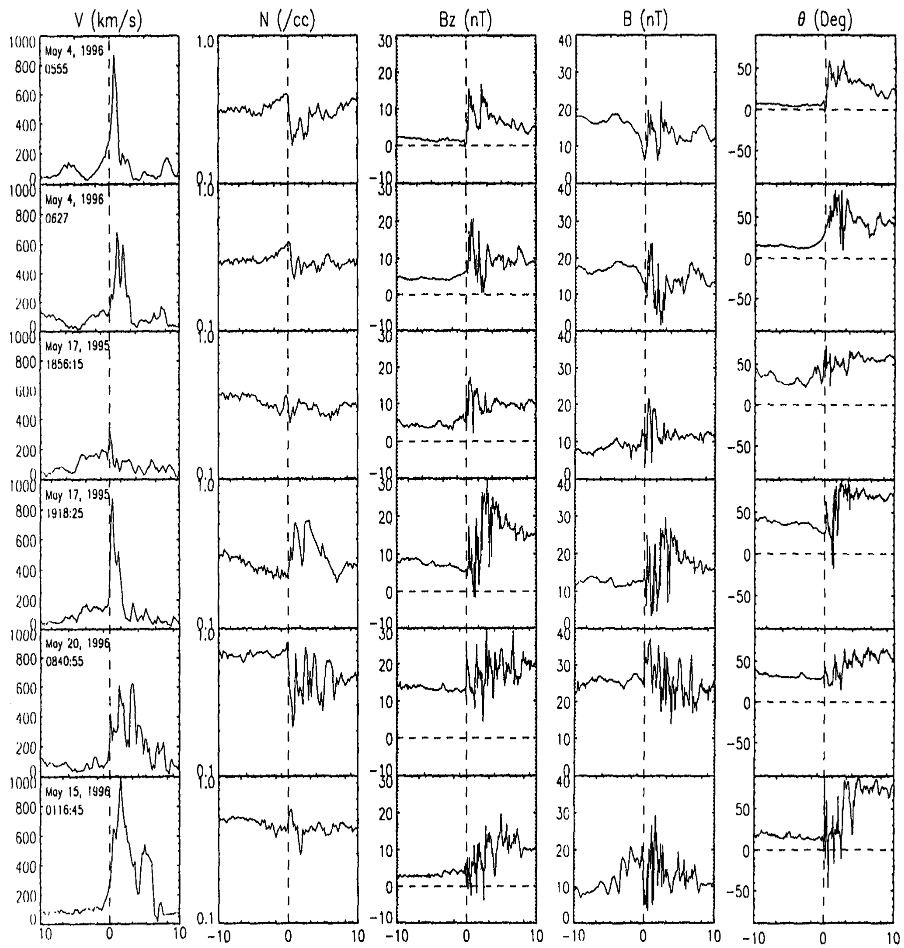
(Takahashi, et al., 1987)

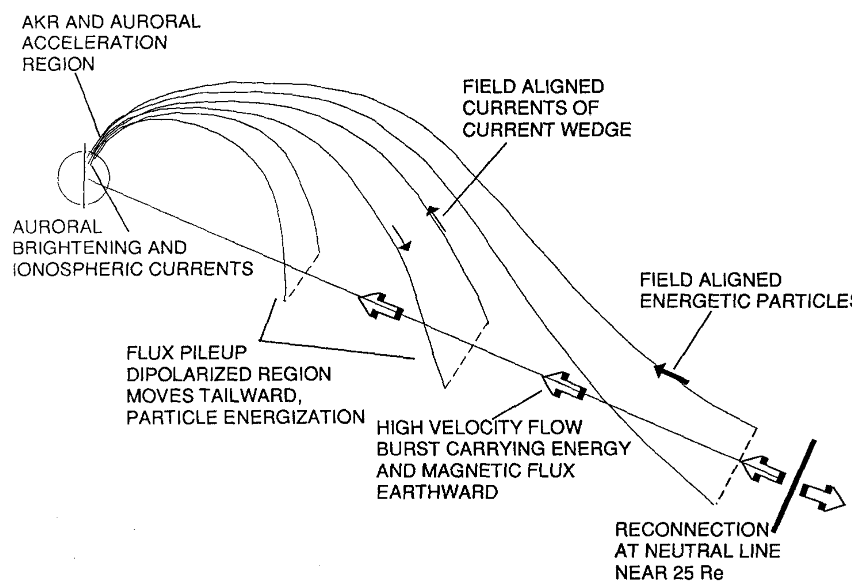




HIGH SPEED FLOWS IN THE INNER PLASMA SHEET

(Fairfield et al., JGR, 104(A1), 355, 1999)

