Physics of Substorms

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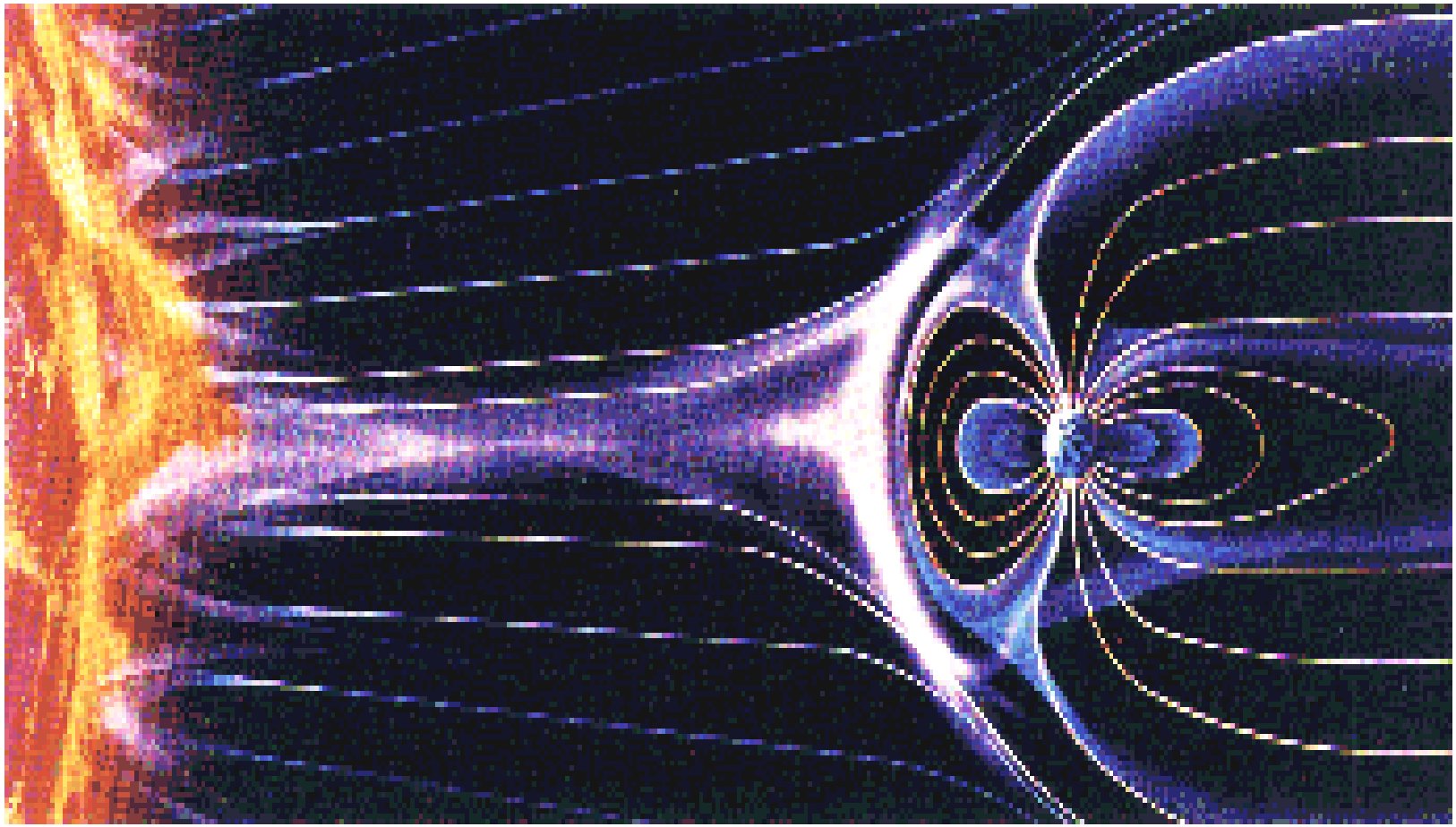
Solar Wind-Magnetosphere Interaction



- Solar Wind: n ~ 10cm^{-3} , T ~ 10eV, $\mathbf{V} = \mathbf{E}\mathrm{x}\mathbf{B}_{IMF}/B_{IMF}^{2}$ ~ 400km/s
- Particles entering magnetosphere are stored mainly in plasma sheet and form current system

Outstanding Magnetospheric Physics Issues

- Energy Storage Processes:

  - How are mass, momentum and energy transferred from solar wind into magnetosphere across the magnetopause?

  - How is the plasma sheet energized?

- Substorms – A Major Energy Storage and Release Process:

  - How is the plasma built up in the plasma sheet during substorm growth phase?

  - What is the onset mechanism of substorm expansion?

  - What is the nonlinear plasma dynamics during substorm expansion phase?

- Magnetosphere-Ionosphere Coupling:

  - How are auroral arcs formed?

  - Why are auroral arcs so thin (~ 1 - 10 km)?

  - How are electrons accelerated to > 1 keV to produce arcs?

Substorms are the most powerful energy storage and release processes in the magnetosphere:

$$\sim 10^{20} - 10^{22} \text{ ergs released in } 10^{2} - 10^{3} \text{ s}$$

About $10^{19} - 10^{21}$ *ergs* (~10% released energy) dissipated in ionosphere.

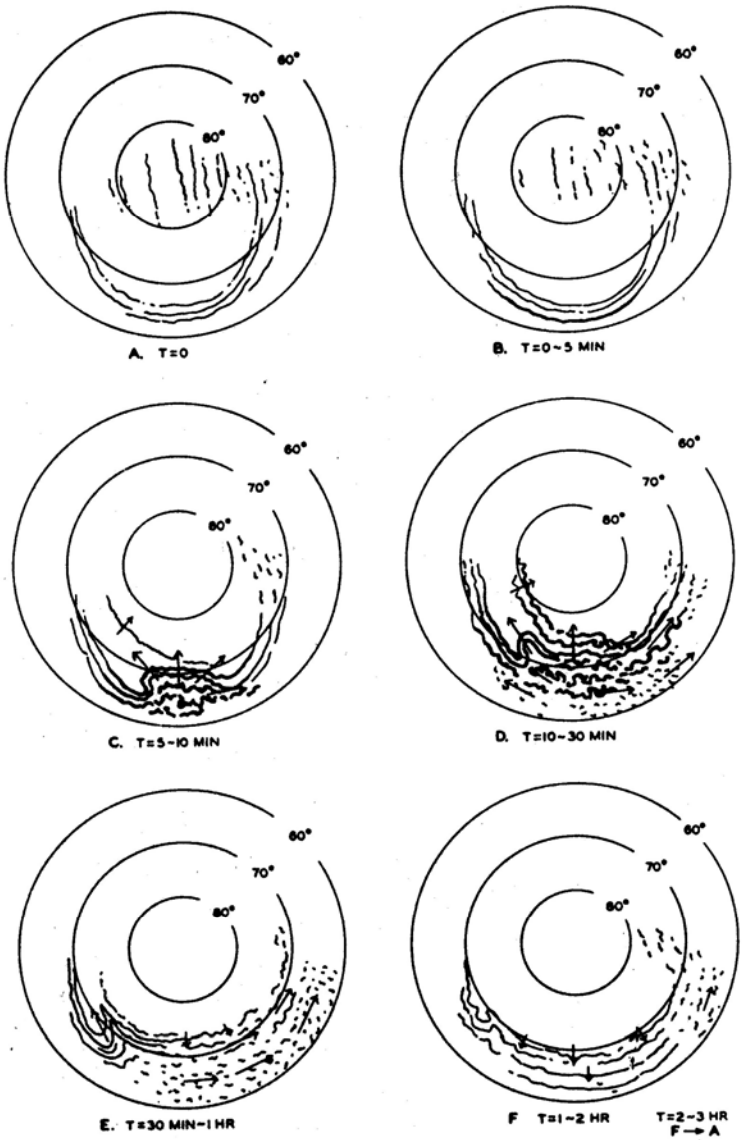
➔ When, where and how do substorms occur and evolve?

Auroral Arcs

Auroral Spiral

Auroral and Magnetospheric Substorm Features

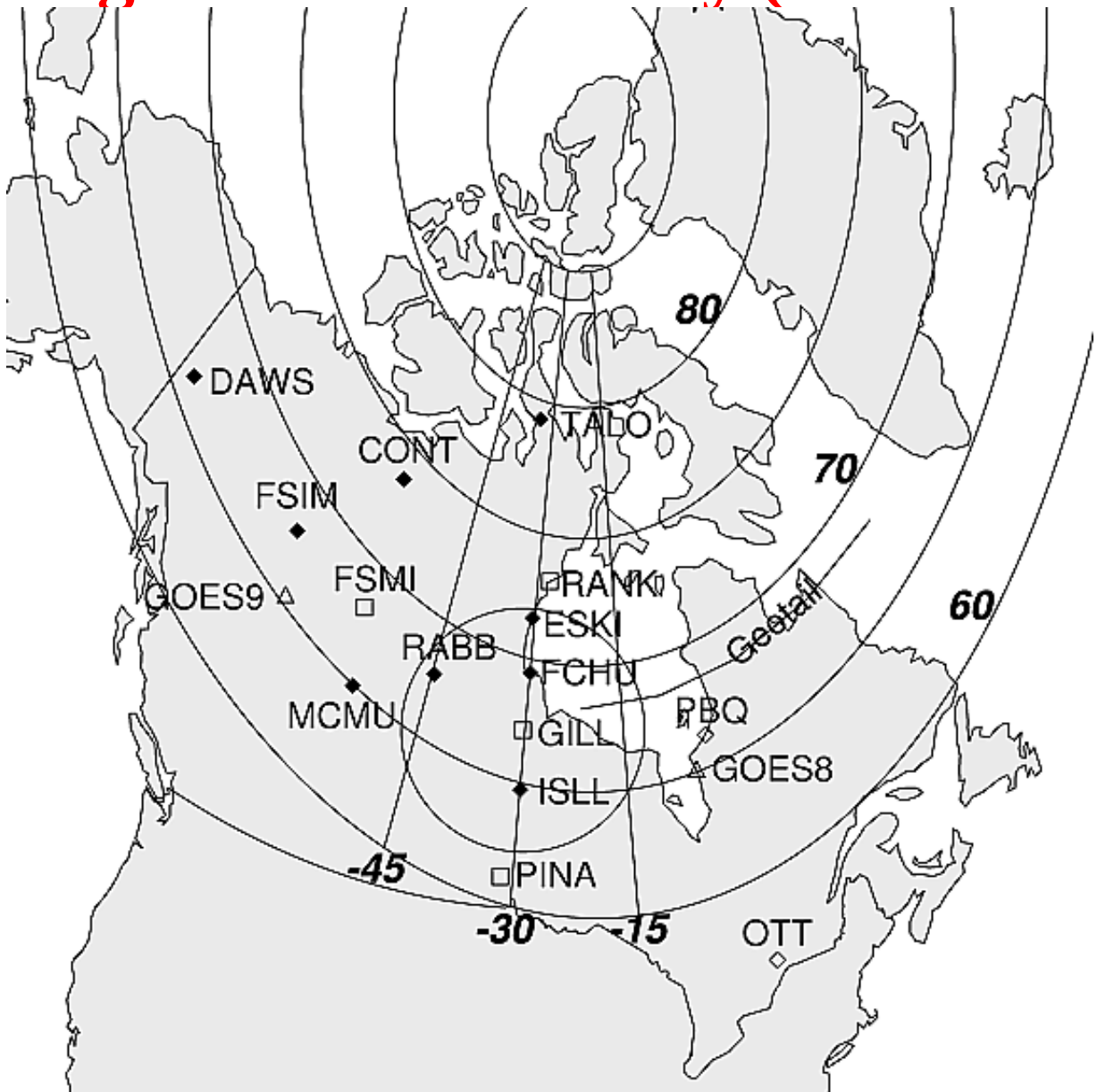
Auroral Substorms (S. I. Akasofu)



