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The Paleomagnetosphere

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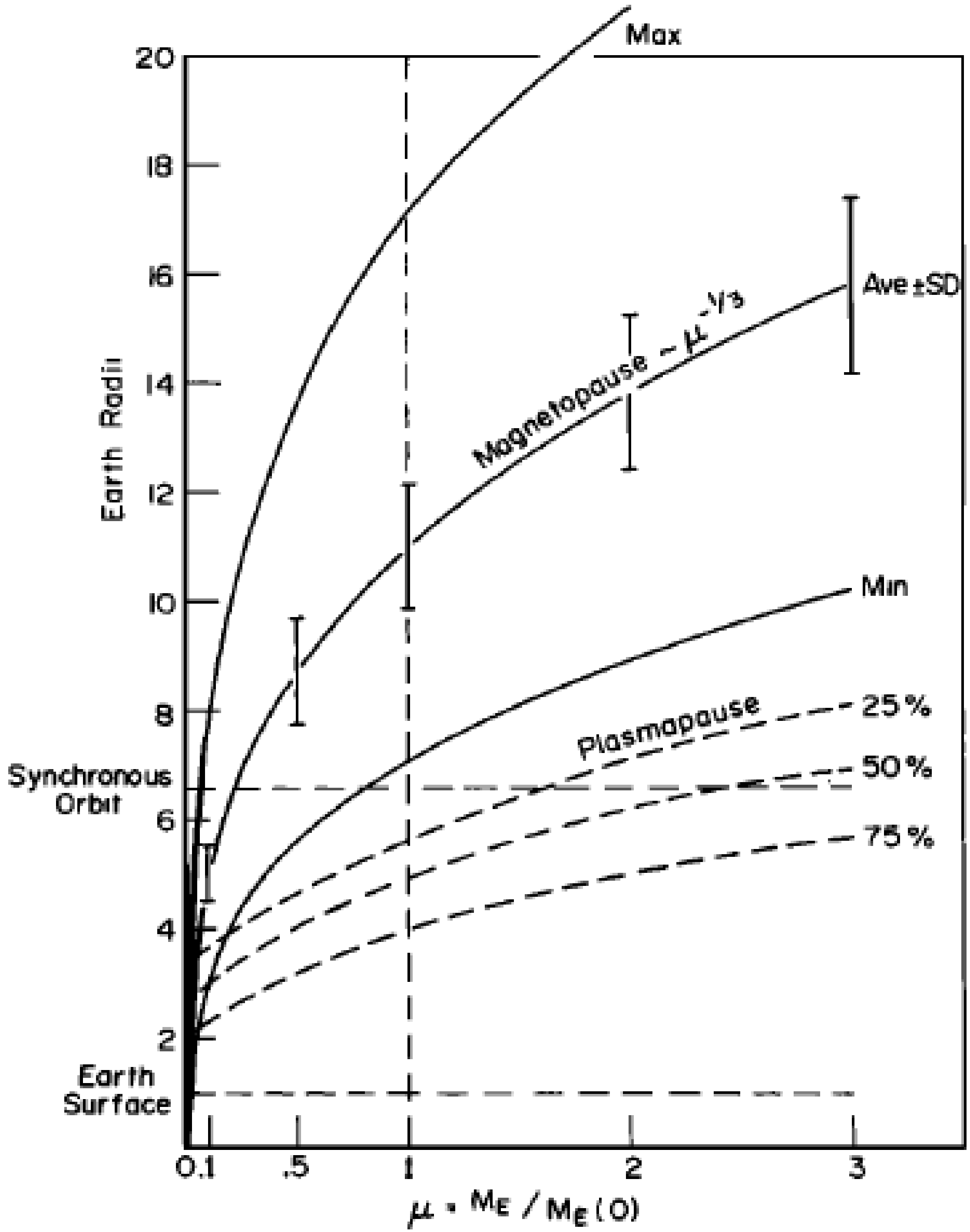
Paleomagnetic research indicates that the strength of the earth dipole varies over the range 0.1 to 3.0 of the present value. Consequences for magnetospheric physics of changes in the strength of the magnetic dipole are explored in this paper. The changes in the sizes of the magnetosphere and plasmasphere due to variations in dipole strength and to variations in solar wind parameters at a given dipole strength are given. The plasmasphere size varies more slowly with dipole strength than the magnetosphere size over the range considered. Thus the plasmasphere occupies a relatively larger fraction of the magnetosphere for small dipole strengths. The plasmasphere frequently extends beyond synchronous orbit for dipole strengths greater than twice the present value. For a given solar wind condition the power into the magnetosphere and the brightness of auroras increase for larger dipole strengths. However, for smaller dipole strengths, auroras are seen at lower latitudes and over a greater range of latitudes. Magnetic storms are stronger and more frequent for smaller dipole strengths.



Max
20
18
16
14
12
10
8
6
4
2
Earth Radii
Ave ±SD
Magnetopause ~ μ^-1/3
Min
Plasmapause
25 %
50 %
75 %
Synchronous Orbit
Earth Surface
0.1
.5
1
2
3
μ = ME / ME (O)

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Scaling relations in the paleomagnetosphere derived from MHD simulations

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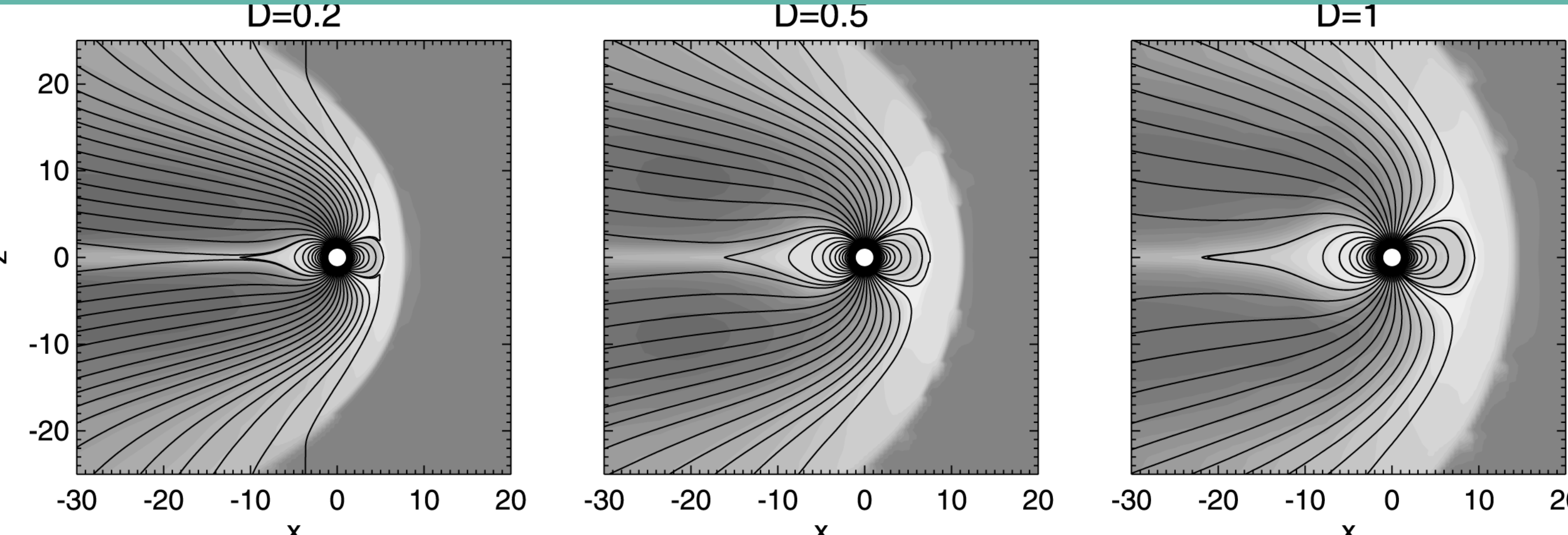
[1] On geological timescales the Earth's dipole moment can vary between 0.1 and 2 times the present value. The weakest internal magnetic fields occur during geomagnetic polarity transitions when the Earth's internal dipole field reverses. Theoretically, the size of the paleomagnetosphere is expected to change in the function of the dipole moment according to a power law scaling relation. We carried out a series of numerical magnetohydrodynamic (MHD) simulations of axial dipolar paleomagnetospheres, gradually decreasing the relative dipole moment from 1 to 0.1, in order to test the validity of the theoretical scaling relations for different values of the north-south interplanetary magnetic field component (IMF B_z). We study the dipole moment dependence of the standoff distance, the flank distances, and the polar cap size, and derive power law scaling relations with significantly differing scaling exponents as compared to the theoretically expected ones. The extent of deviation from the theoretical scaling exponents is controlled by the magnitude of the southward B_z. We quantify the B_z-dependence of the size of the magnetosphere and validate our results with the Roelof-Sibeck bivariate function of magnetopause shape obtained from in-situ satellite measurements for the present-day magnetosphere. We conclude that the Roelof-Sibeck function cannot be applied for southward B_z values stronger than 5 nT. A new B_z-dependent dipole scaling relation is suggested for the magnetospheric scale size. Inserting our corrected scaling relation in the Hill model of magnetosphere-ionosphere coupling, a better fit can be obtained between simulated and theoretically calculated paleomagnetospheric transpolar potentials.



D=0.2
D=0.5
D=1
20
10
0
-10
-20
z
-30
-20
-10
0
10
20
x

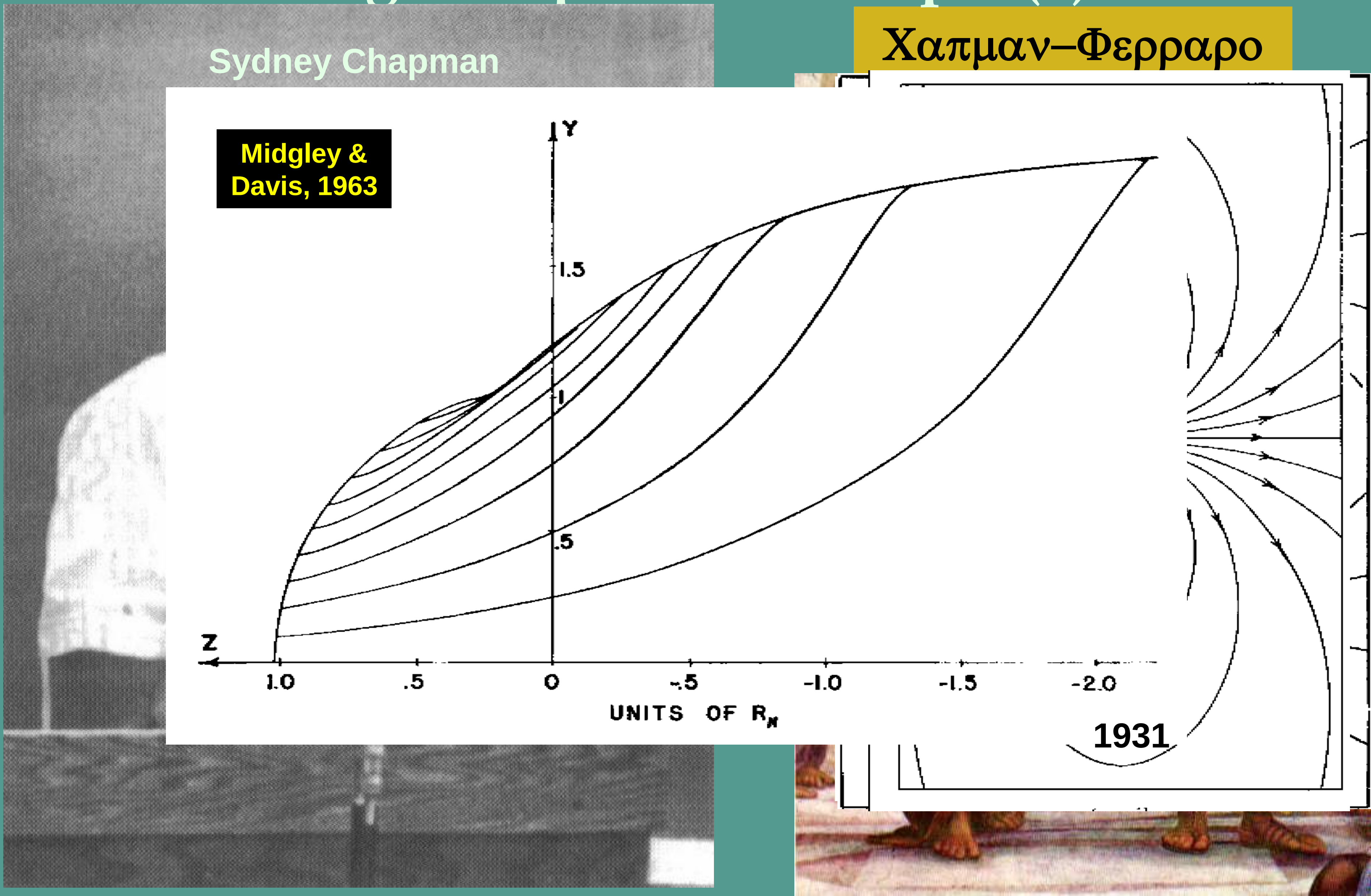
From the Chapman-Ferraro Magnetosphere To the Dungey-Alfvén Magnetosphere

- **Two Magnetosphere Types**
  - Chapman-Ferraro
  - Dungey-Alfvén
- **Chapman-Ferraro Type**
  - Hands-off, no-touch vacuum coupling
- **Dungey-Alfvén Type**
  - Hands-on, bow shock-to-ionosphere Alfvén coupling
- **Hybrid Type**
  - Chapman-Ferraro type usually dominates

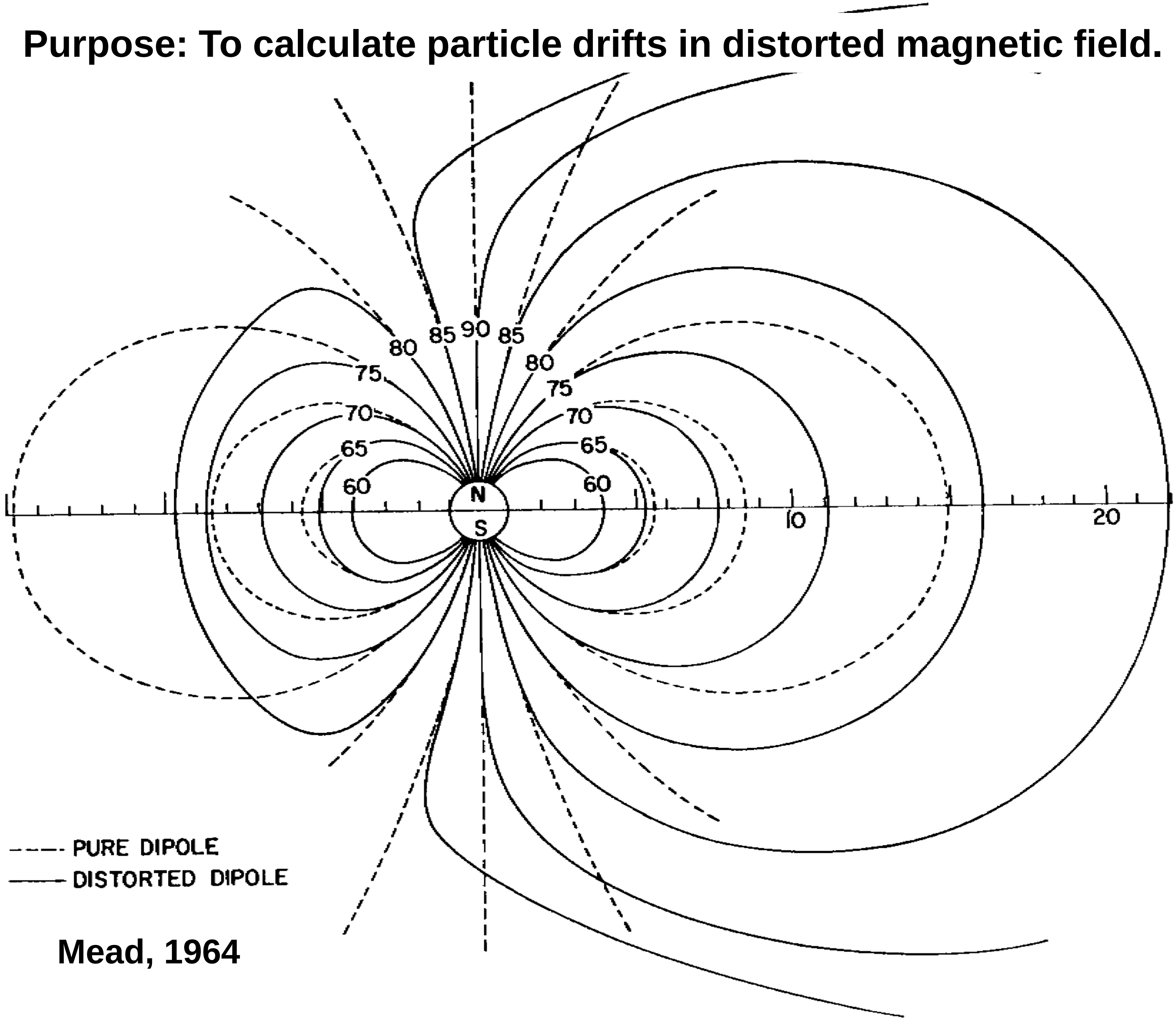
Chapman-Ferraro Magnetosphere

Dungey-Alfvén Magnetosphere

Highlights in the History of Magnetospheric Concepts (1)