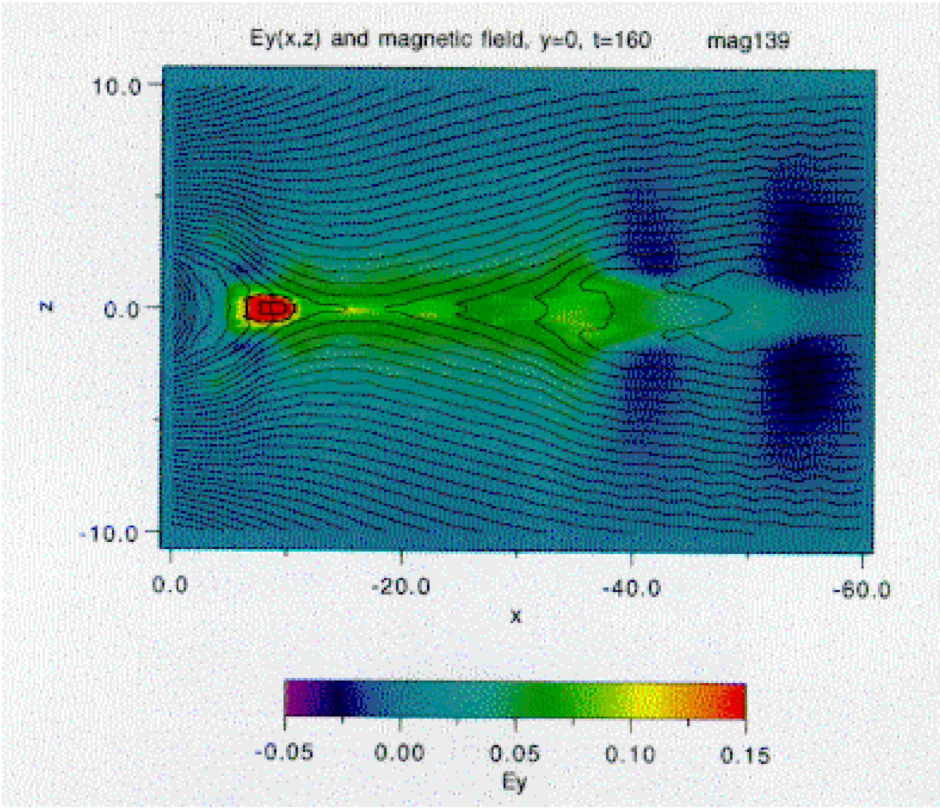




INDUCED ELECTRIC FIELDS

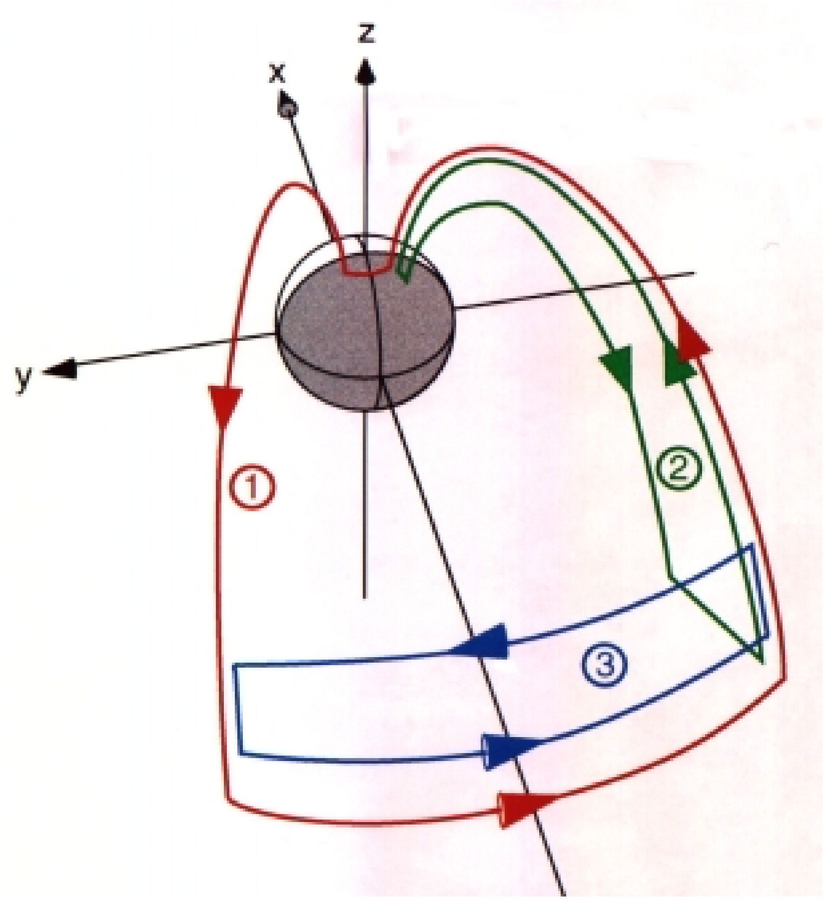
(Birn and Hesse, JGR, 101(a7), 15,345, 1996)

- Pile up of magnetic flux causes an inductive electric field.
- The field is strongest at the inner edge of the flow where the flow is decelerated
- The electric field is very strong over a limited region and can accelerate particles to energies E > 100 keV
- These particles cause the phenomenon of dispersionless injection



CURRENT SYSTEMS CREATING THE SUBSTORM CURRENT WEDGE

(Birn et al., Preprint, 1999)



OUTSTANDING SUBSTORM QUESTIONS ???????????????????

- What causes the onset of the substorm expansion?
- Is every substorm onset triggered by a change in external conditions?
- What processes facilitate magnetic reconnection?
- What processes create magnetic turbulence at the inner edge of plasma sheet?
- Why does auroral breakup occur on the equatorward most discrete arc?
- What is the link between reconnection, bursty bulk flows, Pi 2 pulsations pseudo breakups, substorm onsets and expansion intensifications?
- What terminates a substorm expansion?
- Why do most substorm expansions develop in a quasiperiodic sequence of discrete intensifications?
- Why does each intensification consist of quasi-periodic high speed flows?
- What circumstances allow a convection bay to develop?
- What role does the distant x-line play in substorms?
- Does the magnetosphere ever become completely closed (no distant x-line)?