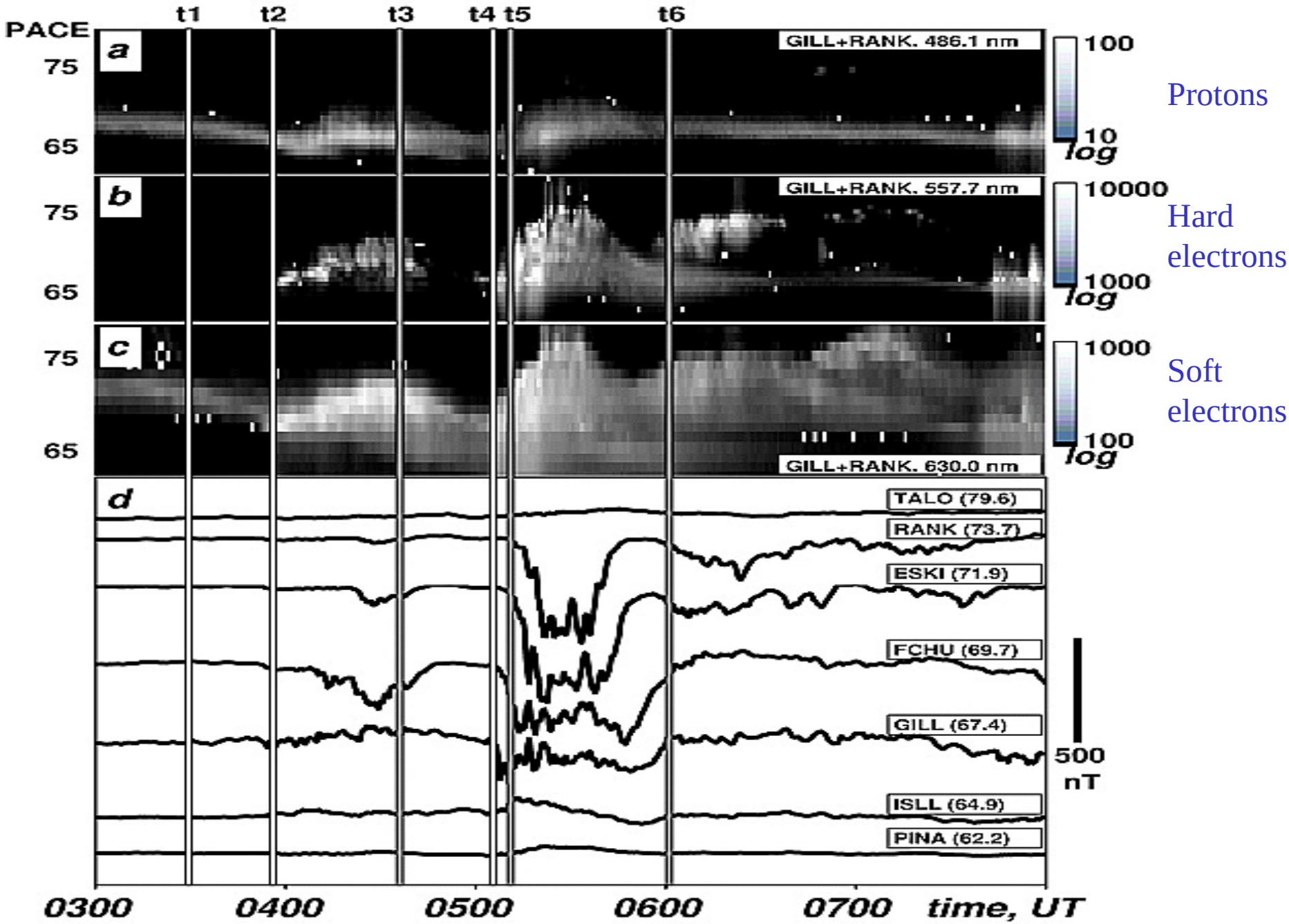
Magnetospheric Substorms

- Growth Phase (~30 min)
  - Storage of plasma & magnetic energy in plasma sheet
  - Tail-like magnetic field
- Expansion Phase (~10 min)
  - Release of plasma & magnetic energy in plasma sheet
  - Current disruption
  - Dipolarization of magnetic field
- Recovery Phase (~hours)
  - Return of Magnetosphere to Quiet Condition

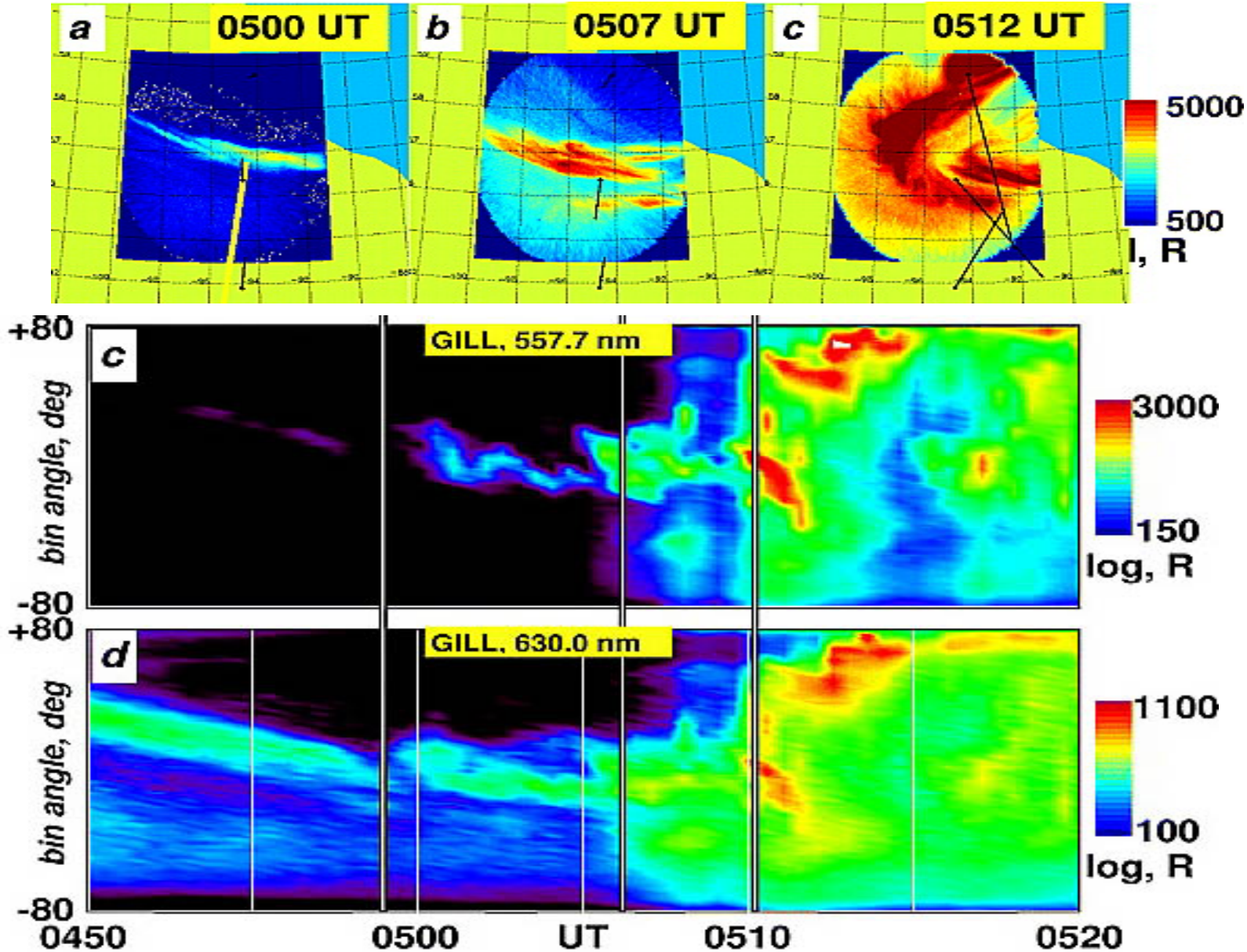
Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS)



CANOPUS Observation of Substorm (2/19/96)



Substorm Auroral Breakup (2/19/96) (Voronkov et al., 2003)

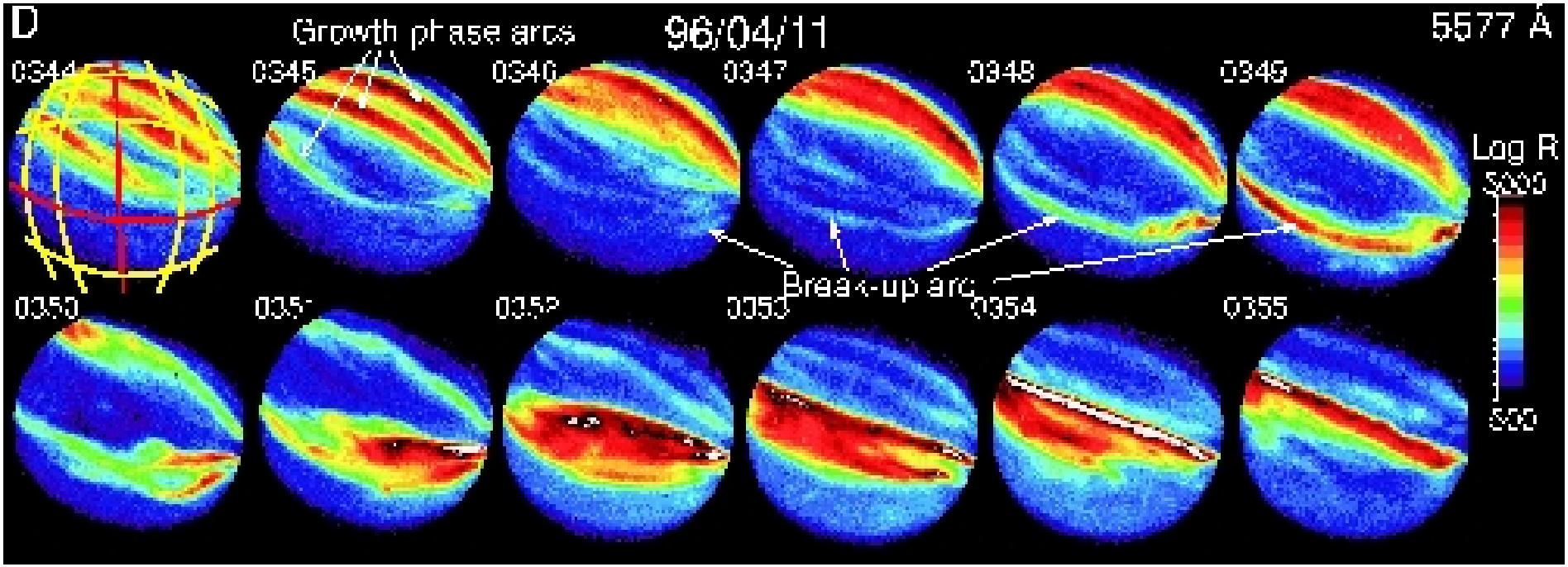


Breakup arc is located in the transition region between R-1 and R-2 Birkeland currents.