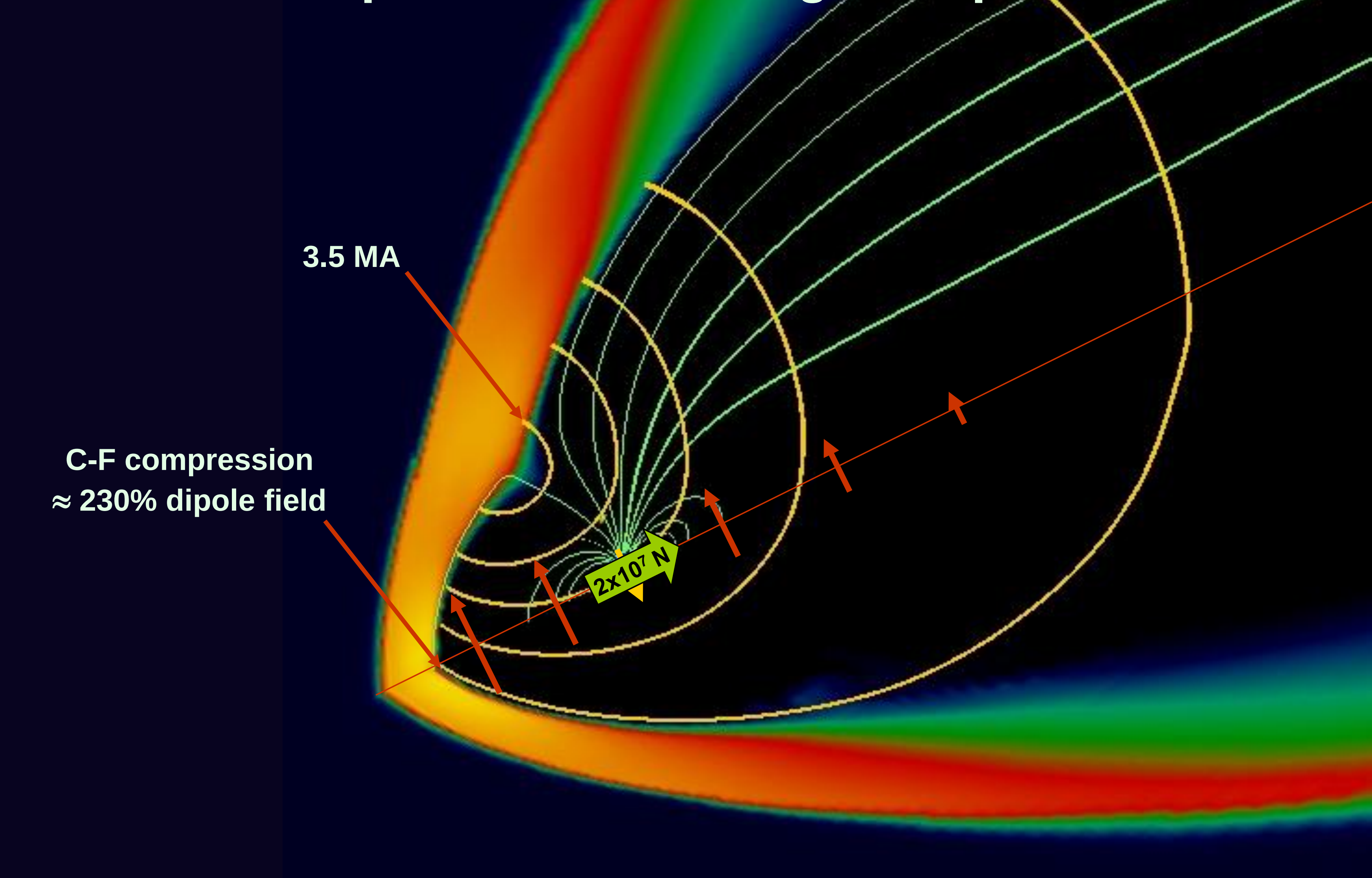


Purpose: To calculate particle drifts in distorted magnetic field.

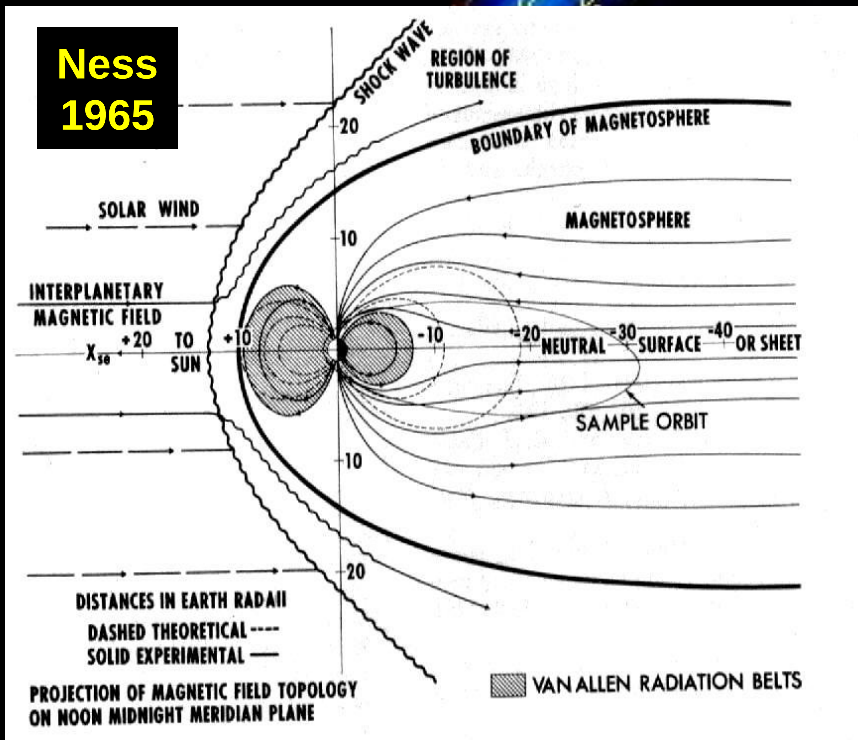


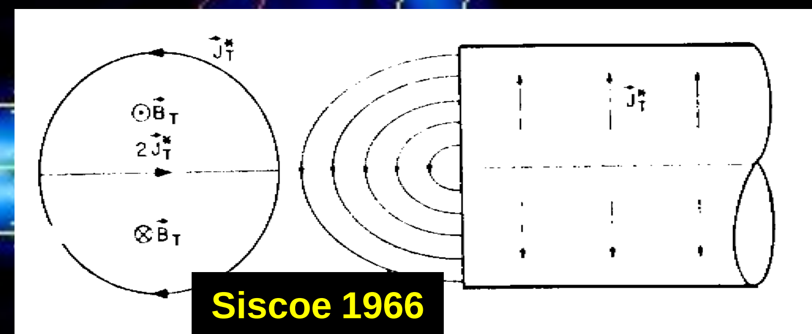
Mead, 1964

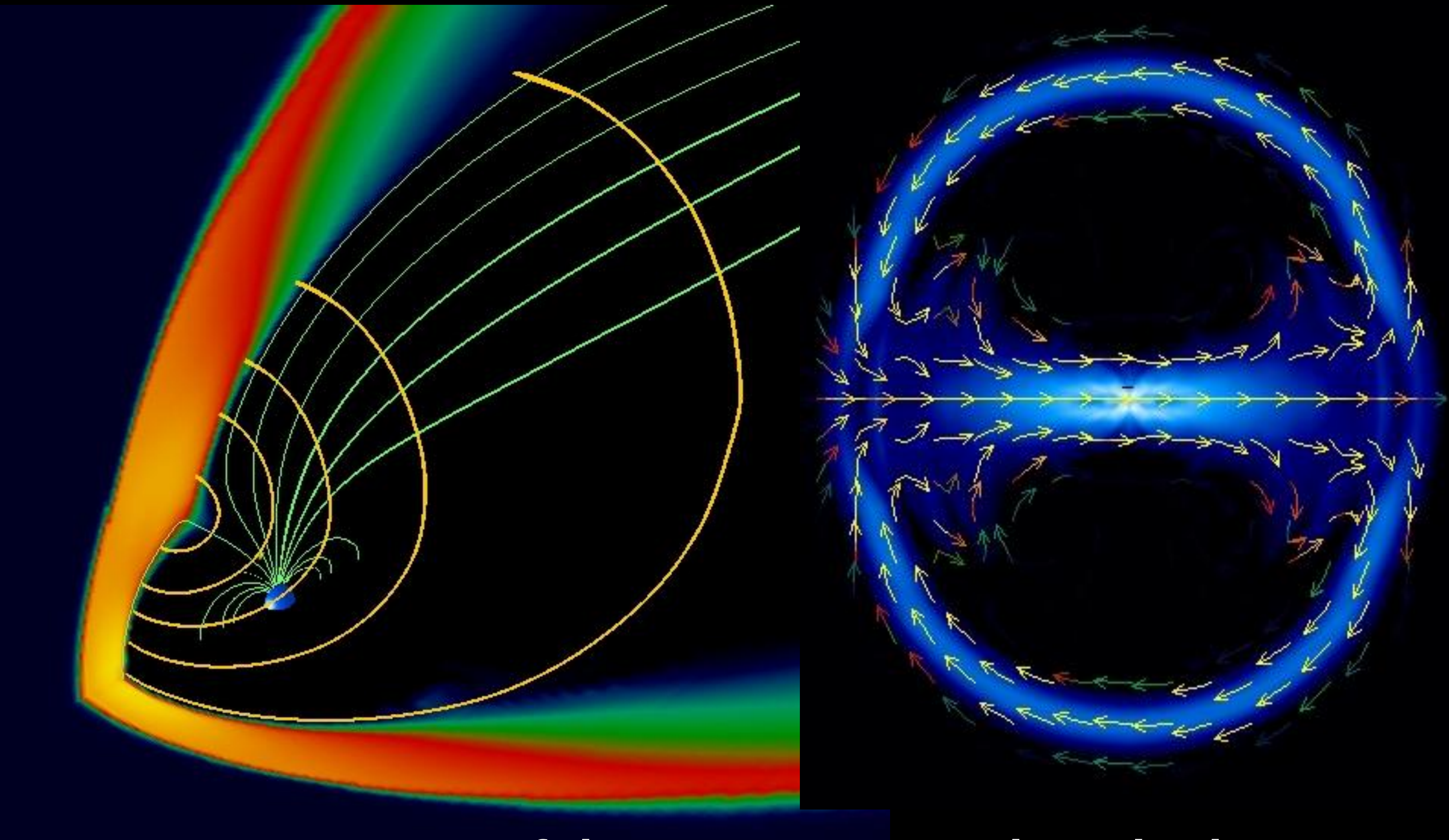
Properties of the Chapman-Ferraro Magnetosphere



New Element
Magnetotail Current System

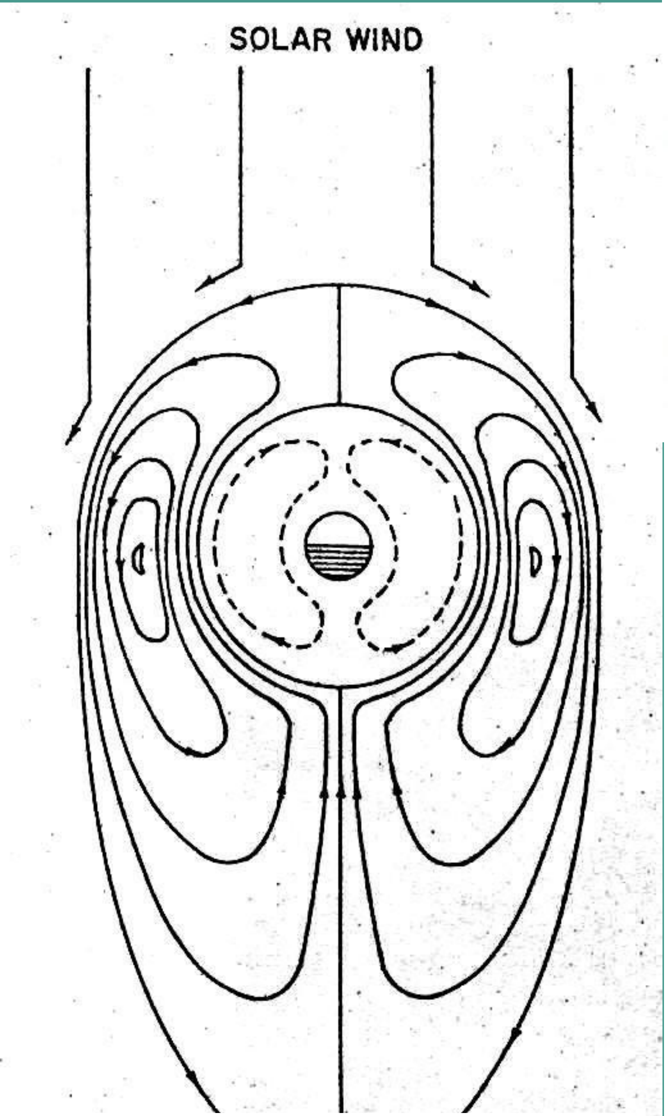




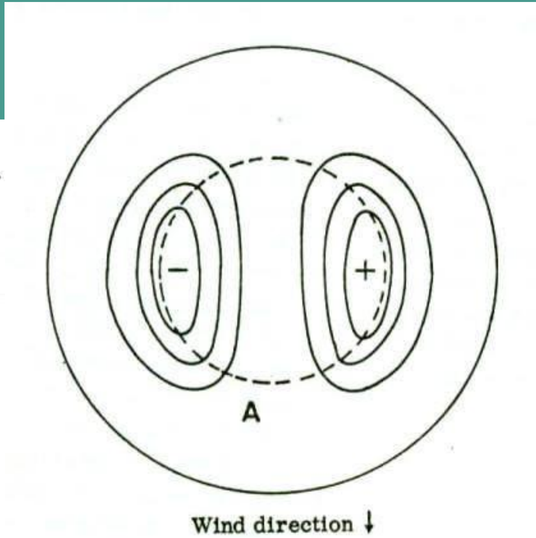


Components of the CF magnetosphere in the 1960s
Total field confinement and vacuum magnetic interactions

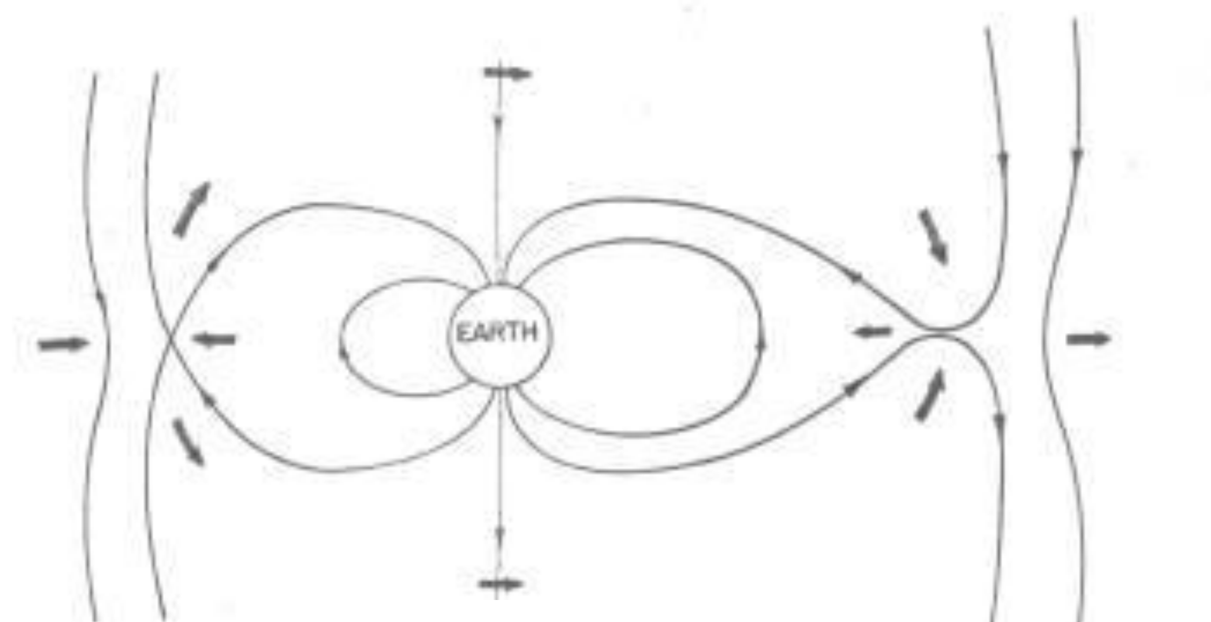
Things that did not fit the C-F picture



Axford and Hines, 1961

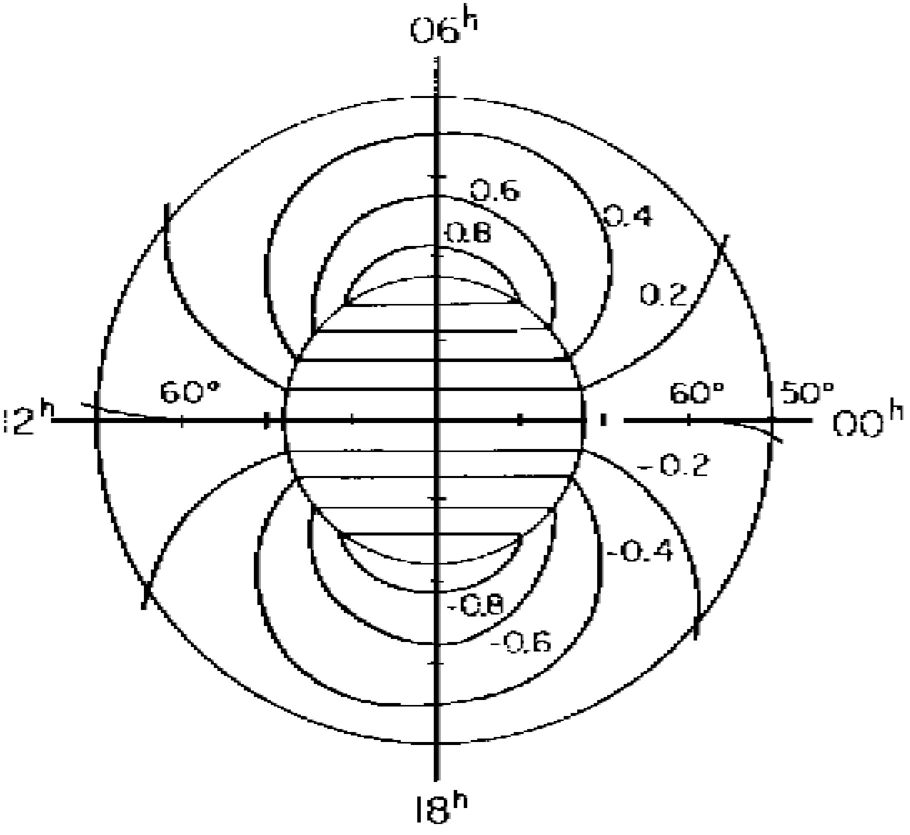


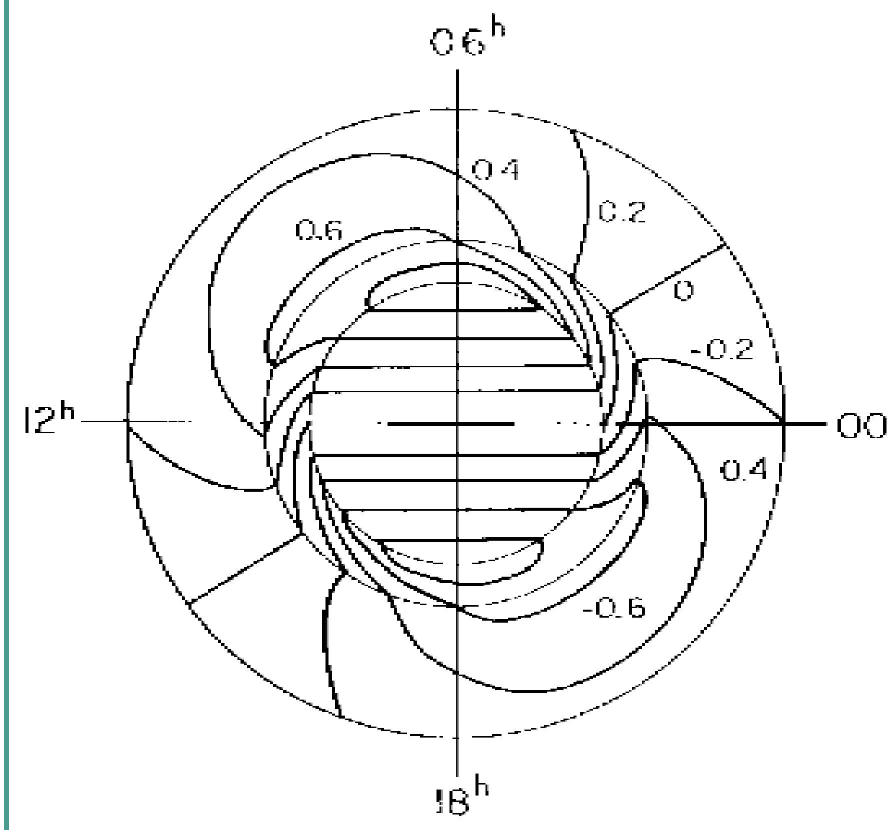
Two cell, sun-fixed ionospheric circulation pattern



Dungey, 1961
Violates C-F field confinement

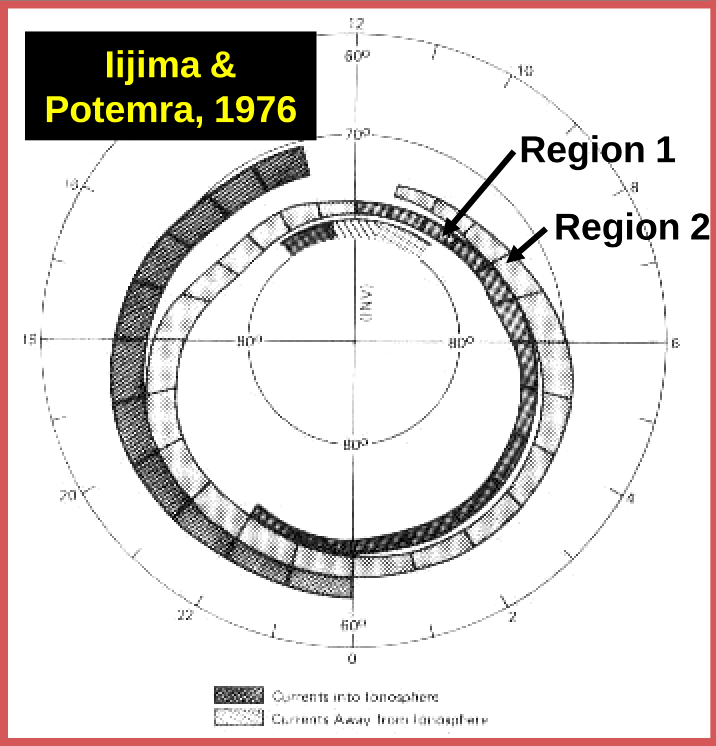
Vasyliunas MI Coupling Results 1970-1972

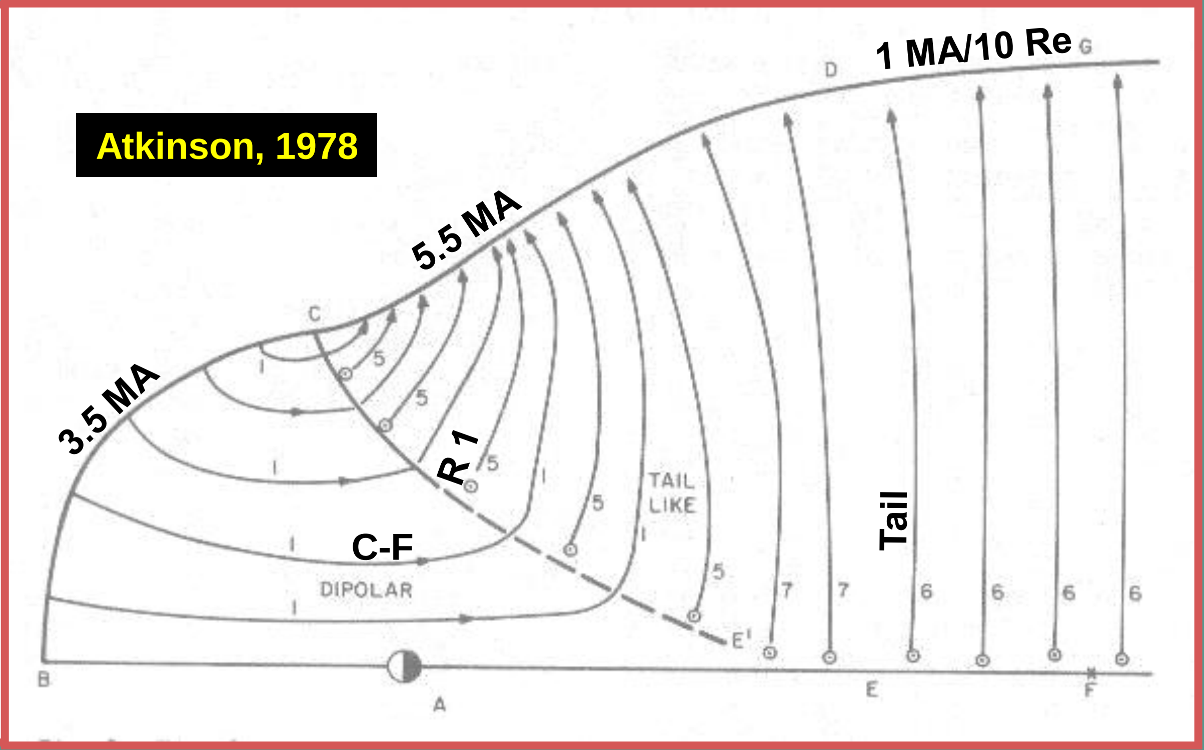




Violates C-F vacuum magnetic interactions

Ultimate Crisis to the CF Picture
Discovery of Strong Field-Aligned Currents





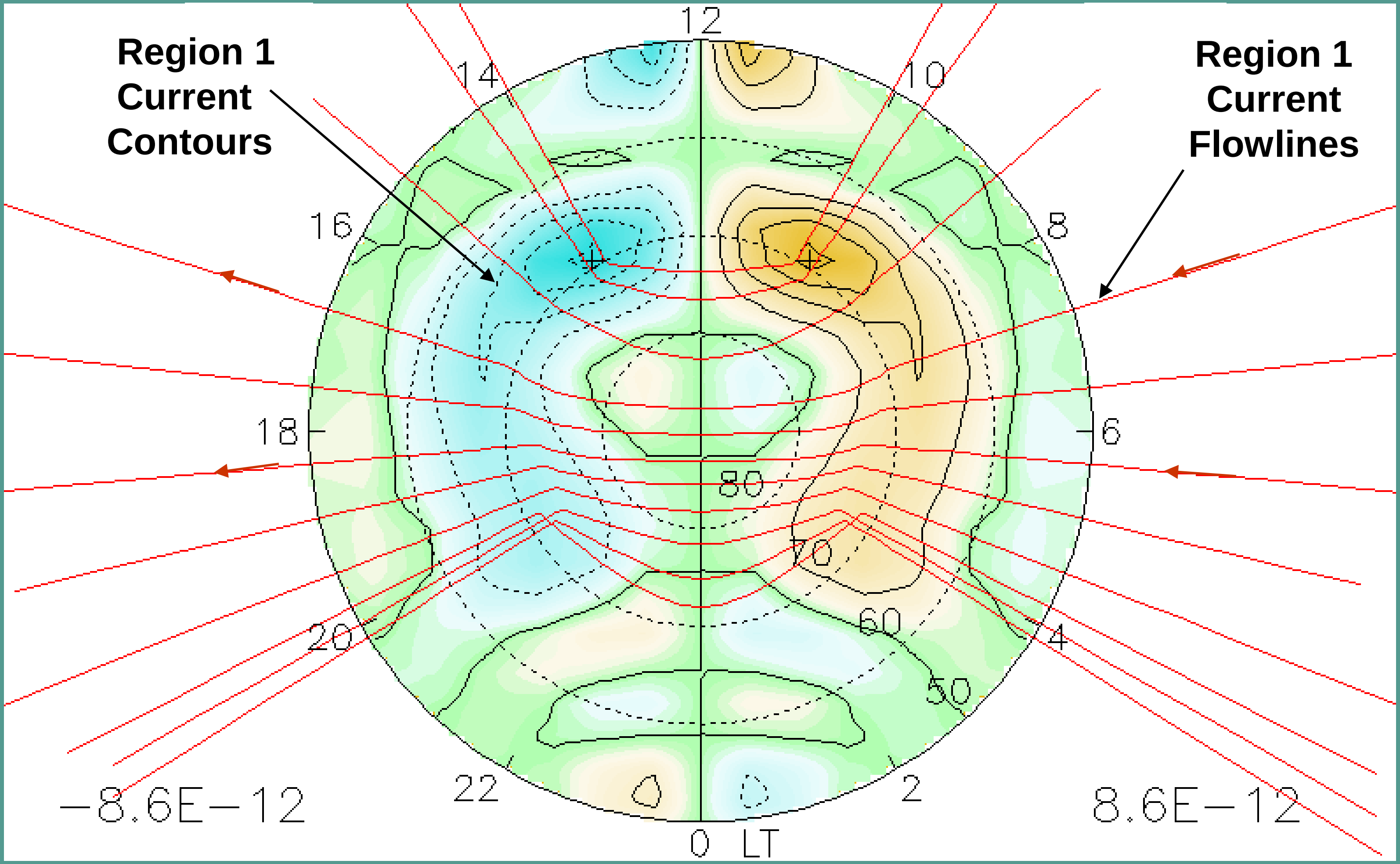
Total Field-Aligned Currents for Moderate Activity

(IEF ~1 mV/m)