Arcs and Auroral Substorms

(Lyons et al., 2002)

CANOPUS All Sky Imager at Gillam



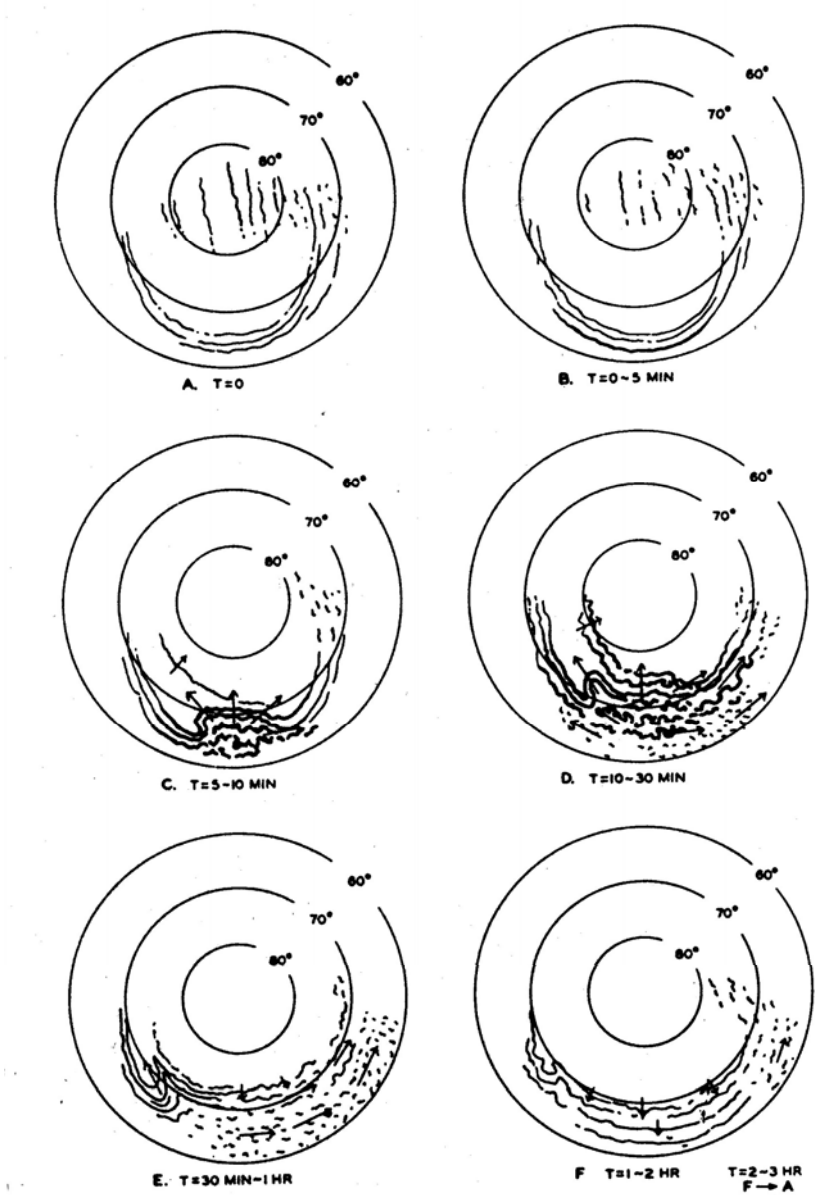
* 5577 Å emissions are produced by hard electrons with energy ≥ 1 keV

* Initial substorm onset brightening occurs at the most equatorward arc.
* Breakup arc appears at ~ 3 min before onset.

Features of Auroral Substorms

- Auroral oval defines polar cap region. For a prolonged period of positive IMF Bz, auroral oval contracts to minimum size.
- During growth phase, polar cap region expands equatorward, auroral oval shrinks in width, several brightening spots are observed in the oval during polar cap expansion.
- At substorm onset, one brightening spot in an arc enlarges and expands poleward as well as eastward and westward. Typically, it occurs in the most equatorial arc.
- The initial localized brightening spot is located statistically in a big region typically bounded by 55 – 75 degrees in magnetic latitude and 20:00-02:00 MLT with the most probable location at around 23:00 MLT.

Outstanding Substorm Onset Issue



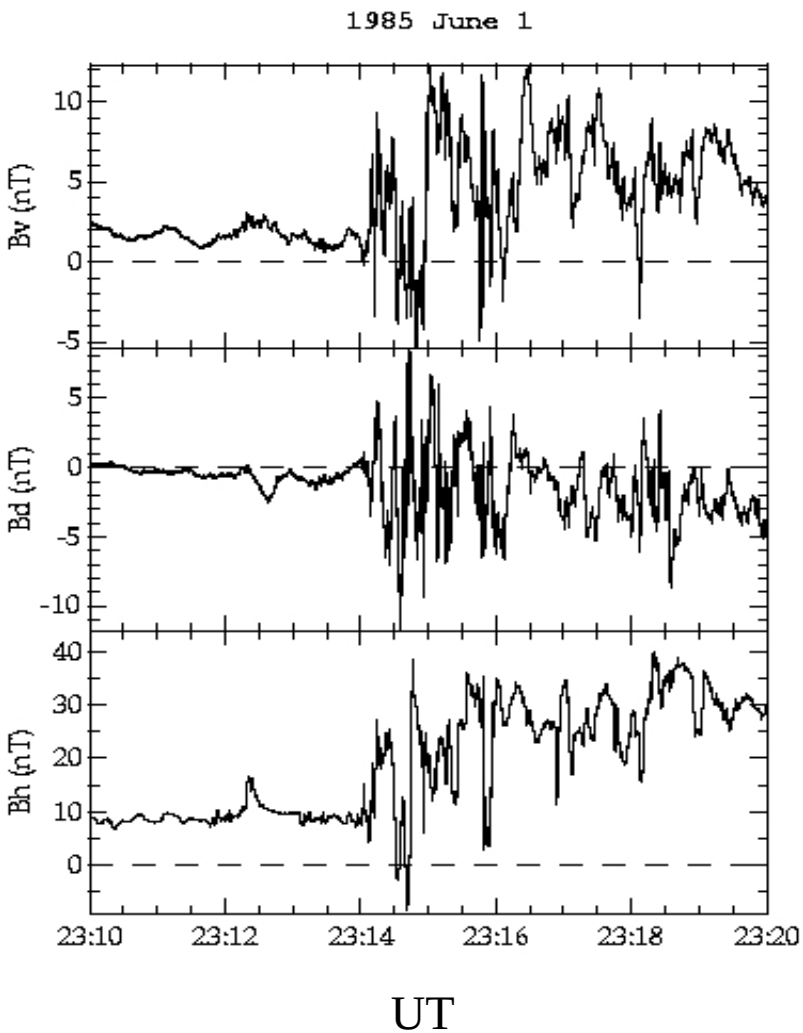
- Location and Mechanism of Substorm Onset in Magnetotail?

- Model 1: Near Earth region (~ $9R_E$) due to Instability Associated with Current Disruption

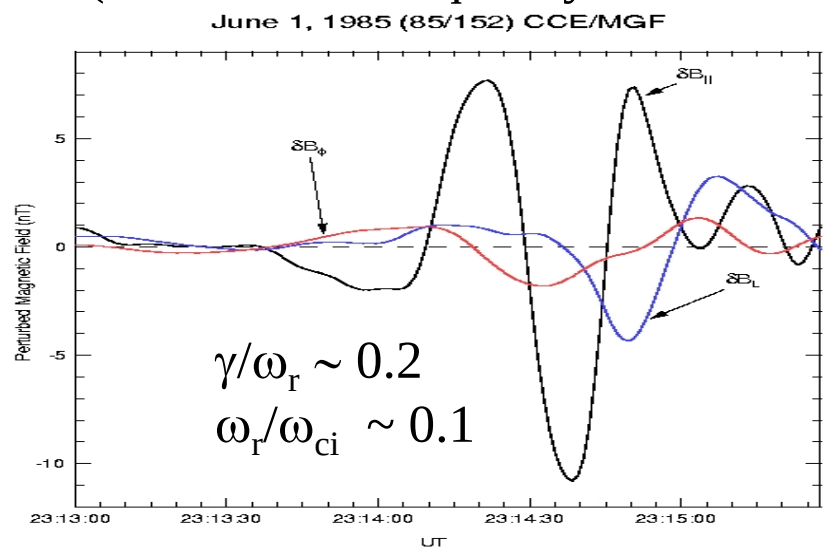
- Model 2: Mid-Tail Due to Magnetic Reconnection

Substorm and Cross-Tail Current Disruption

Observation of substorm magnetic field turbulence, current disruption and dipolarization by AMPTE/CCE at x ~ 8.8 R_E, 23:30 MLT [Cheng and Lui, GRL, 1998].

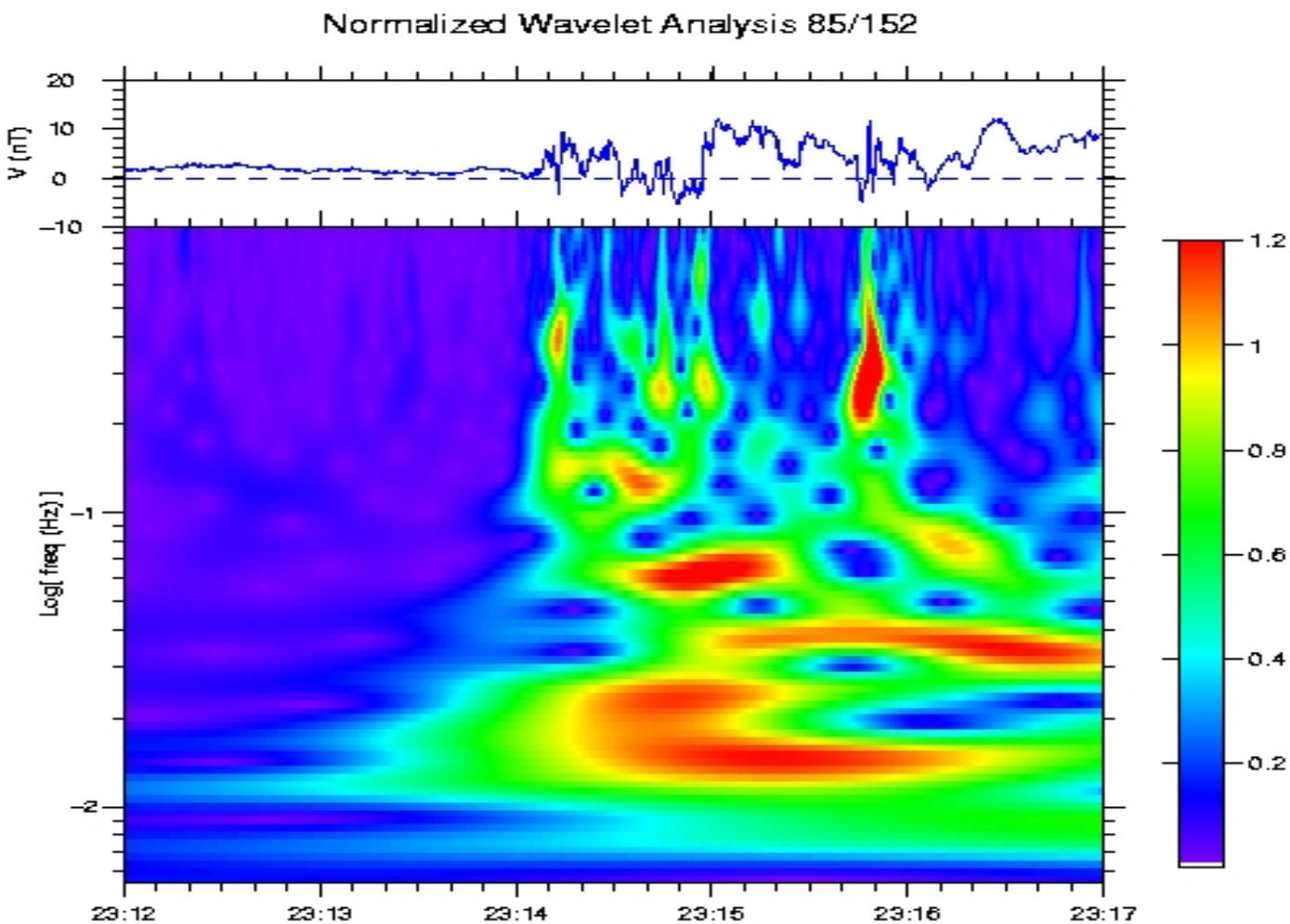


Kinetic Ballooning Instability
(Filtered low frequency fluctuation)