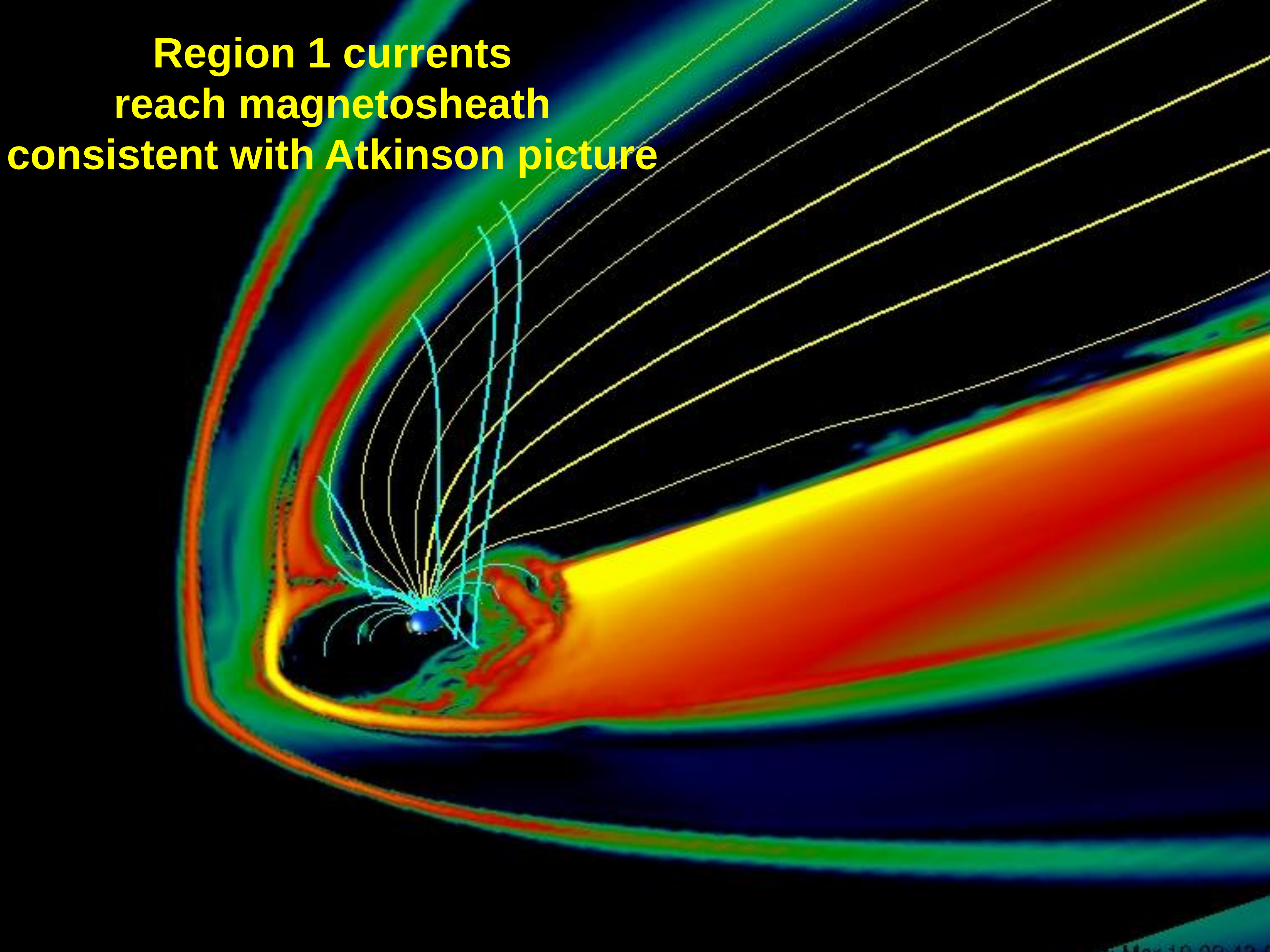
Region 1 : 2 MA
Region 2 : 1.5 MA

Question: How do you self-consistently accommodate the extra 2 MA?

Appeal to MHD Simulations
Region 1 Currents
IMF = 5 nT South

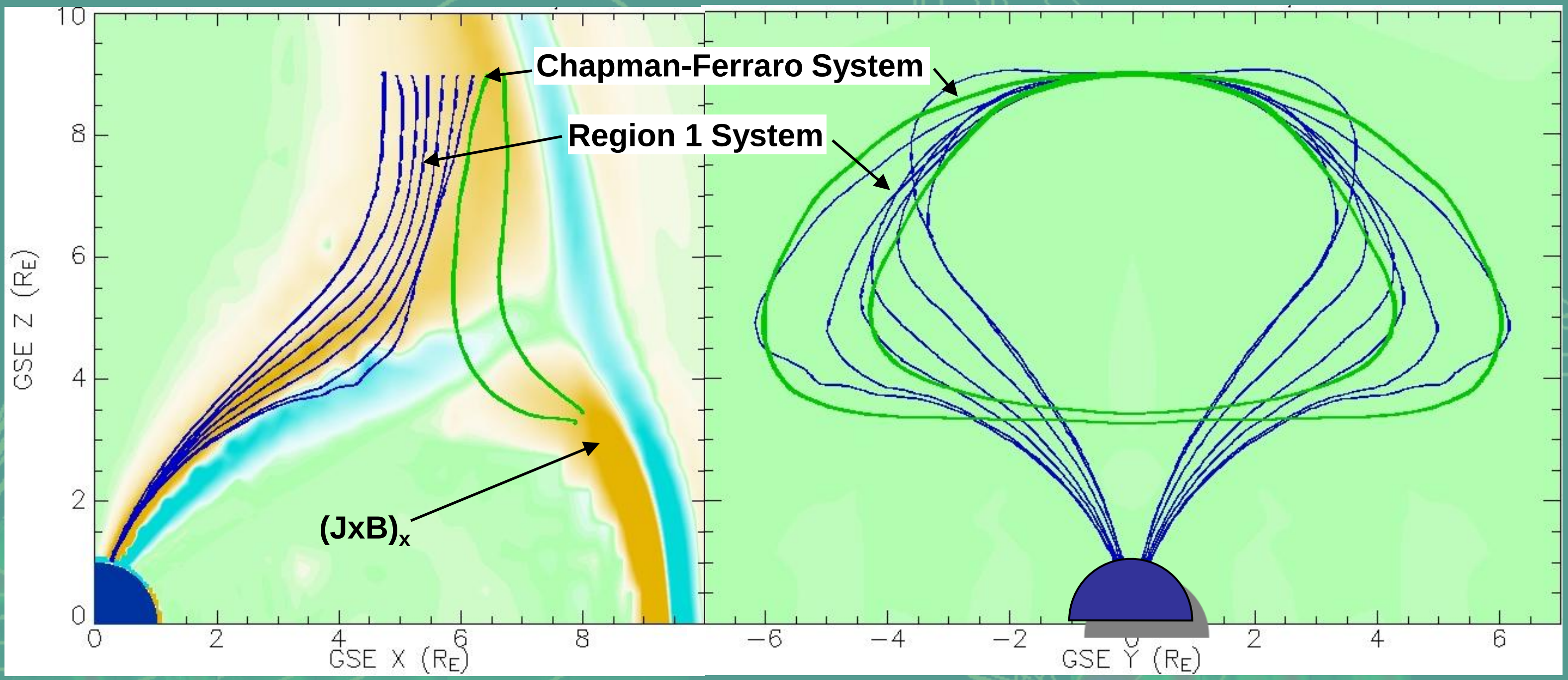


Region 1 currents
reach magnetosheath
consistent with Atkinson picture



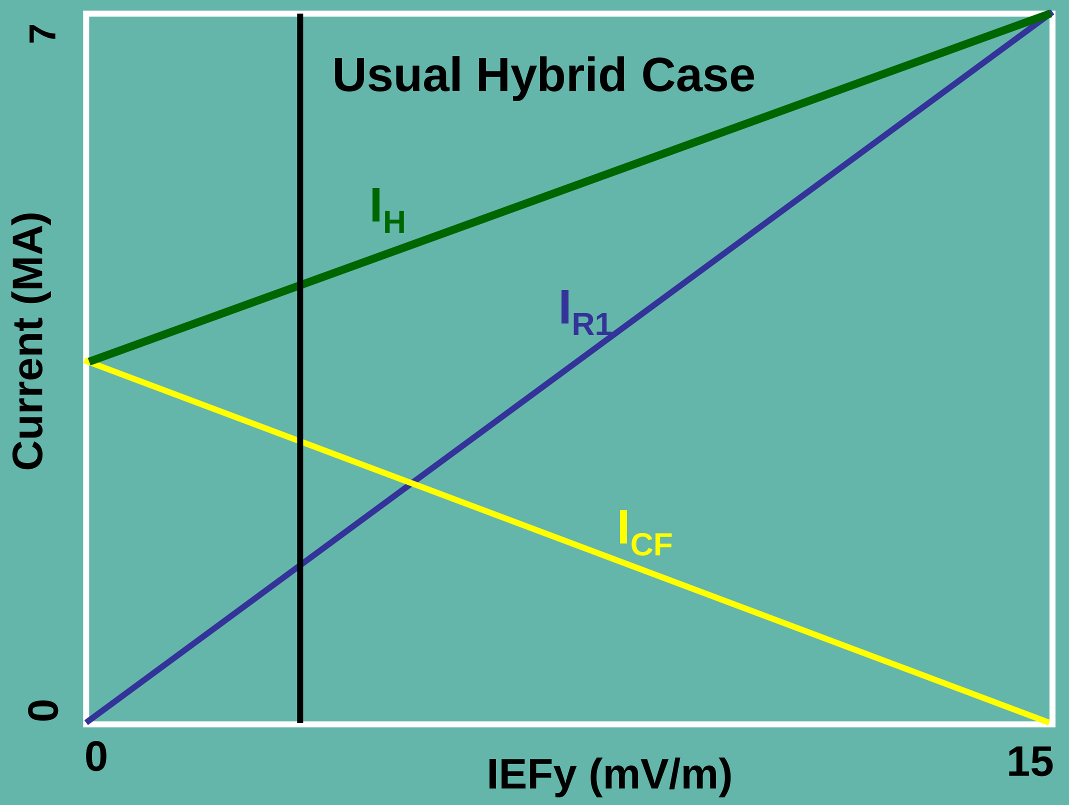
Q: How do you self-consistently accommodate an extra 2 MA current system?

A: You replace the Chapman-Ferraro current with it.



IMF = (0, 0, -5) nT

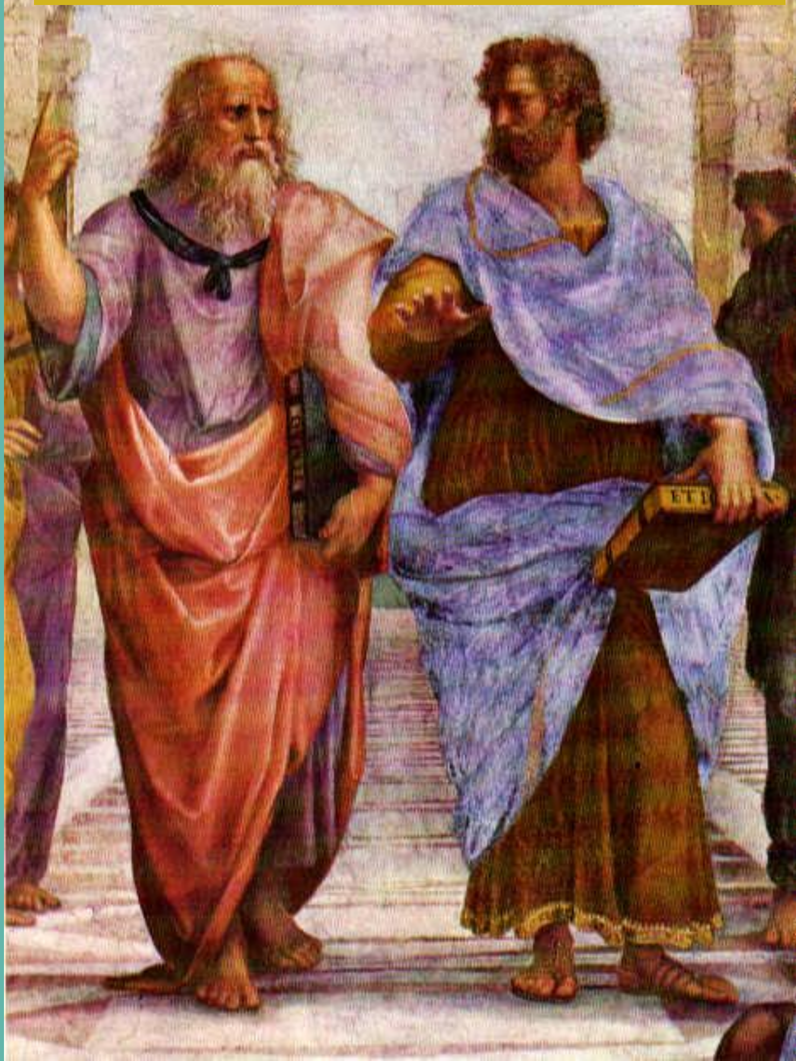
Current Quasi-Conservation Principle

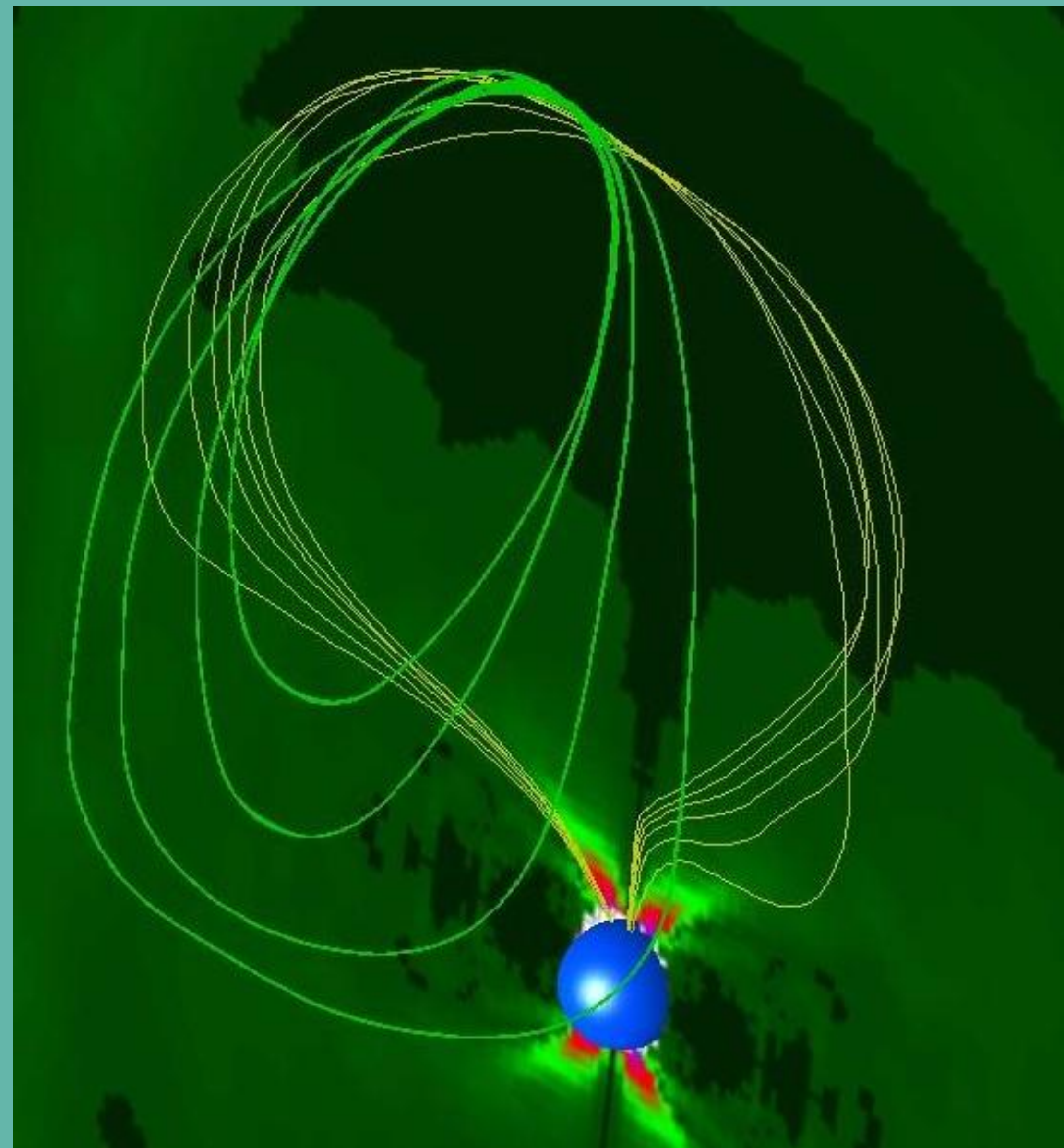


Highlights in the History of Magnetospheric Concepts (2)

Υβρίδιο

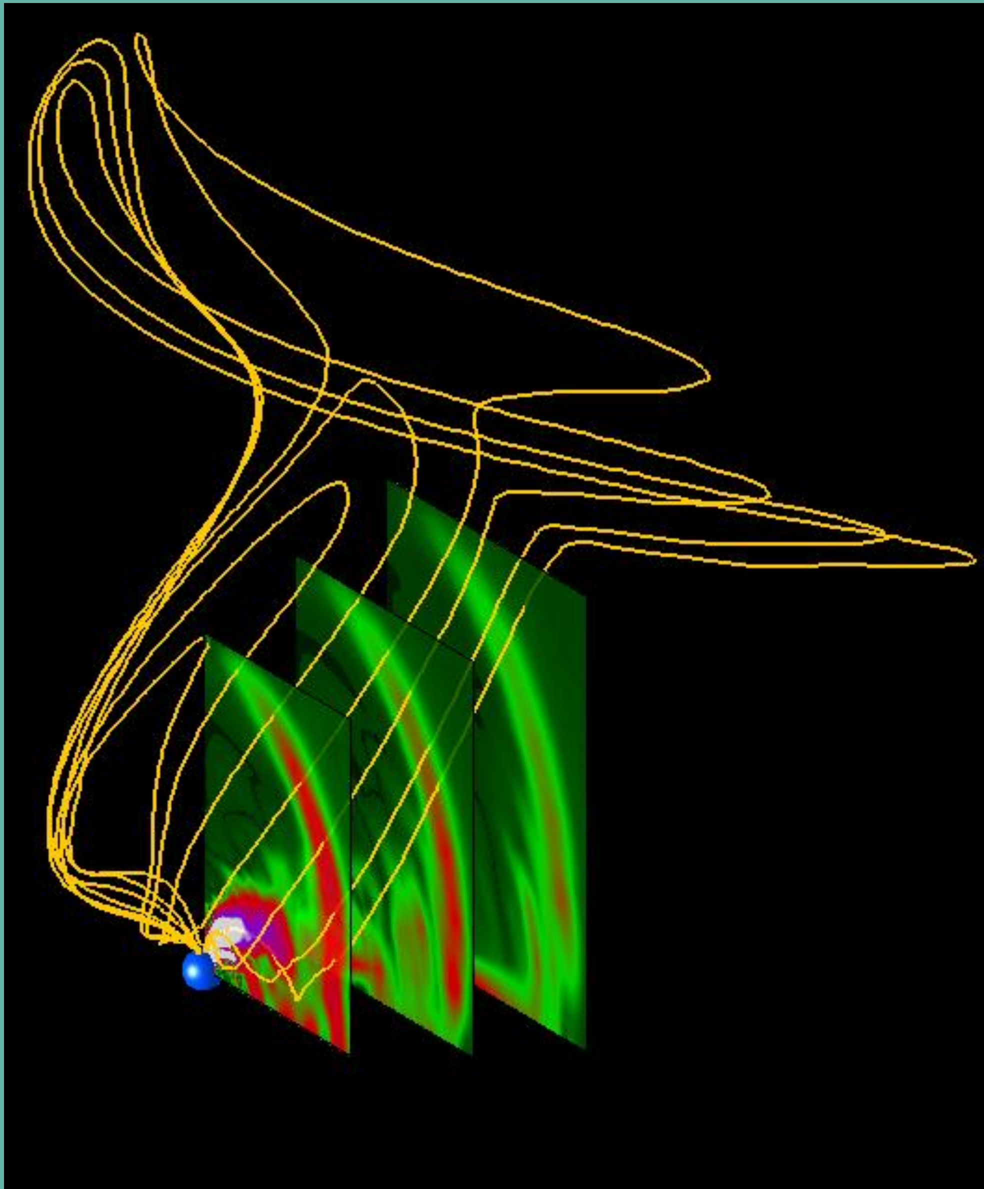
μέση οδός μαγνετοσφερα





Highlights in the History of Magnetospheric Concepts (3)

Dungey-Alfvén
ist die Über-Magnetosphaere



The Vasyliunas Criterion for Quantifying the Two Magnetosphere types

Vasyliunas (2004) divided magnetospheres into solar wind dominated (CF-like) and ionosphere dominated (DA-like) depending on whether the magnetic pressure generated by the reconnection-driven ionospheric current is, respectively, less than or greater than the solar wind dynamic pressure.

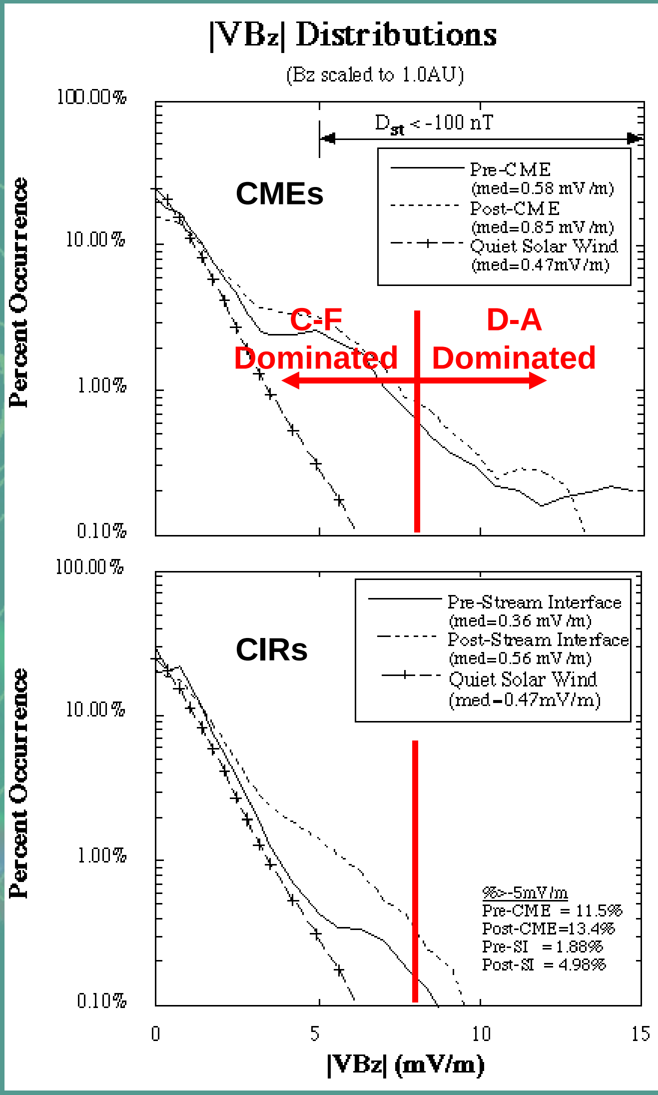
The operative criterion is

$\mu_o \Sigma_P V_A \varepsilon \sim 1$

Σ_P = ionospheric Pedersen conductance

V_A = Alfvén speed in the solar wind

ε = magnetic reconnection efficiency

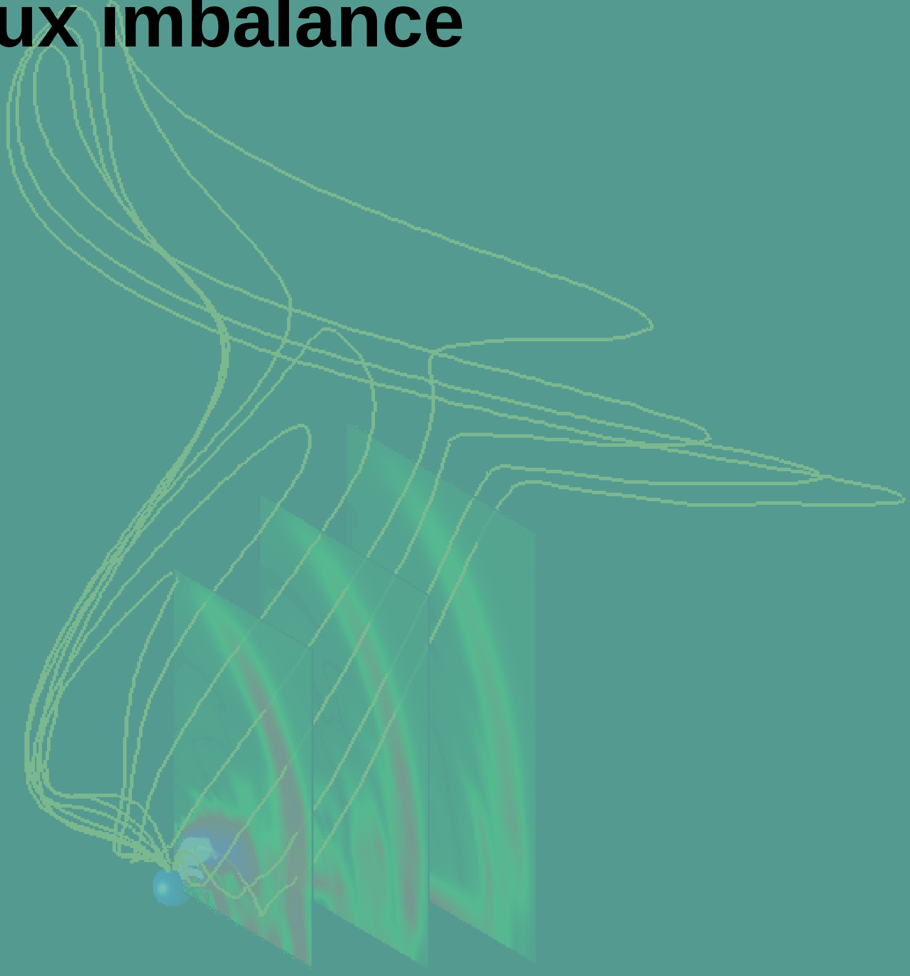


Lindsay et al., 1995

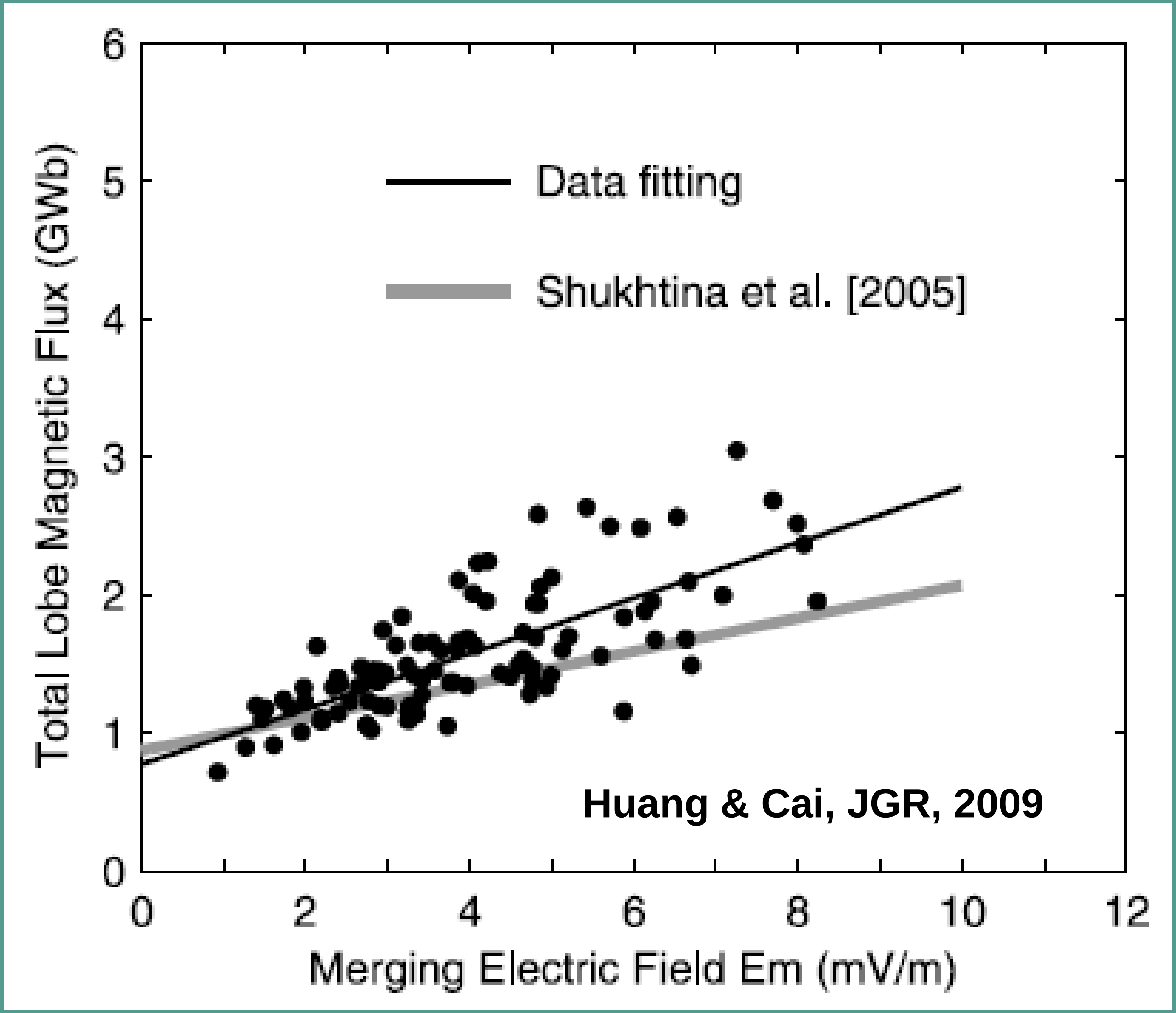
By this criterion, the standard magnetosphere is solar wind (C-F) dominated; the storm-time magnetosphere, ionosphere (D-A) dominated.