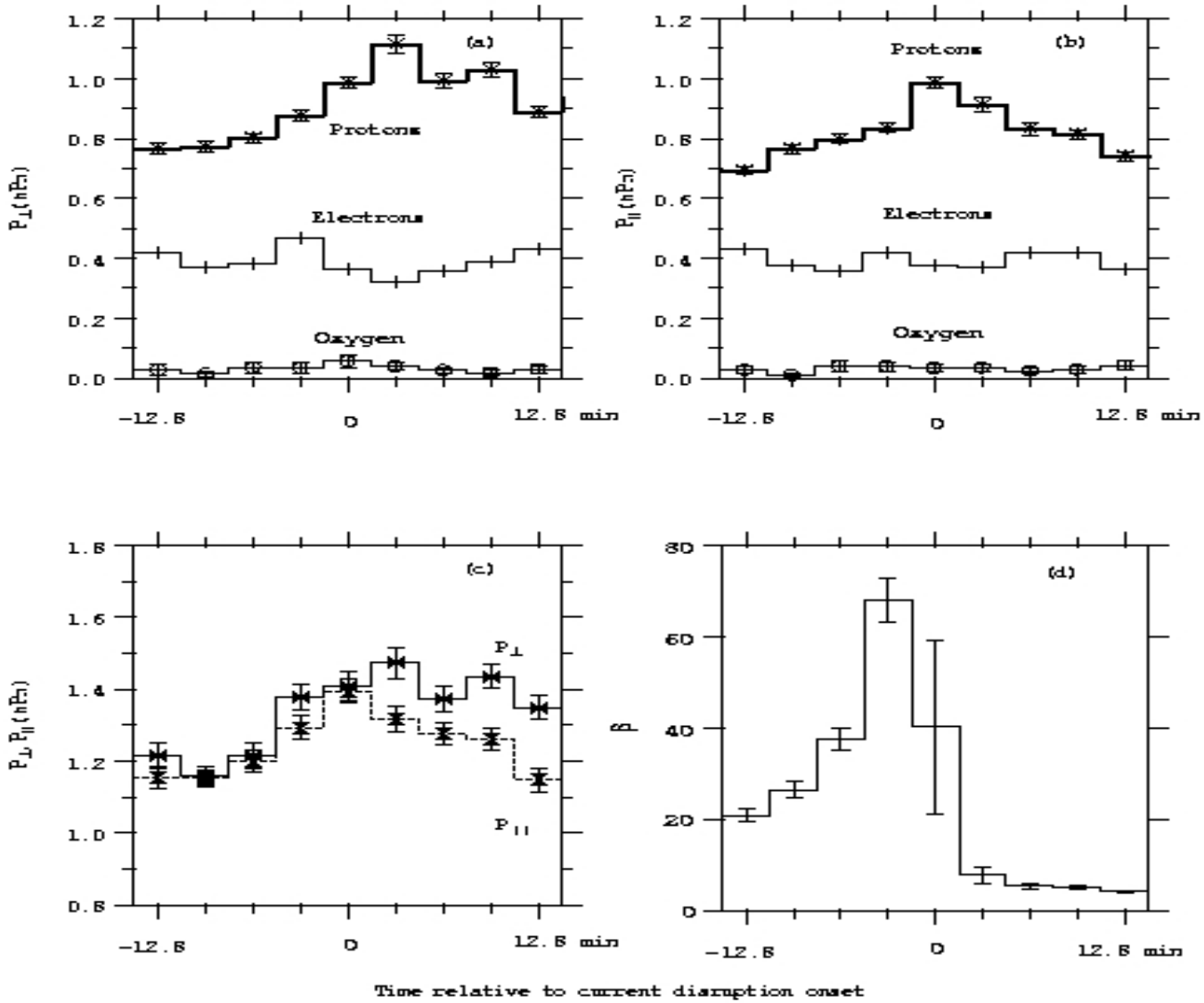
- KBI is excited at ~ 23:13:30 UT when $\beta > 50 >> \beta_C^{MHD} \sim O(1)$
- Kinetic effects of ion gyroradius and trapped electron increases β_C over β_C^{MHD} by a factor of $n_e T_e / n_{eu} T_i$
- KBI is responsible for onset of turbulence and cross-tail current disruption at 23:14:20 UT

85152 Wavelet Analysis



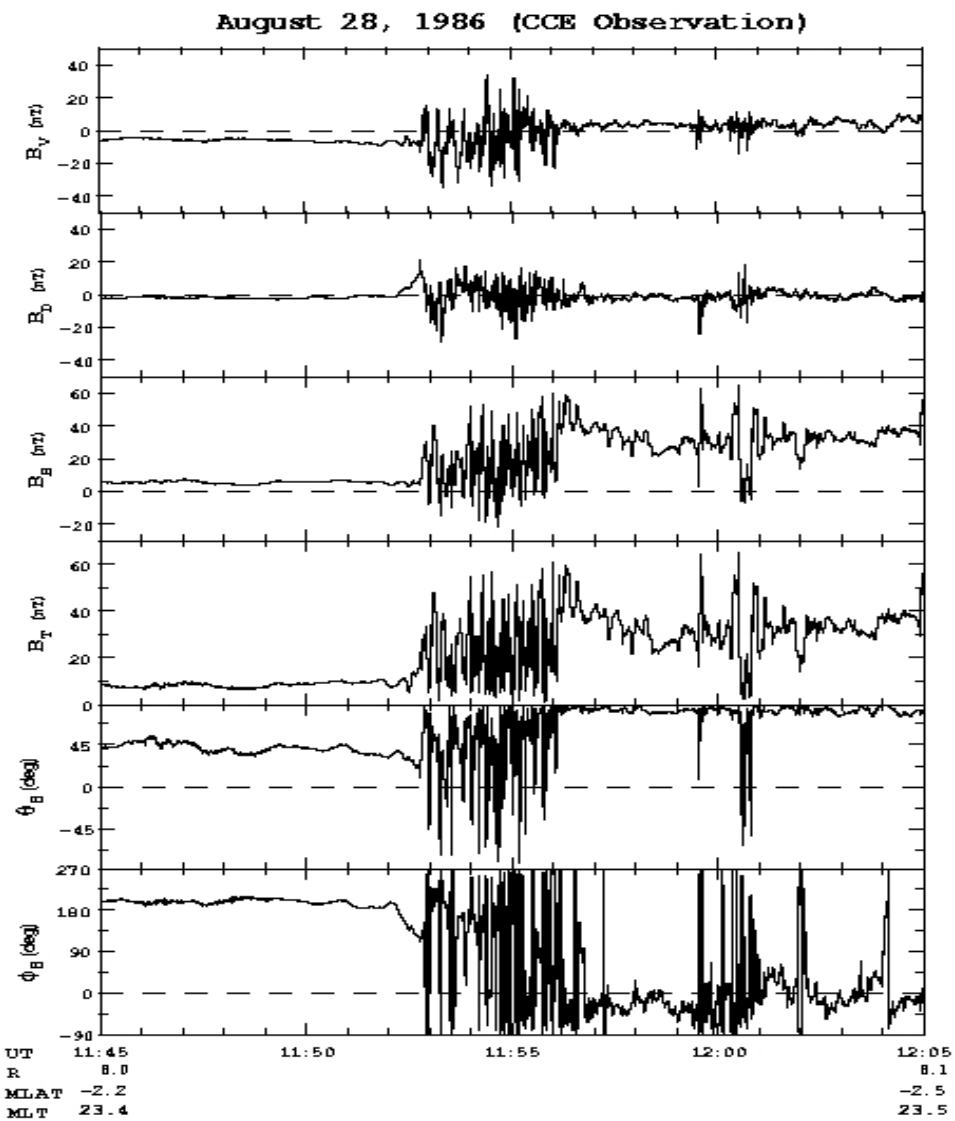
UT

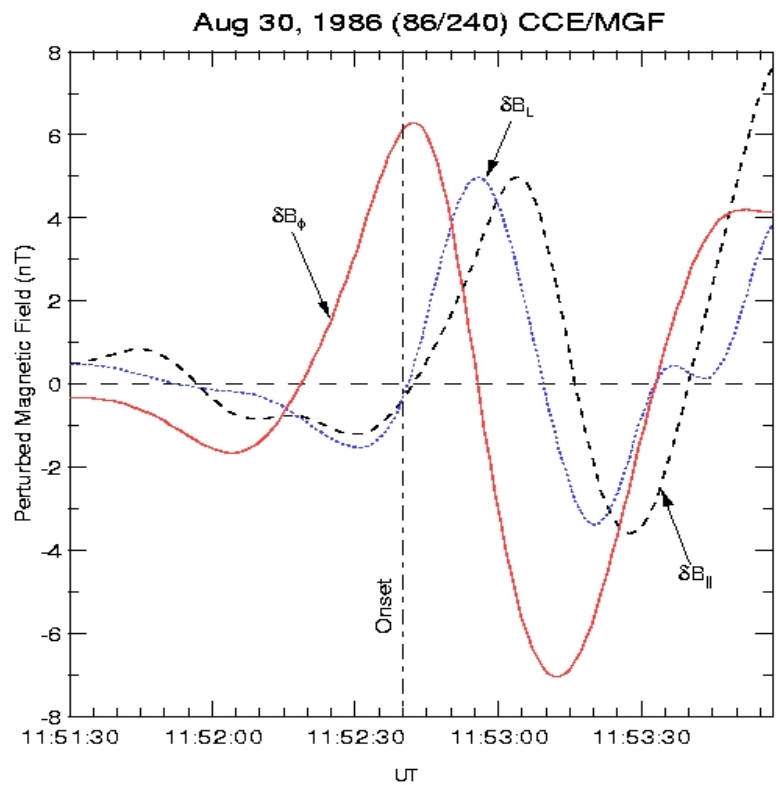
1985 June 1 Substorm Event



Lui et al., JGR, 1993.

Low Frequency Instability in 86240 Event





Substorm Onset Mechanism at Near-Earth Plasma Sheet Region

(Cheng and Lui, GRL, 1998)

- Low Frequency instability ($\gamma/\omega_r \sim 0.2$ and $\omega_r/\omega_{ci} \sim 0.1$) is excited at ~ 2 min before substorm onset when the plasma $\beta(=2P/B^2)$ at the satellite location (~ 8.8 R_E at 22:30 MLT) increases from ~20 to about 60 or higher in ~ 10 min.
- Is the observed low frequency instability a ballooning mode? Probably Yes!
- What do MHD theories of ballooning mode predict? Unstable when $\beta_{eq} > \beta_c^{MHD} \sim O(1)$.
- Why is observed β_C much larger than β_c^{MHD} and why is there a finite real frequency?

Particle kinetic effects.

Key Signatures of Substorms

Ionosphere:

- Growth Phase – equatorward movement of proton and electron aurora, appearance of “breakup” arc in proton precipitation region (Samson, 1992).
- Onset – local brightenting and vortex formation in intensified “breakup” arc.
- Expansion Phase – poleward expansion of breakup arc emission and diffuse proton and electron aurora.

Magnetosphere:

- Growth Phase – plasma sheet thinning, tail-like **B** fieldlines, enhancement of plasma pressure gradient and cross-tail current in near-Earth plasma sheet, and instability (KBI) initiated in localized region at 1-2 minutes before onset .
- Onset – KBI grows to a large amplitude and forms strong turbulence with higher frequency instabilities.
- Expansion Phase –spread of turbulence region causes pressure profile relaxation, current disruption, and **B** dipolarization.