Properties of the Dungey-Alfvén Magnetosphere

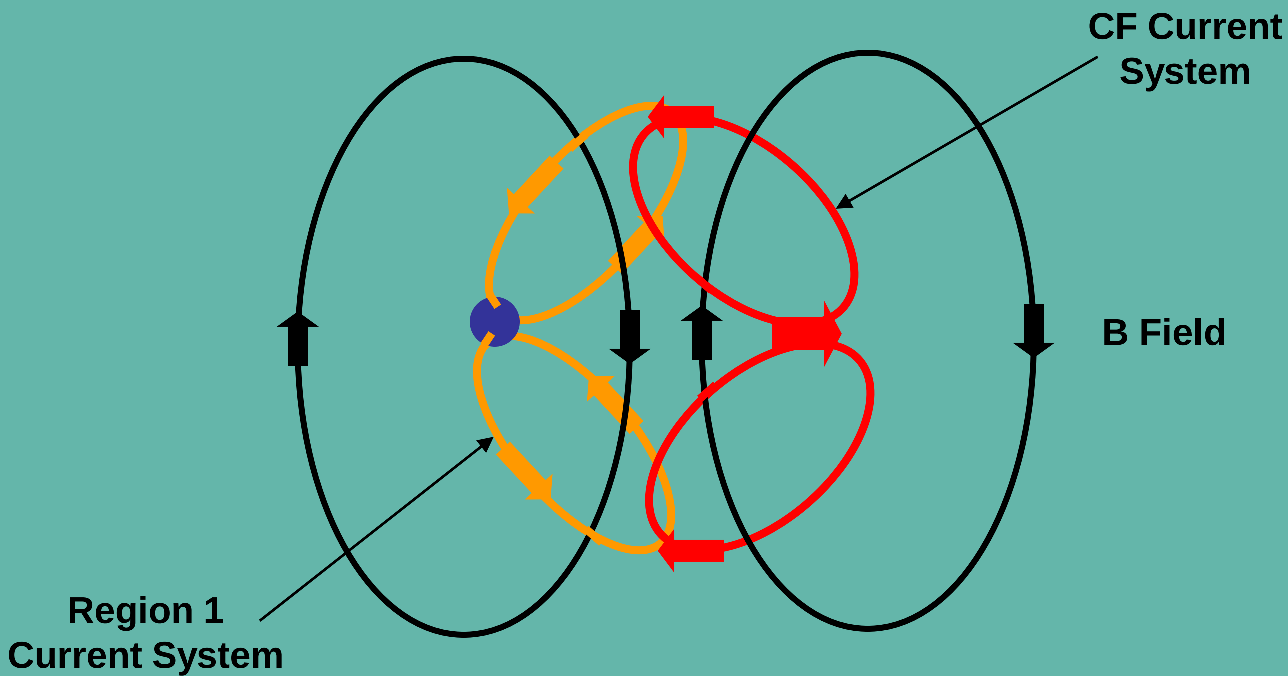
- **Huge dayside-nightside flux imbalance**



Massive Magnetic Flux Transfer



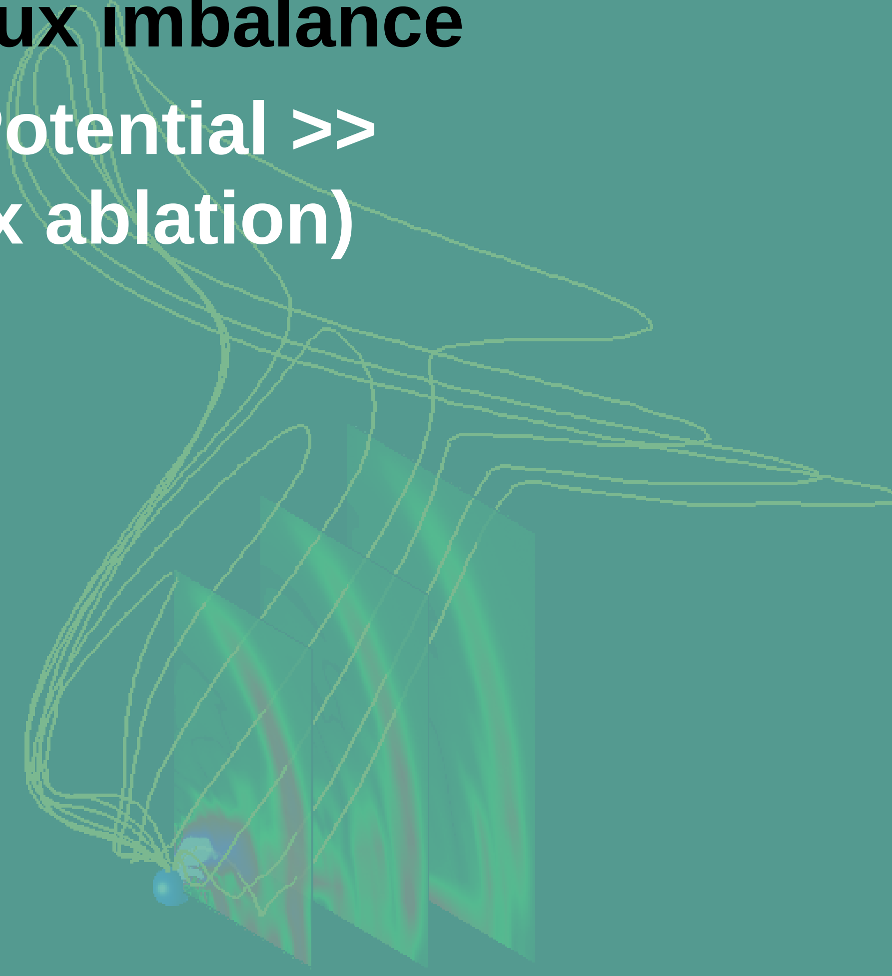
Explanation



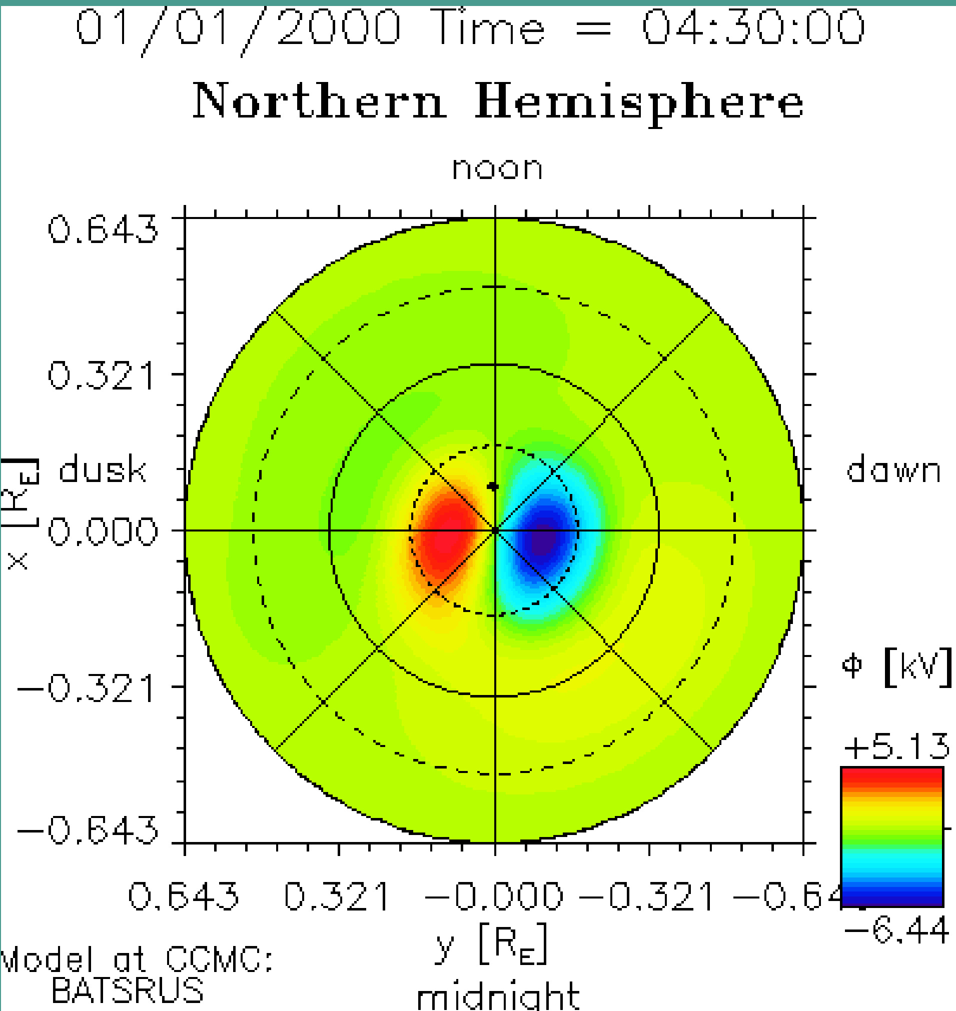
One consequence: Big EMF

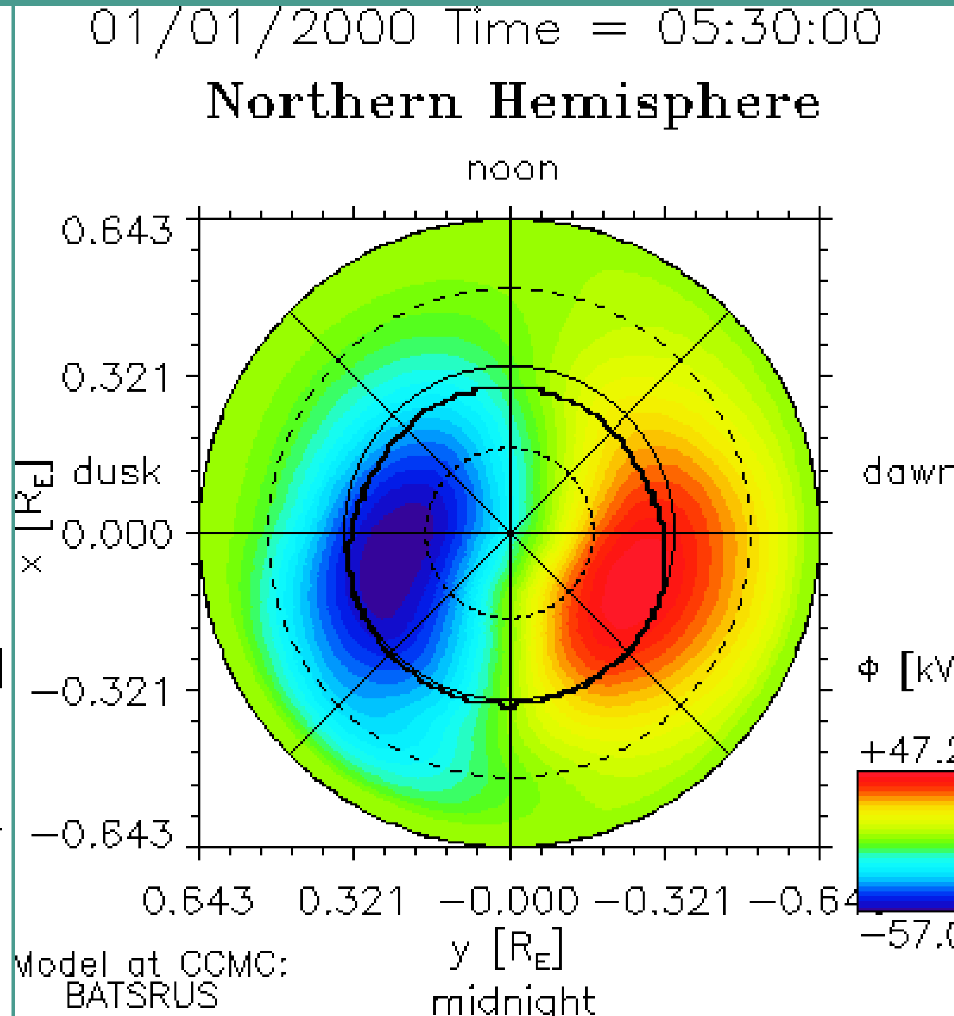
Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
- **- Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)**



Natasha_Buzulukova_093008_1 CCMC Run
IMF Bz goes from +10 nT to -10 nT at 4:30

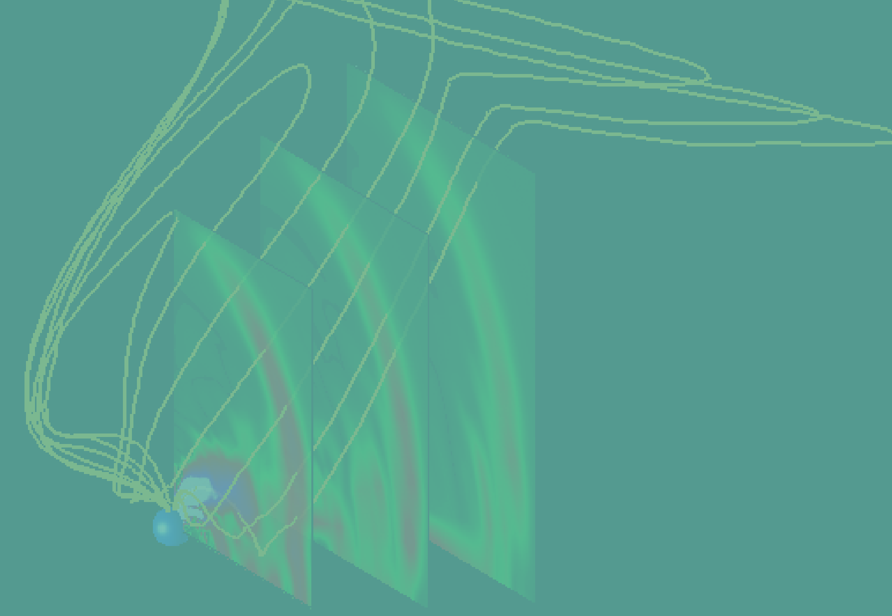


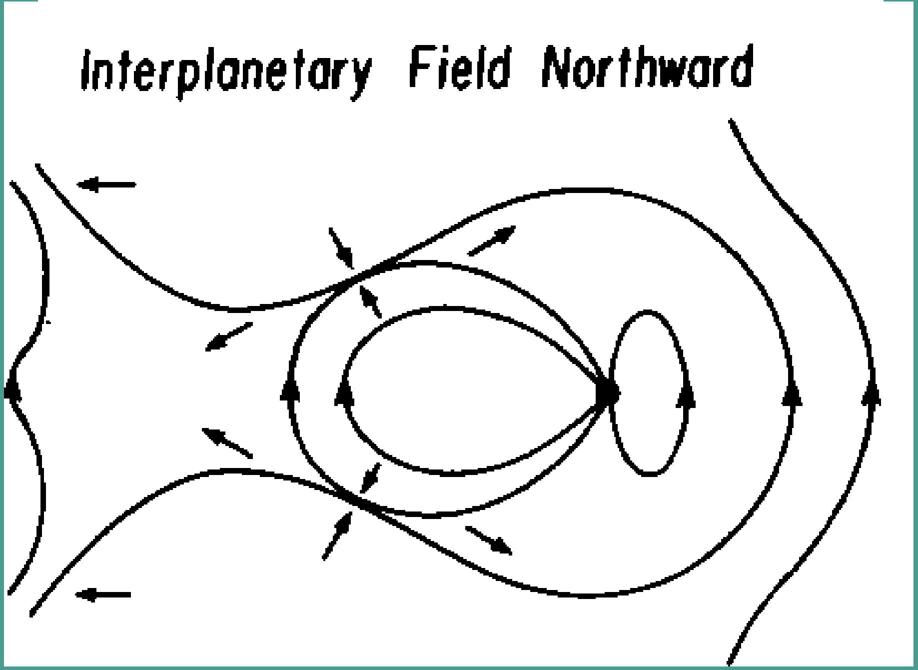


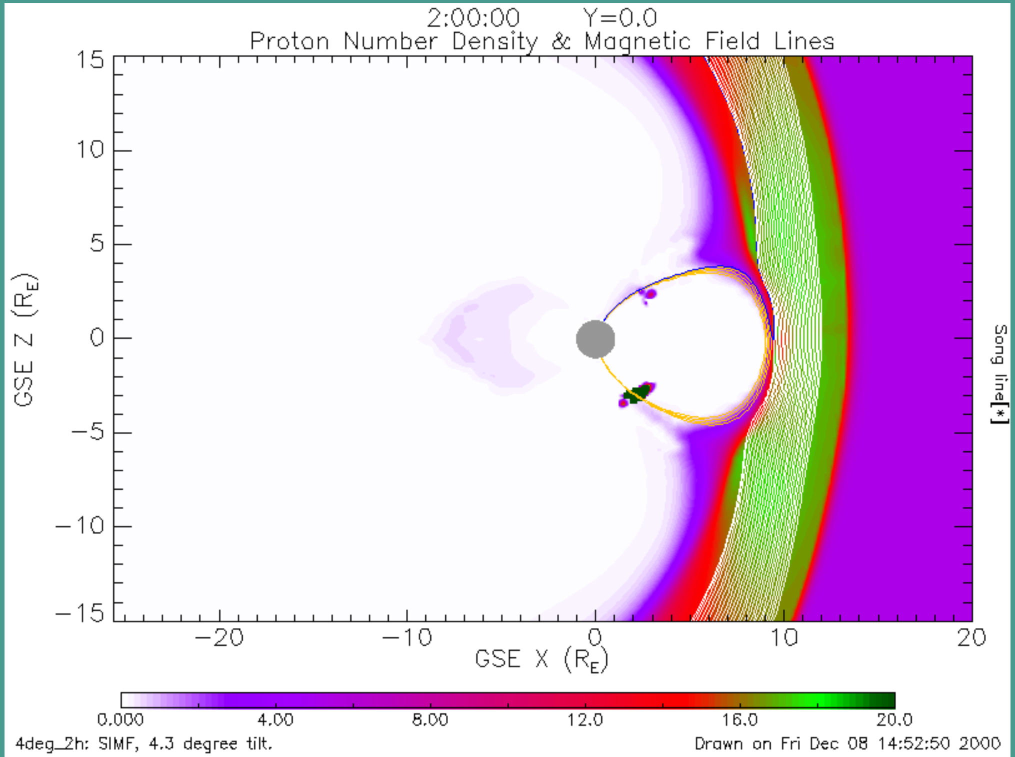
EMF = 257 kV

Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
- - Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)
- - An aside on flux accretion