Modeling of 3D Magnetosphere

- Single-fluid, isotropic P:

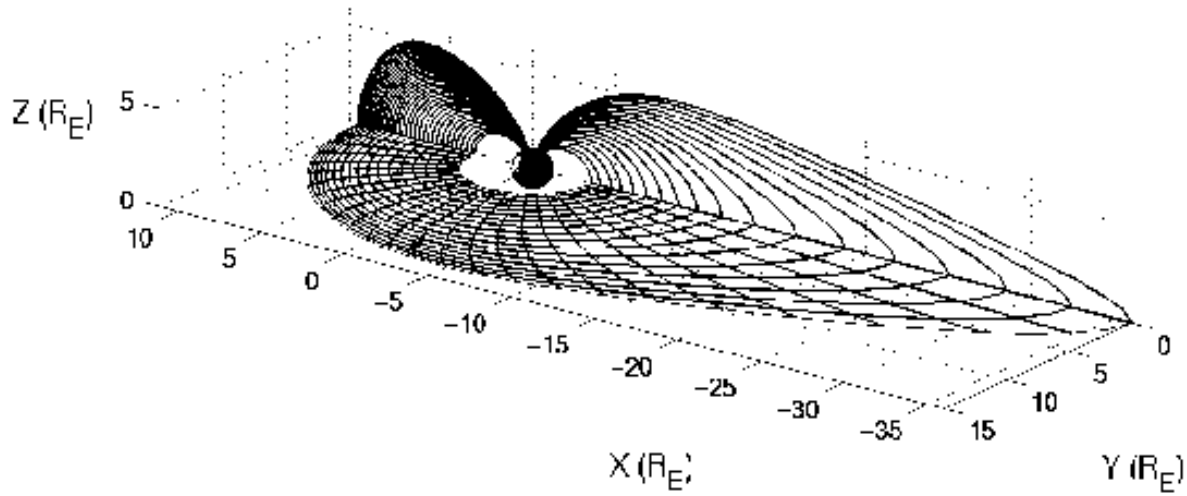
$$\rho\left[\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\,\mathbf{v}\right]=\mathbf{J}\times\mathbf{B}-\nabla P$$

Small flow:

$$\mathbf{J}\times\mathbf{B}=\nabla P$$

$$\nabla\times\mathbf{B}=\mathbf{J}$$

$$\nabla\cdot\mathbf{B}=0$$



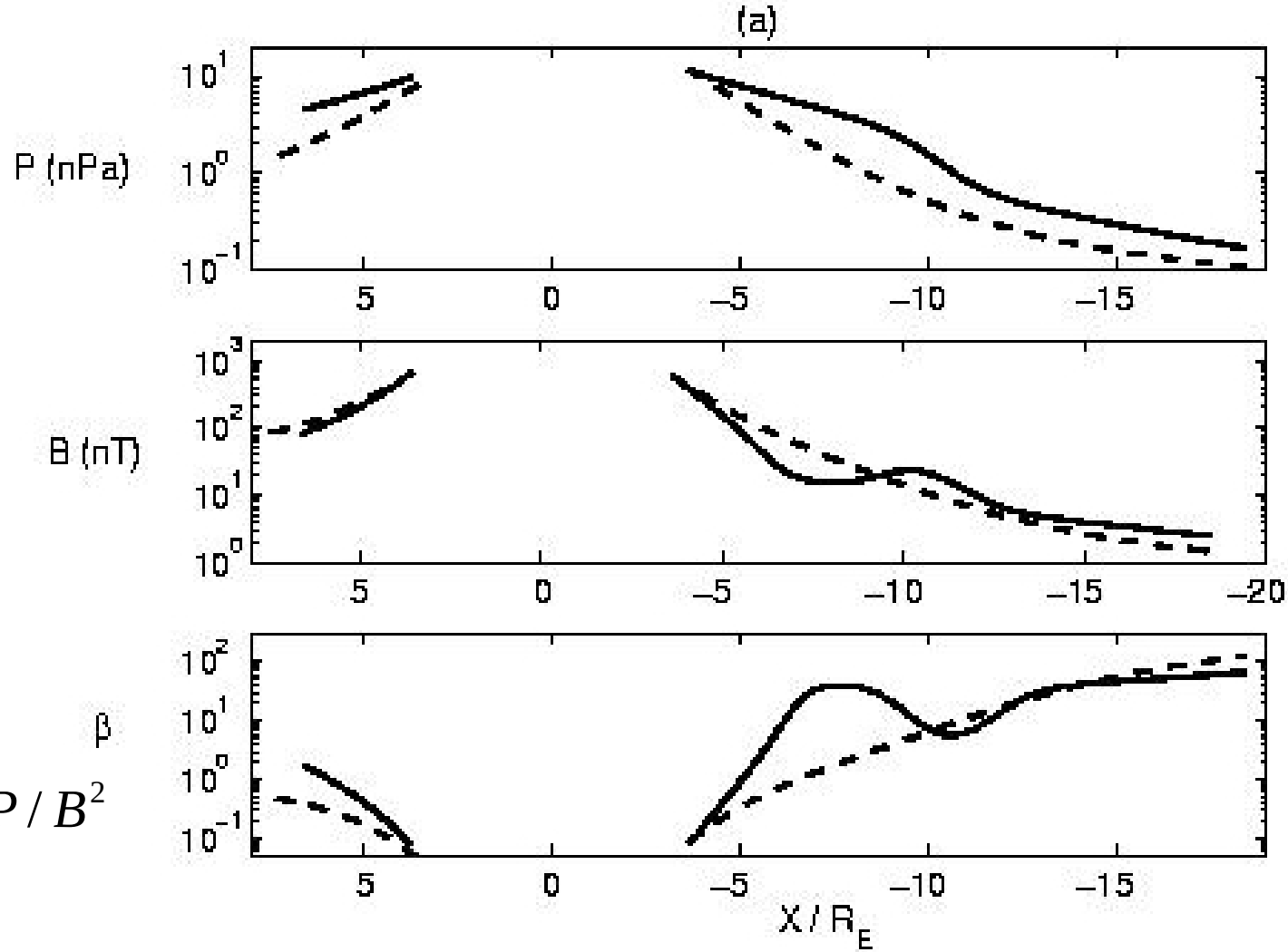
- Pressure is constant along a field line.
- Growth phase magnetosphere is considered as a series of snap shots of quasi-static equilibria, which are solved by imposing P(x,y,z=0) and boundary condition.

Modeling Magnetosphere in Growth Phase

(Zaharia and Cheng, Geophys. Res. Lett., 2003)

- During Growth phase plasma pressure is enhanced in the plasma sheet due to enhanced earthward convection.
- Thin cross-tail current sheet (Width ~ 1 R_E) is formed in the near-Earth plasma sheet with enhanced current density of ~ 10 nA/m^2 and plasma β ~ 50 between 7 – 10 R_E (magnetic well region) in comparison with quiet time.
- Magnetic field becomes more tail-like.
- Birkeland currents move equatorward, are more localized in latitude and become more intense at ~ 3 μA/ m^2.

Quiet-Time & Growth Phase: Profiles Along Sun-Earth Axis

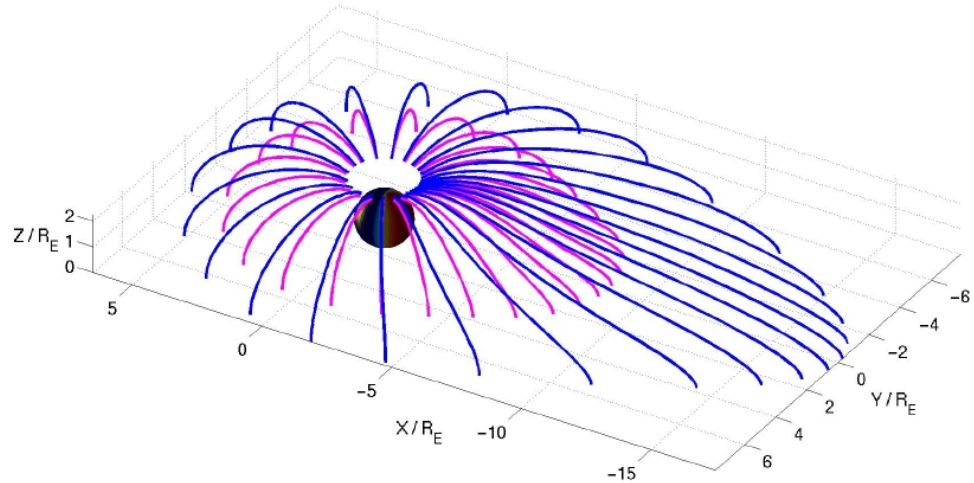


$$\beta = 2P / B^2$$

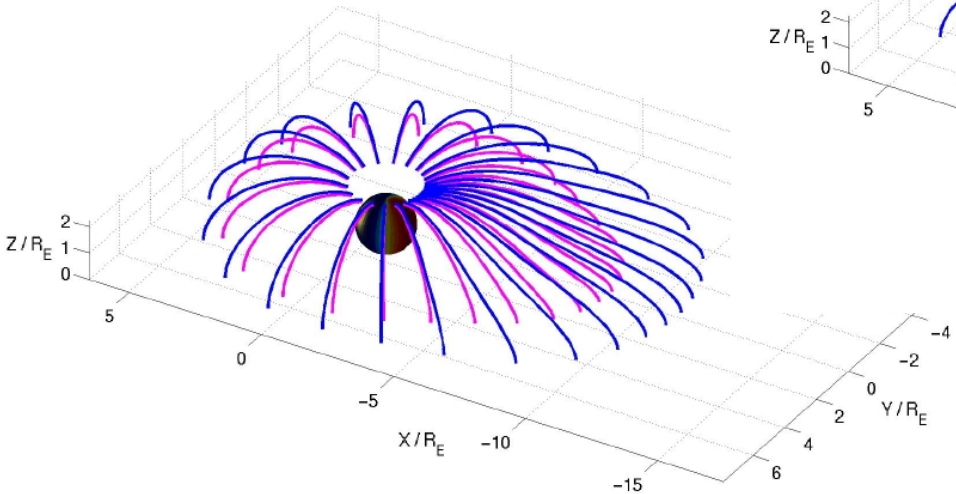
- Dashed lines are for typical quiet time values.
- Magnetic well at ~ 7.5 R_E for growth phase.

Magnetic Fields

Growth Phase Field



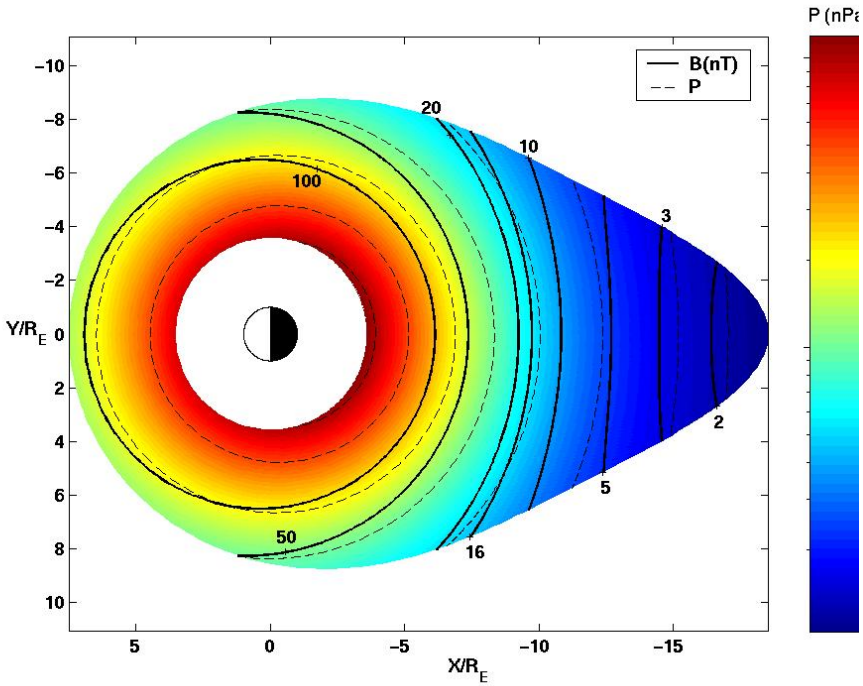
Quiet Time Field



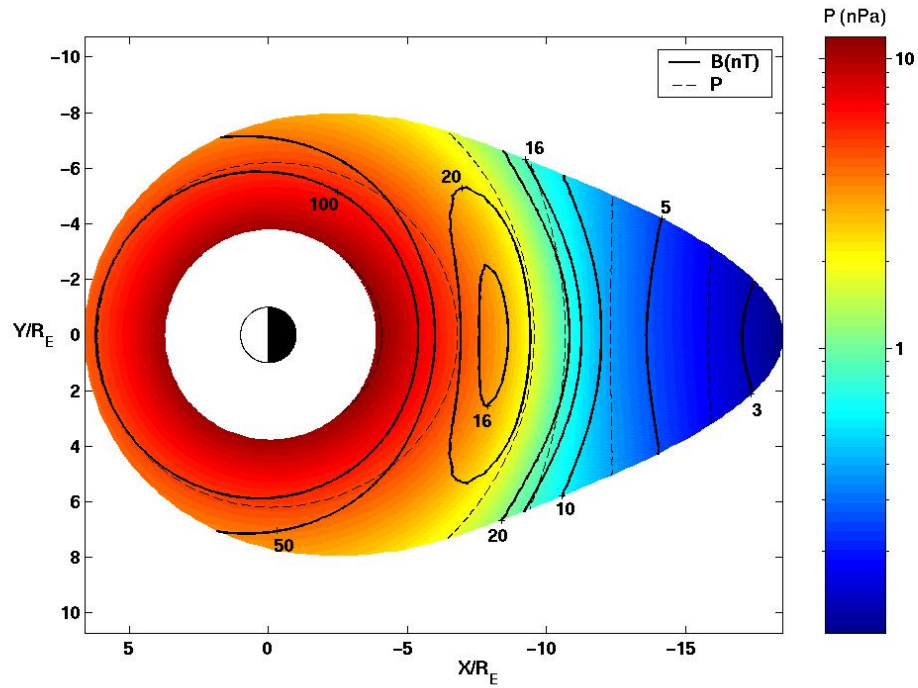
Pink flux surface: L = 4.1 ($\theta = 60.5^\circ$);
Blue flux surface: L = 5.2 ($\theta = 64.1^\circ$)