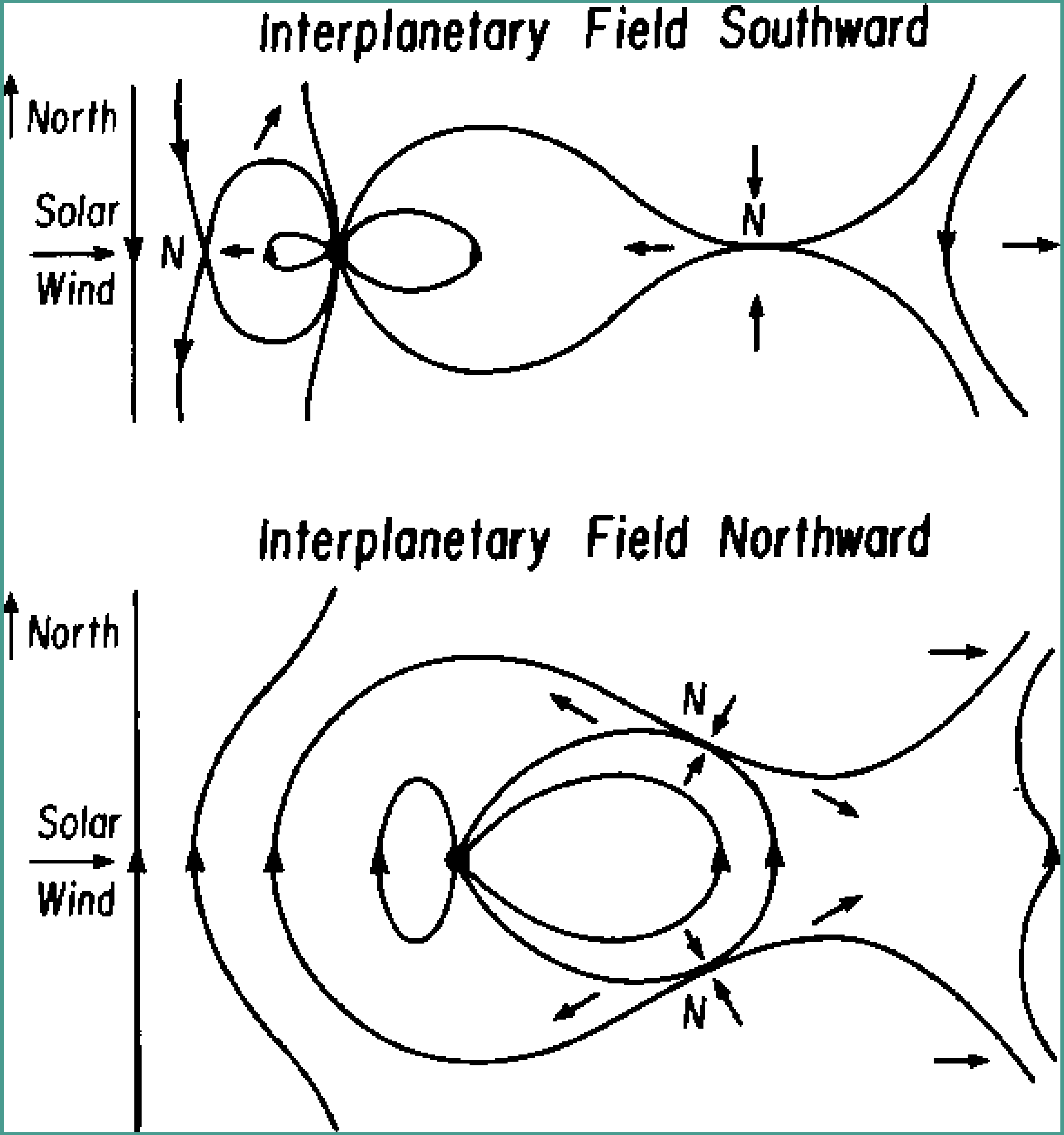



Interplanetary Field Northward


2:00:00 Y=0.0
Proton Number Density & Magnetic Field Lines
15
10
5
0
−5
−10
−15
GSE Z (R_E)
−20
−10
0
10
20
GSE X (R_E)
0.000
4.00
8.00
12.0
16.0
20.0
Song line[*]
4deg_2h: SIMF, 4.3 degree tilt.
Drawn on Fri Dec 08 14:52:50 2000

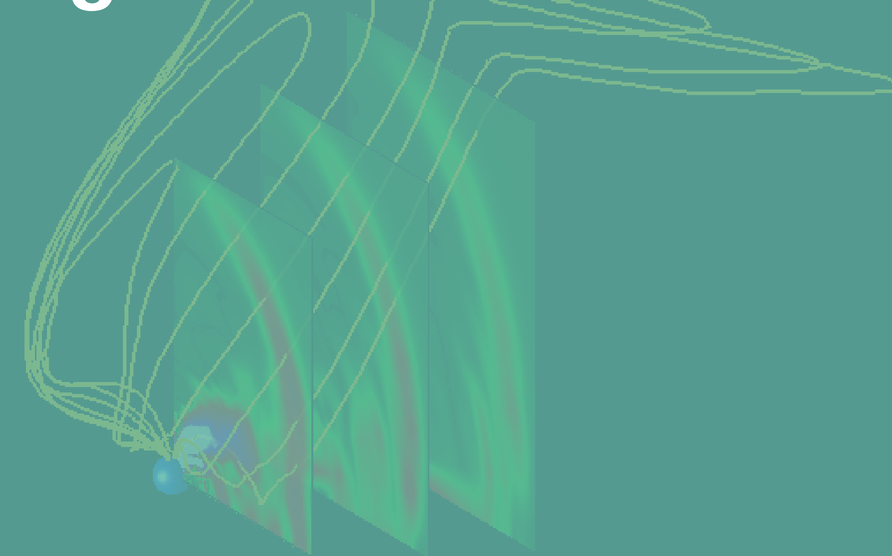
Dayside Shrinks by Flux Ablation

Dayside Grows by Flux Accretion

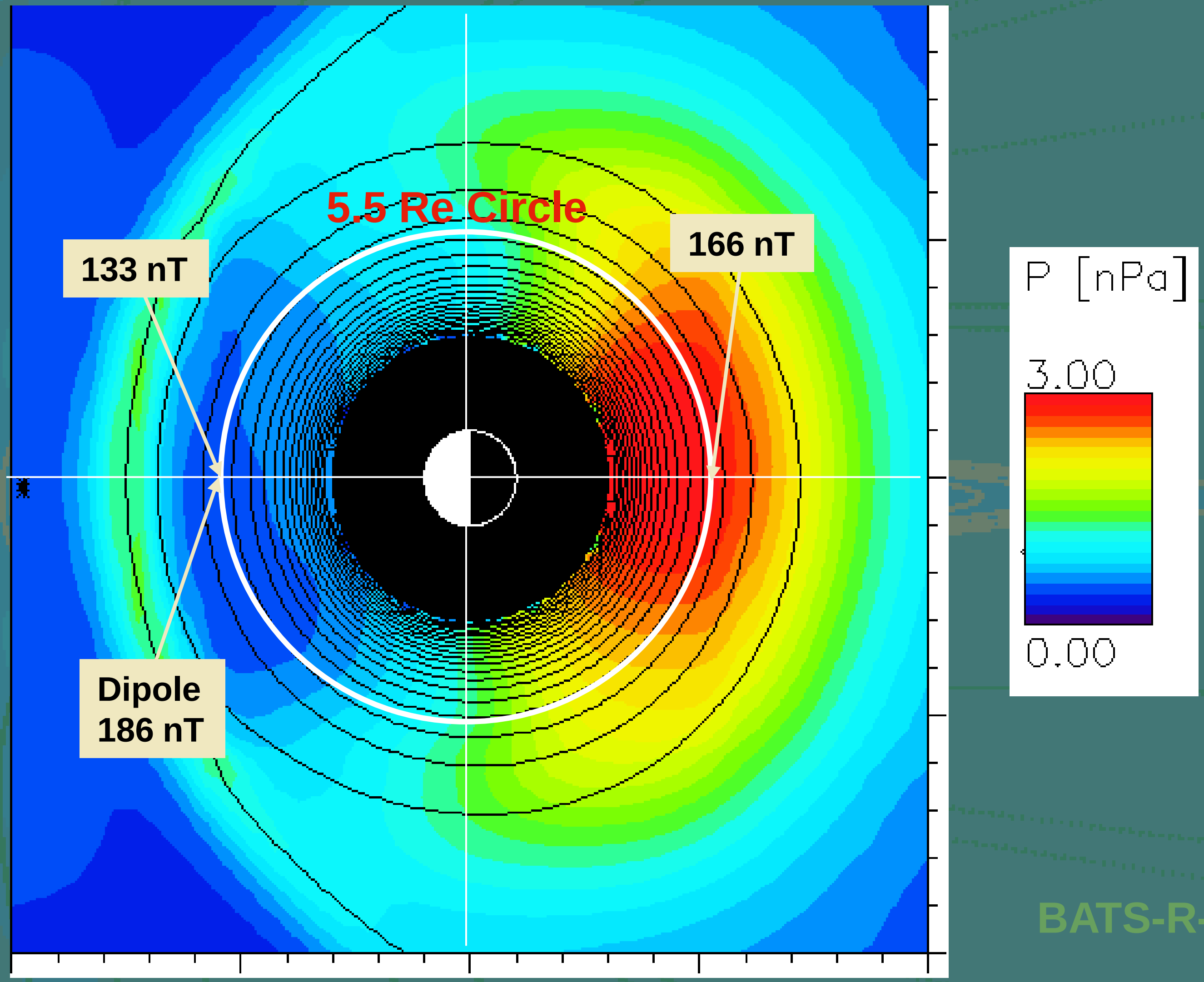


Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
- **- Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)**
- **- Dayside field weakening**



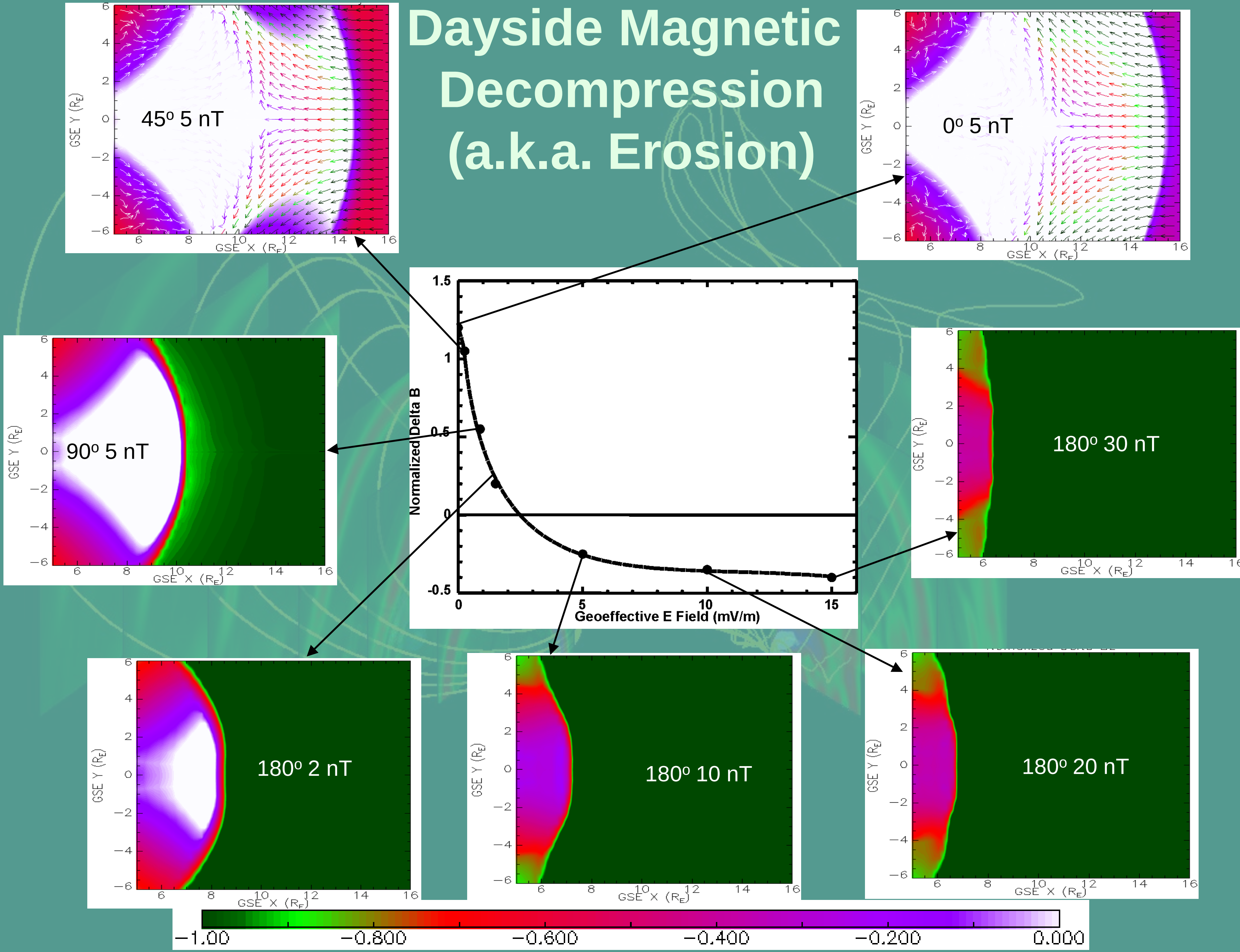
Dayside Field Weakening



BATS-R-US

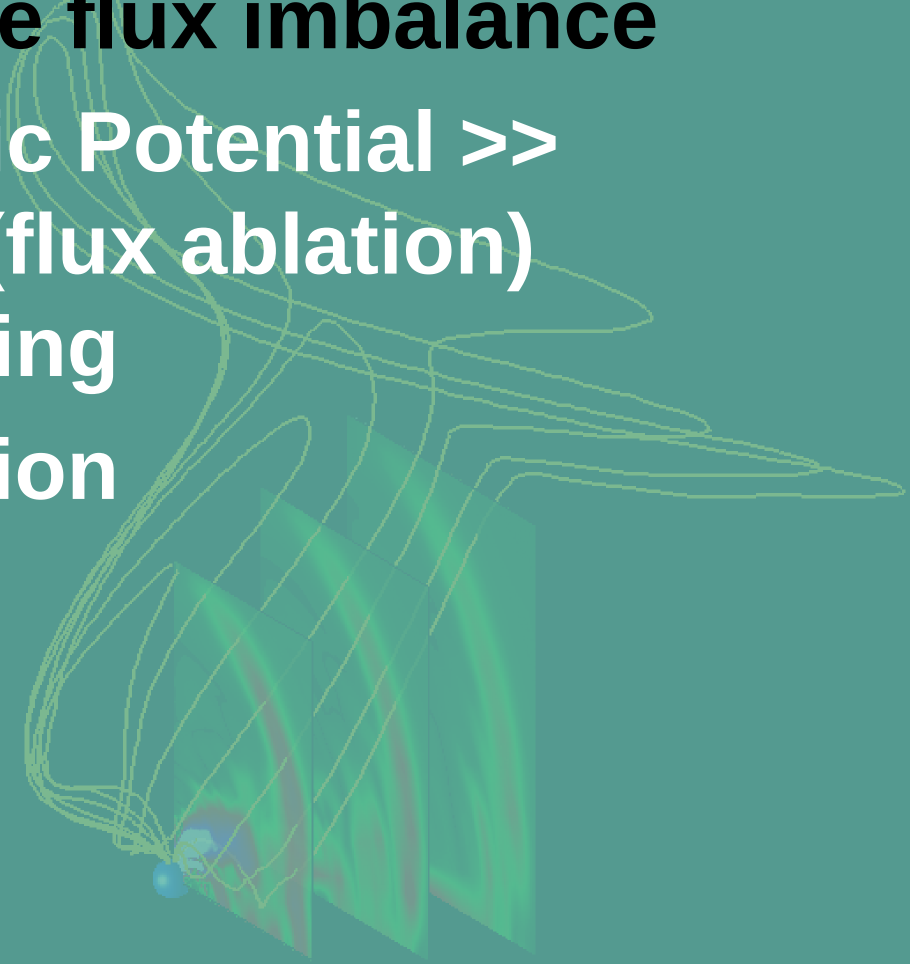
IMF = (0, 0, -20) nT

Dayside Magnetic Decompression (a.k.a. Erosion)