P and B in Equatorial Plane

Quiet Time Field



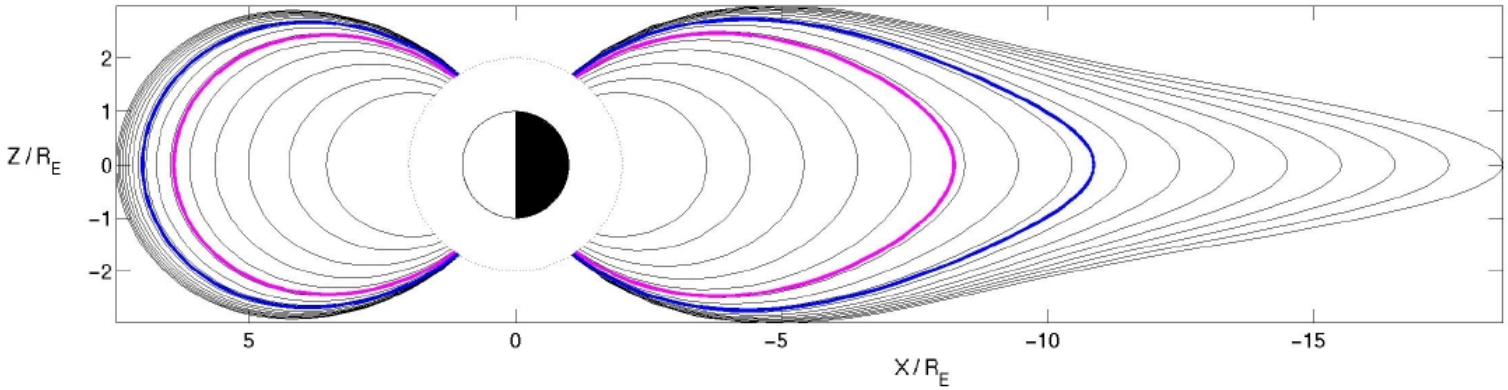
Disturbed Time Field



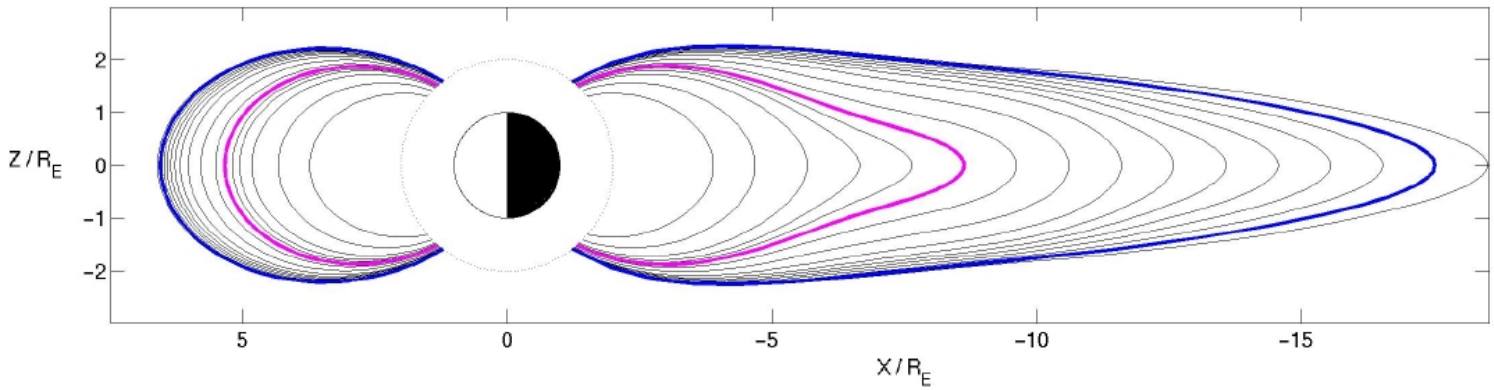
A local magnetic well at X $\simeq -8\ R_E$ for disturbed time case

Field Lines in Noon-Midnight Meridian

Quiet Time Field



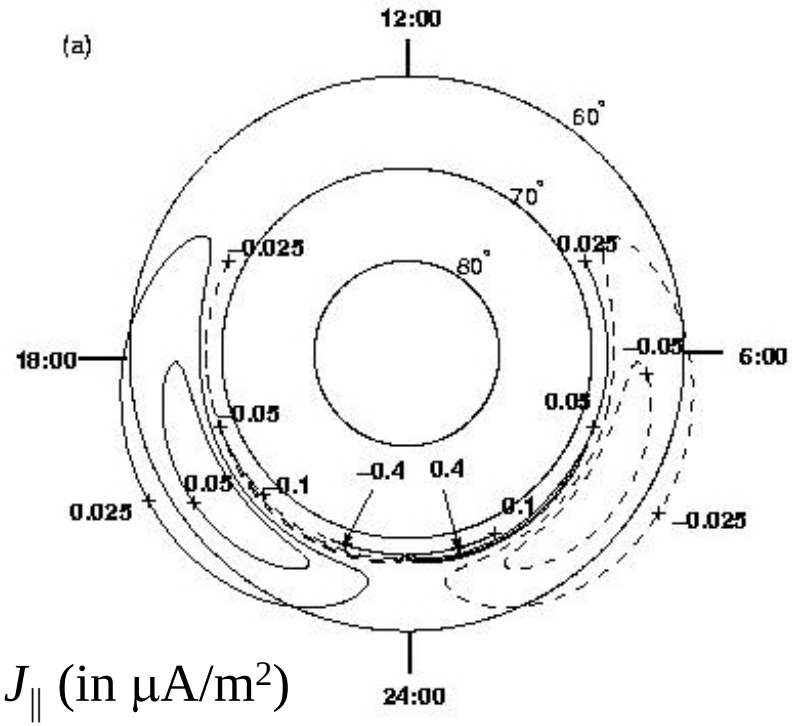
Disturbed Time Field



Inner boundary: L = 3.5 (θ = 57.7°);
pink flux surface: L = 4.1 (θ = 60.5°);
blue flux surface: L = 5.2 (θ = 64.1°)

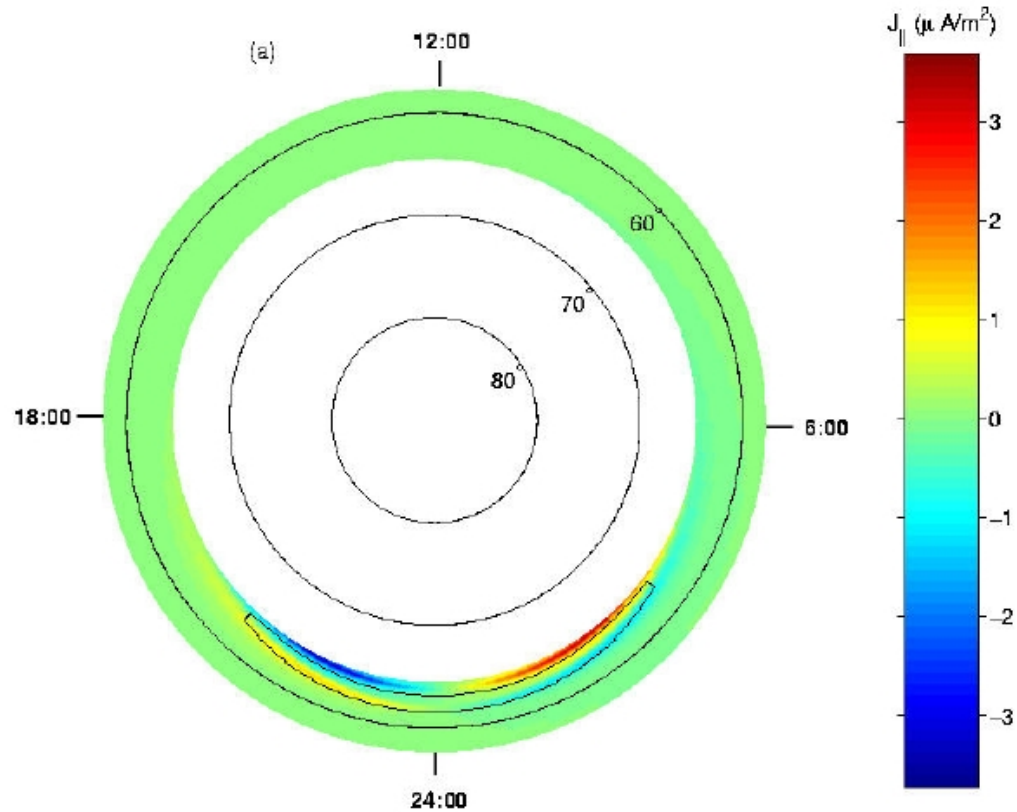
Birkeland Currents

Quiet Time Field



$J_{||}$ (in μA/m^2)

Disturbed Time Field



- Disturbed time Birkeland currents move equatorward, are more localized in latitude and become more intense ~ 3 μA/ m^2.
- Intense cross tail current region maps to transition region (1°-2°) between R-1 and R-2 currents in the ionosphere.

Energy Consideration

Consider a volume within two boundary fluxes L = 3.5 (θ = 57.7°) and L = 5.4 (θ = 64.5°) of the computed growth phase equilibrium

- Quiet-Time

$$V \approx 70.8 R_E^3$$

$$W_B \approx 5.6 \times 10^{20} \text{erg}$$

$$W_P \approx 2.7 \times 10^{20} \text{erg}$$

- Growth Phase

$$V \approx 490\, R_E^3$$

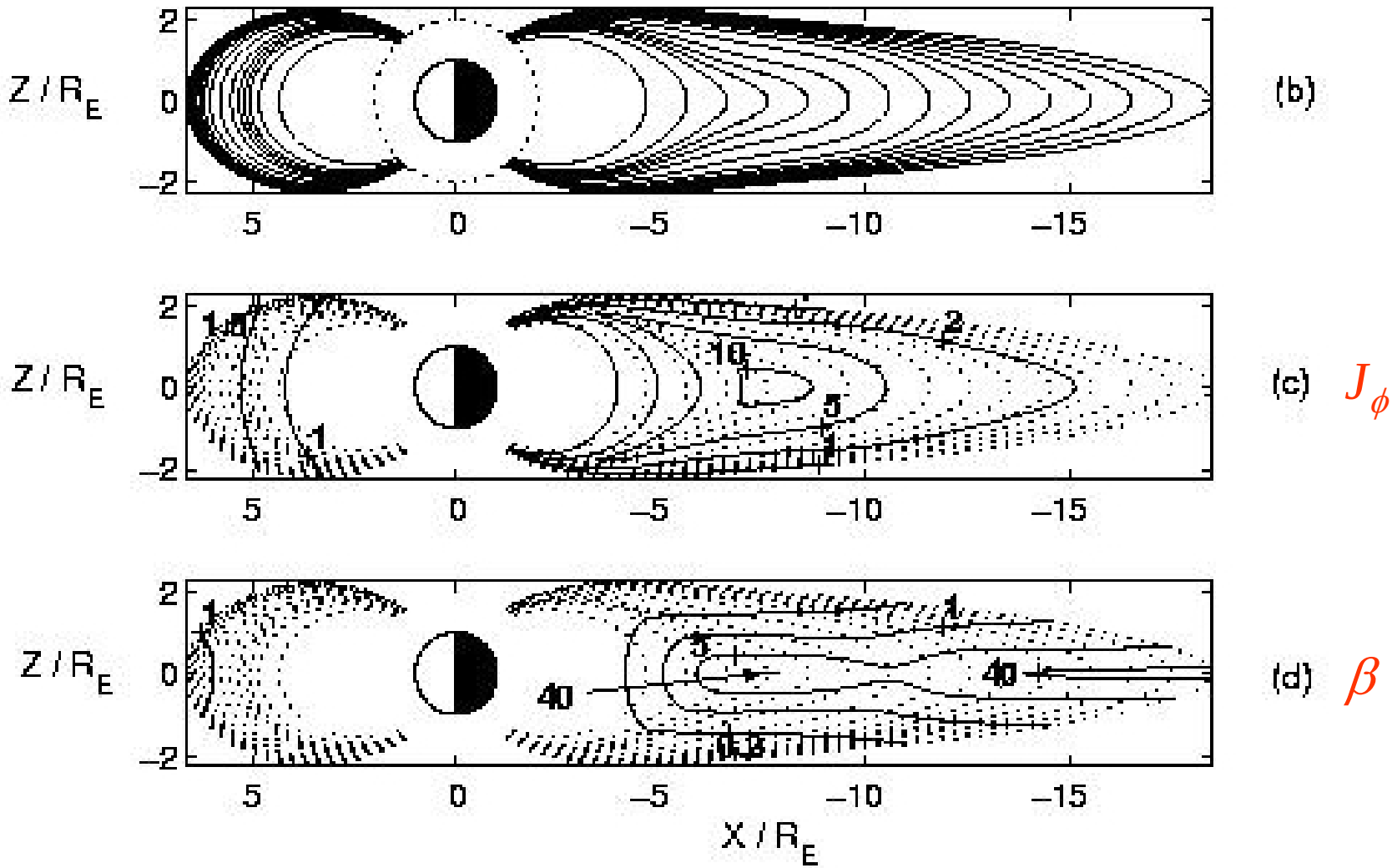
$$W_B \approx 1.9 \times 10^{21} \text{erg}$$

$$W_P \approx 2.7 \times 10^{21} \text{erg}$$

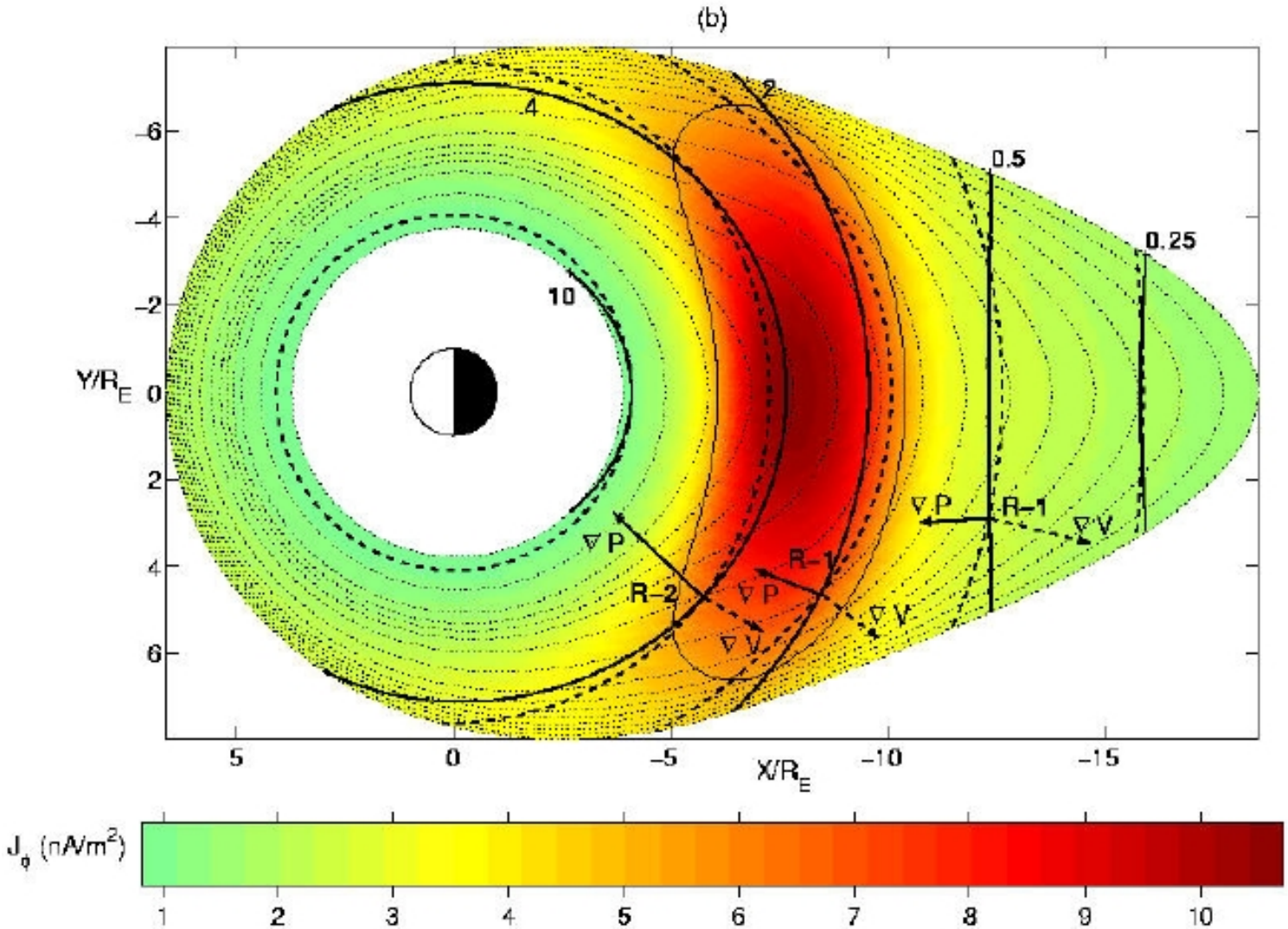
$*$ Energy dissipation in ionosphere

during expansion phase is $\leq 1.8 \times 10^{20}$ erg

Growth Phase: Fieldlines, J_ϕ (nA/m^2) and β Contours

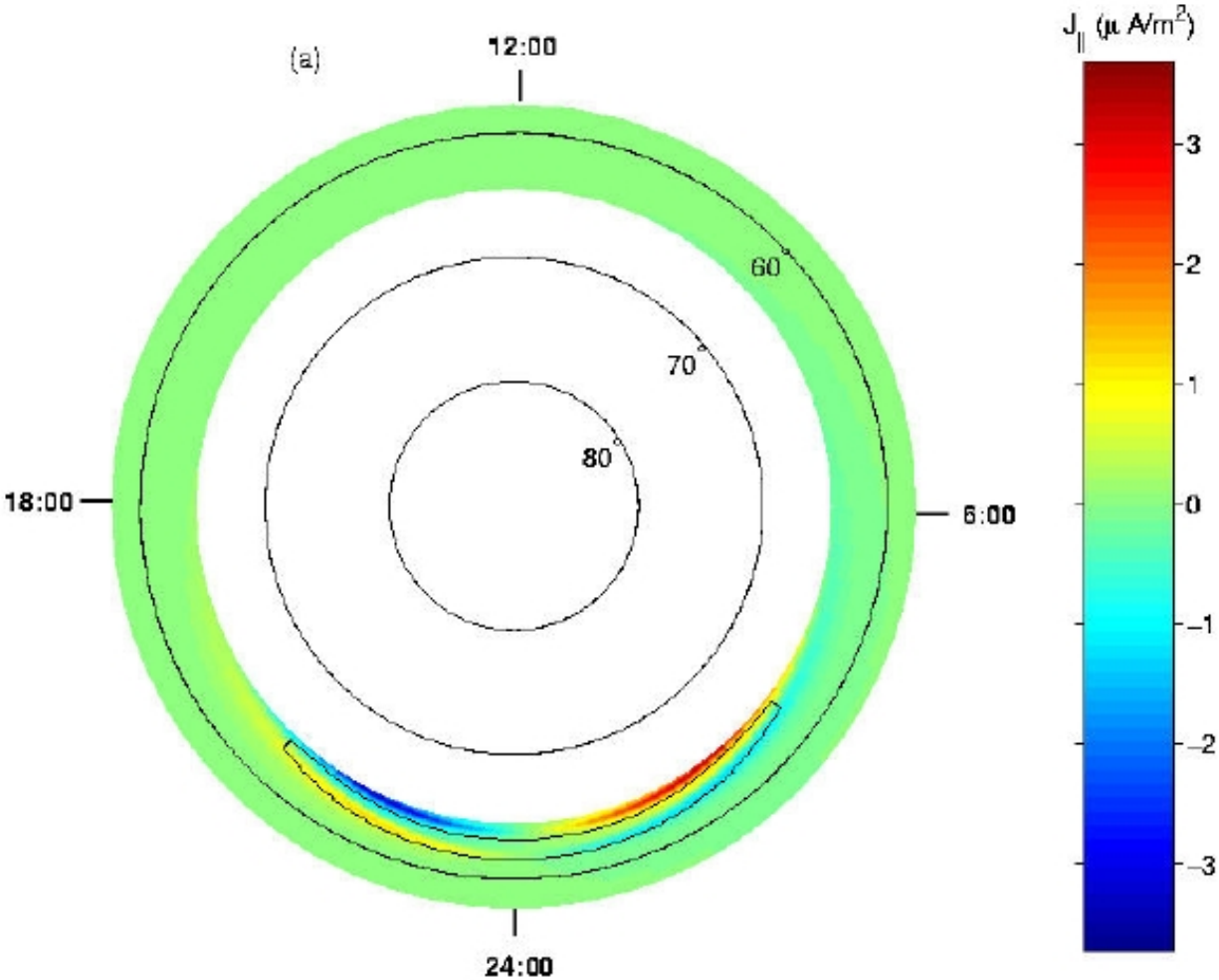


Growth Phase: Cross-Tail Current density in Equator



$$(J_{\parallel}/B)_{iono} = (\vec{B} \bullet \nabla V \times \nabla P / B^2)_{eq} \qquad V = \int dl / B = \text{flux tube volume}$$

Growth Phase: Birkeland Currents



- Birkeland currents move equatorward, are more localized in latitude and become more intense ~ 3 μA/ m^2.

- Intense cross tail current region maps to transition region (1°-2°) between R-1 and R-2 currents in the ionosphere.

- KBI is localized at center of cross tail current sheet consistent with substorm initial break up location.

Ballooning Instability as Substorm Onset Mechanism

- The observed instability has $\gamma/\omega_r \sim 0.2$ and $\omega_r/\omega_{ci} \sim 0.1$. It is excited when the plasma β at the satellite location ($\sim 8.8\ R_E$) increases from ~20 to about 50 or higher in ~ 3 min.
- Is the observed low frequency instability a ballooning mode? Probably Yes!
- Ideal MHD theories of ballooning mode predict purely growing instability when $\beta > \beta_C^{MHD} \sim O(1)$.

- Why is the observed β_C much larger than β_C^{MHD}?
- Why is there a finite real frequency?

Ideal MHD Ballooning Mode Theory

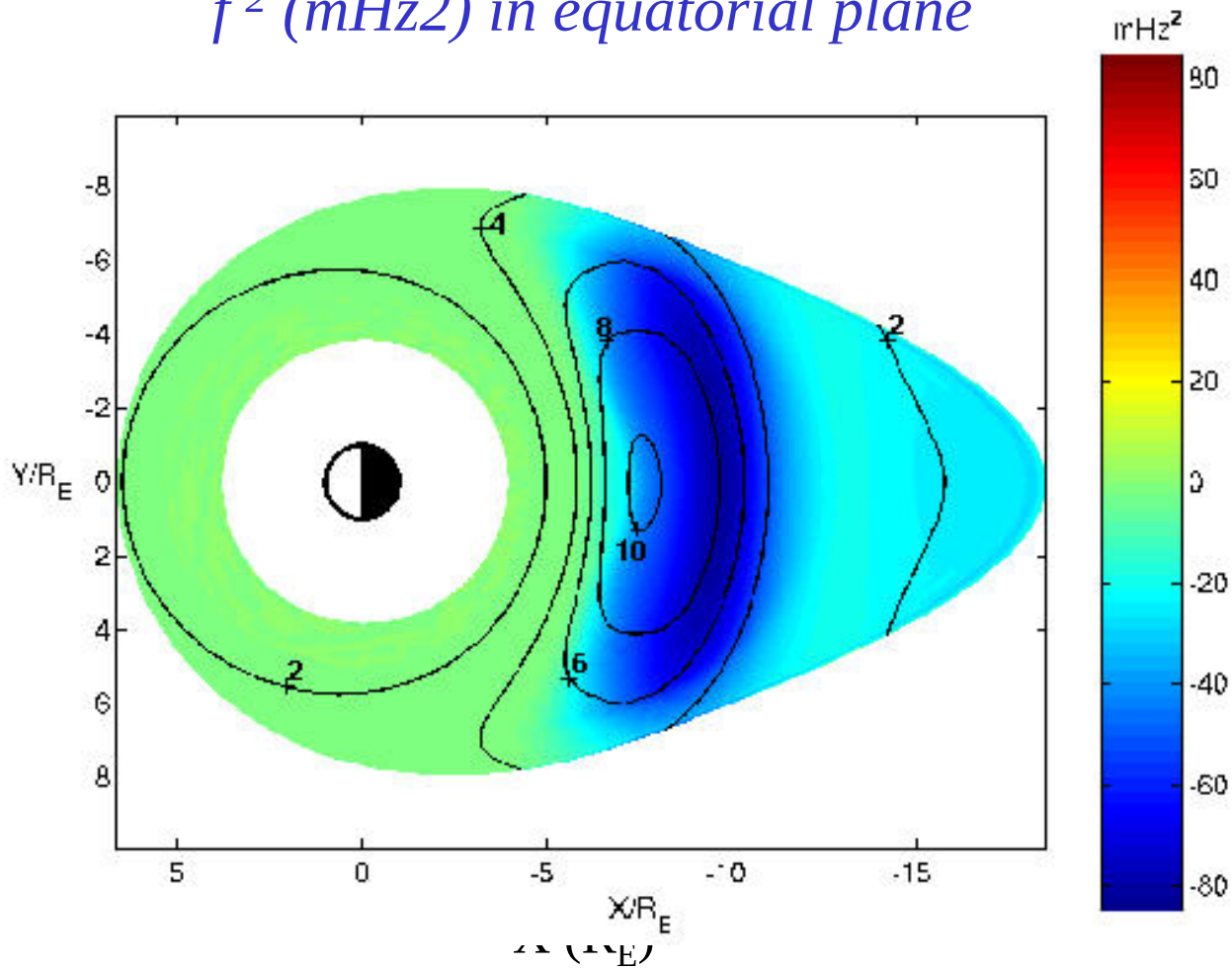
(Cheng and Zaharia, GRL, 2004)

- MHD ballooning mode stability is studied for *3D* growth phase magnetospheric equilibrium fields .
- The stability of ballooning modes crucially depends on field configuration.
- Numerical results: ideal MHD ballooning modes are unstable in large domain of plasma sheet when $\beta_{eq} > \beta_c^{MHD} \sim O(1)$.
- Unstable MHD ballooning modes are purely growing ($\omega_r = 0$).

Ideal MHD Ballooning Instability

f^2 (mHz2) in equatorial plane

Y
(R_E)

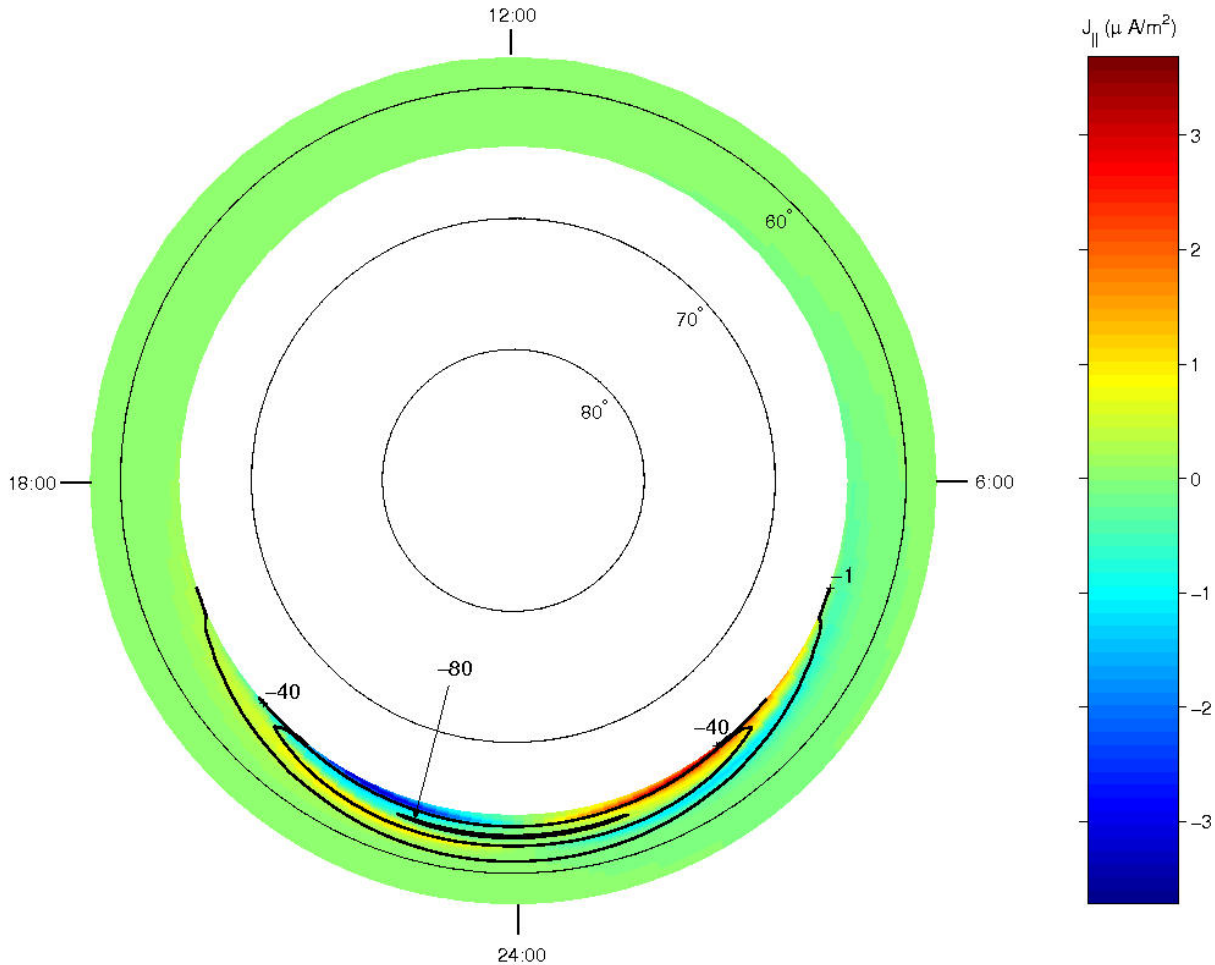


BC:
$\phi = \Delta = 0$

Most unstable ballooning instability is located at tailward side of the cross-tail current sheet !

Ideal MHD Ballooning Instability:

f^2 (mHz^2) Contours in Northern Polar region



Most unstable ballooning instability is at the transition region between R-1 and R-2 field-aligned currents !

Observation of Substorm Onset

(in Near-Earth Plasma Sheet Region)

- AMPTE/CCE observation (at ~ 8.8 R_E, near midnight): an instability (in Pi 2 frequency range) is excited $\sim$ 2-3 minutes prior to onset when plasma β_{eq} increases from $\sim$ 20 to $\sim$ 50.
- Why is observed β_c ($\sim$ 50) much larger than β_c^{MHD} and why is there a finite real frequency?

  Requires kinetic effects of trapped electrons, ion gyroradii, ion diamagnetic drift.

➔ Theory of kinetic ballooning instability (KBI).

Ballooning Mode Stabilization by Kinetic Effects

$$(V_e > \omega / k_{\|} > V_i)$$

[Cheng and Lui, GRL 1998]

- $\delta E_{\|}$ is enhanced due to effects of ion gyroradii and trapped electron dynamics.
- Enhanced $\delta E_{\|}$ increases $\delta j_{\|}$, which increases field line tension to reduce ballooning mode growth rates.
- $\beta_c \simeq S\, \beta_c^{MHD}$, $S \sim (n_e T_e / n_{eu} T_i)\, b_i/(1+b_i)$, $S >> 1$, consistent with observations.
- Mode frequency is ion diamagnetic drift freq. (ω_{*i}), similar to Pi 2 frequencies.
- Prior to substorm onset ballooning modes are unstable only for field lines in strong cross-tail current region.

Mechanism of Expansion Phase

- After substorm onset, higher frequency instabilities (period ~ 3 - 15 seconds, CCI) occurs and together with KBI (period ~ 60 - 100 seconds) forms a strong plasma turbulence.
- Strong turbulence causes plasma transport and relaxes the pressure profile.
- Turbulence region expands in all direction, mostly tailward.
- Pressure profile relaxation leads to magnetic field dipolarization.
- Convection electric field increases due to B field dipolarization.

Dipolarization by Pressure Reduction

- Consider B and P averaged over fluctuation time scale ($\sim$ 100 s).
- Force balance: $\nabla_{\perp}\left(P + B^2/2\right) = \vec{\kappa}\, B^2$
- In the near-Earth plasma sheet, a small reduction in P leads to a large increase in B (dipolarization):

P	+	$B^2/2$	$\simeq$	constant
50		1	gives	$\beta = 50$
45		6	gives	$\beta = 7.5$

➔ 10% reduction in P causes B to increase 2.45 times and β to decrease 6.6 times, consistent with AMPTE/CCE observation!

Summary and Conclusion

- A theoretical substorm model explains growth phase features, substorm onset, and dipolarization in expansion phase:
- Growth Phase — near-Earth plasma sheet thins to ~ 1 R_E, $\beta_{eq} \sim 50$ at the onset location (~ 7 — 10 R_E). Birkeland currents move equatorward, are more localized in latitude, and becomes more intense.
- Onset — Kinetic Ballooning Instability (KBI) is excited at $\sim$ 2-3 minutes prior to onset and is responsible for substorm onset. KBI is unstable in strong cross-tail current region, which maps to location of breakup arc formation.
- Expansion Phase — turbulence causes plasma transport to relax the pressure profile, which causes dipolarization and enhanced convection electric field.

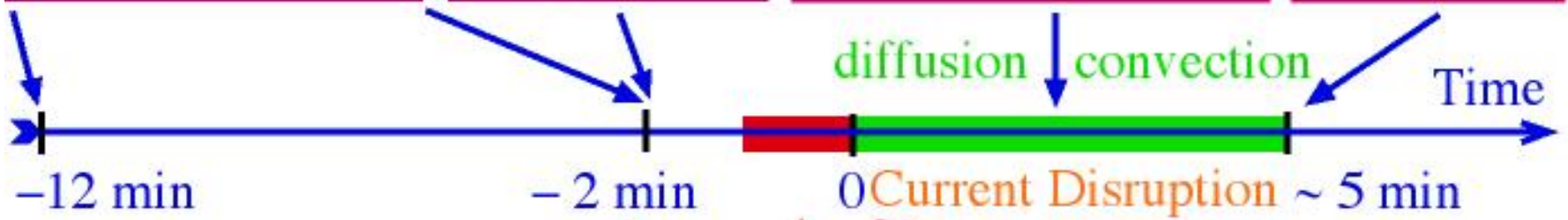
A Possible Scenario for Onsets of Current Disruption

P_i increases ~30%
$P_\perp \approx P_\parallel$
B reduces from 15 nT to 10 nT
$\beta \approx 20$ to 50
Almost no δB fluctuations

Kinetic Ballooning Instability (KBI) occurs with
$T \approx 60$ sec
$\omega_r/\omega_{ci} \approx 0.1$
$\gamma/\omega_r \approx 0.2$

Cross-field Current Instability
high frequency waves: $\delta B/B \sim 0.5$
$T \approx 15$ s, 10 s, 5 s
=>Turbulence
=>Plasma Transport and Heating

$\vec{B}$ recovers to a more dipole-like geometry.



Physical mechanism: KBI

Enhanced westward ion drift

Physical mechanism: CCI

Cheng & Lui [1998]