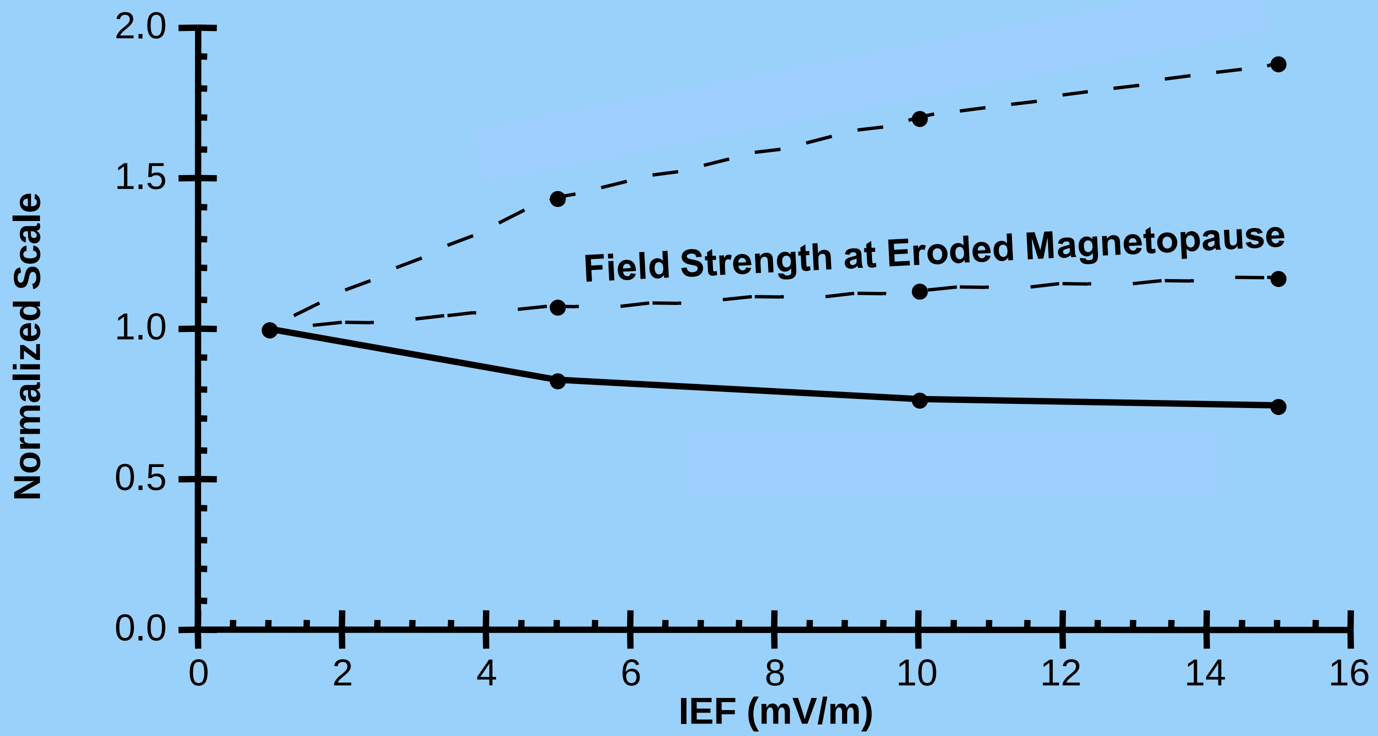


Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
  - **- Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)**
  - **- Dayside field weakening**
  - **- Magnetospheric erosion**



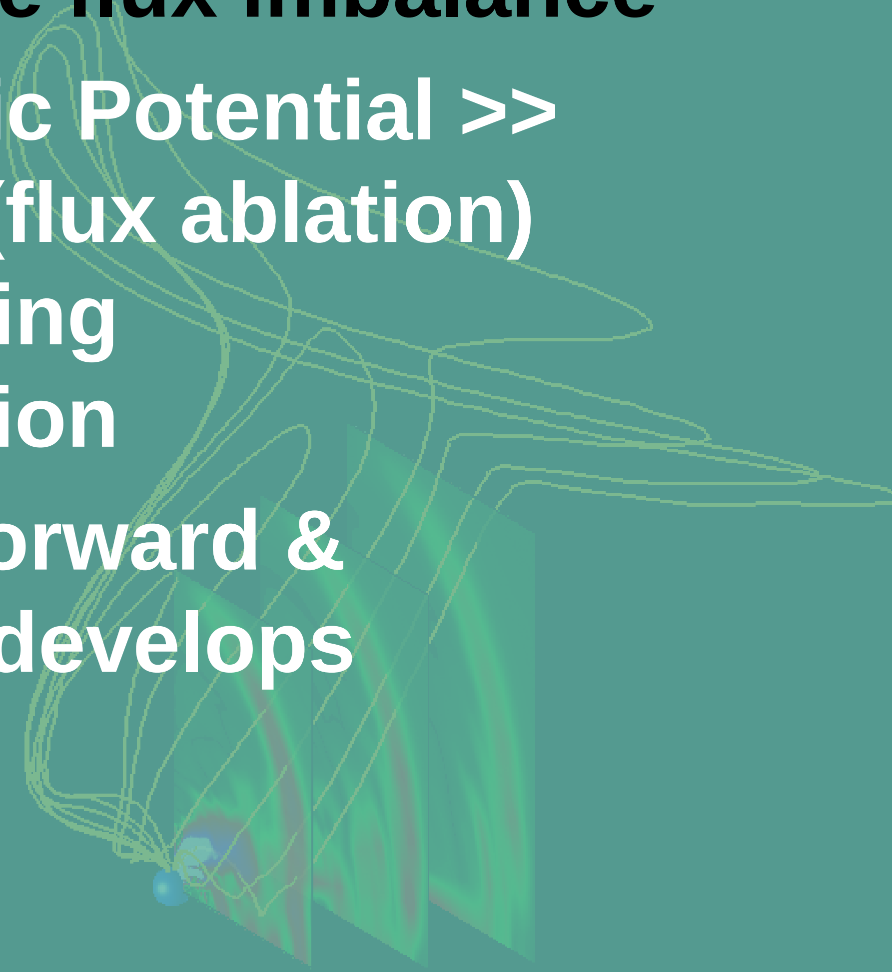
Equivalence of Magnetospheric Erosion and Region 1 Current System Buildup

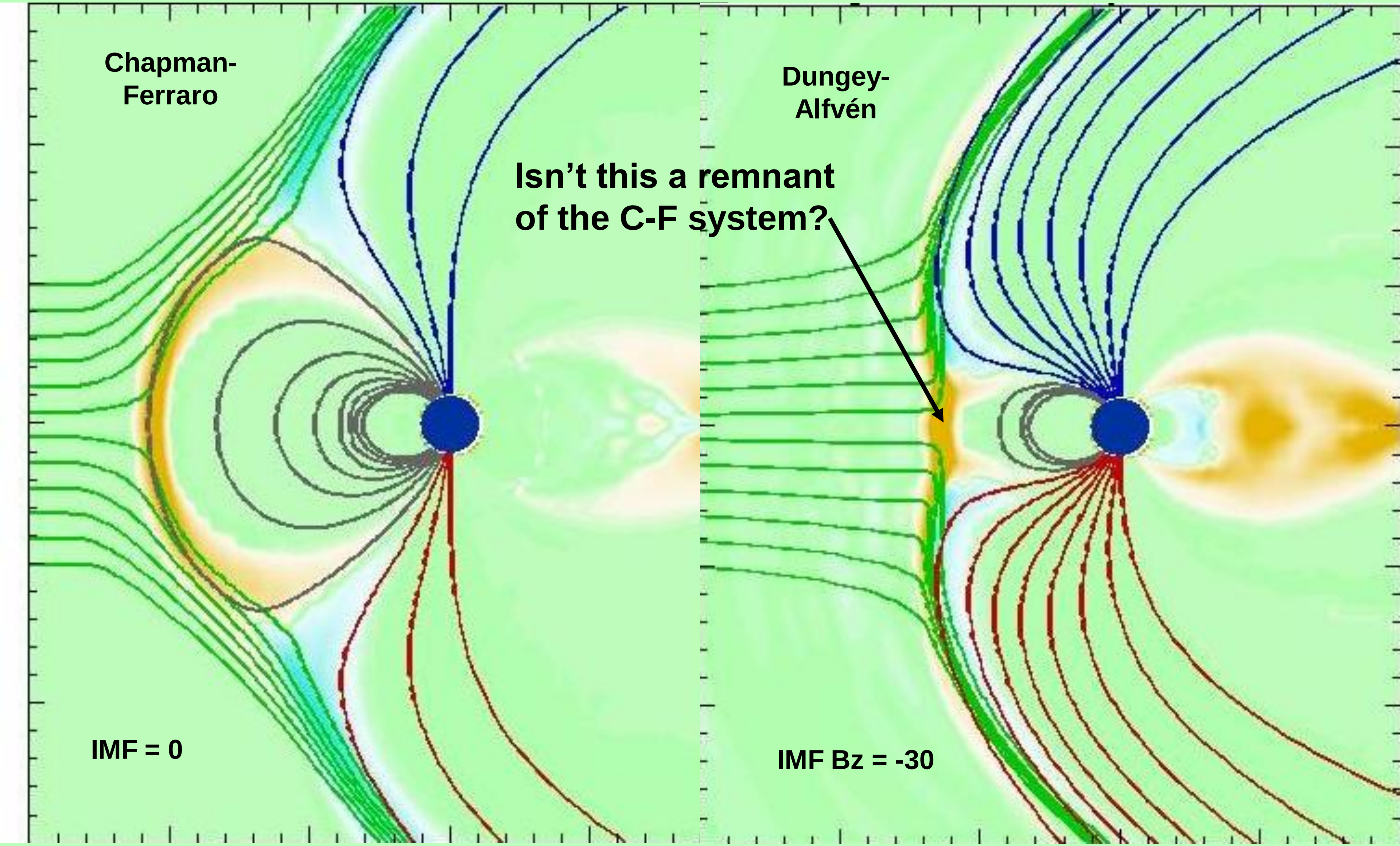


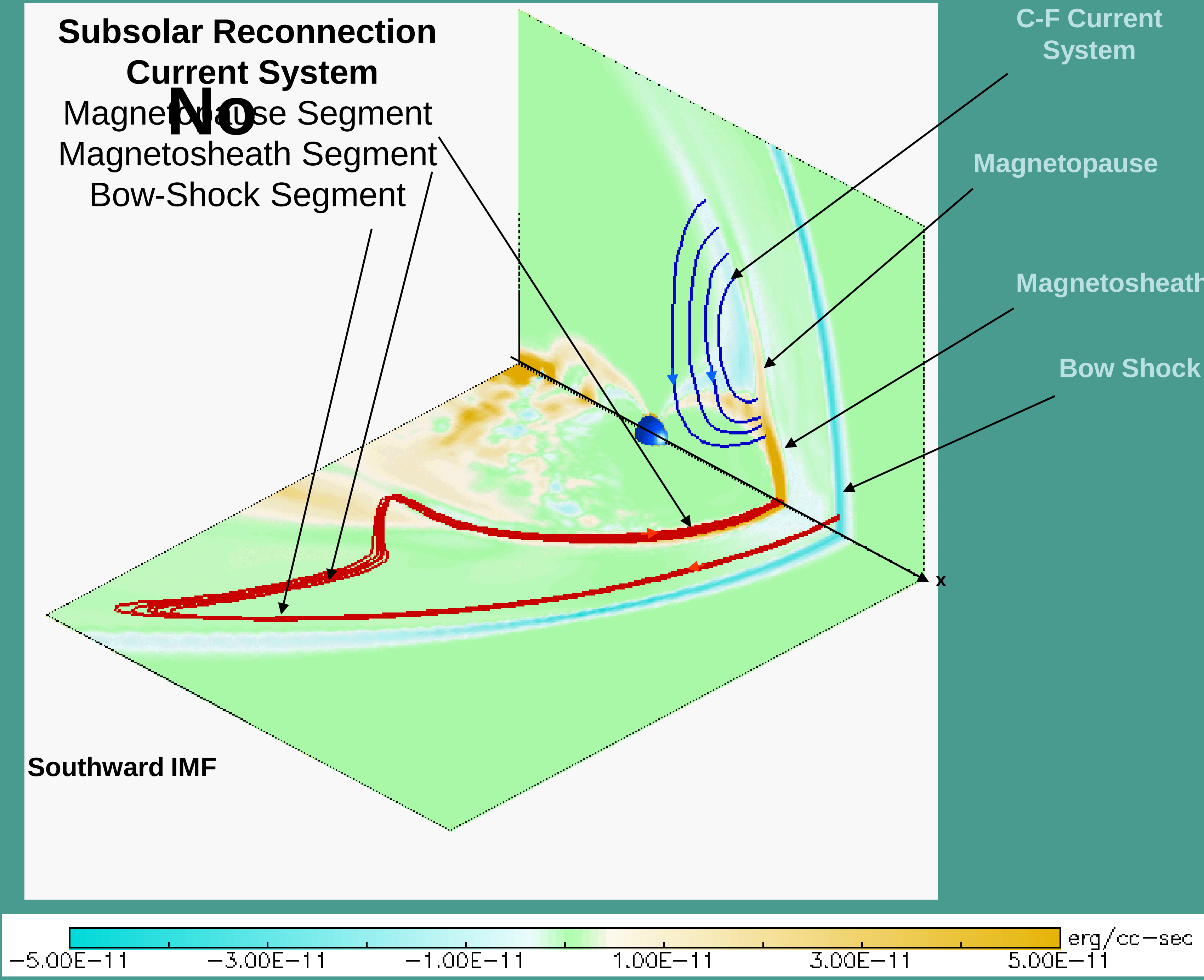
Boundary moves earthward to hold stagnation field strength ~ constant as region 1 current increases. This is magnetospheric erosion.

Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
  - Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)
  - Dayside field weakening
  - Magnetospheric erosion
  - Cusps migrate equatorward & reconnection dimple develops

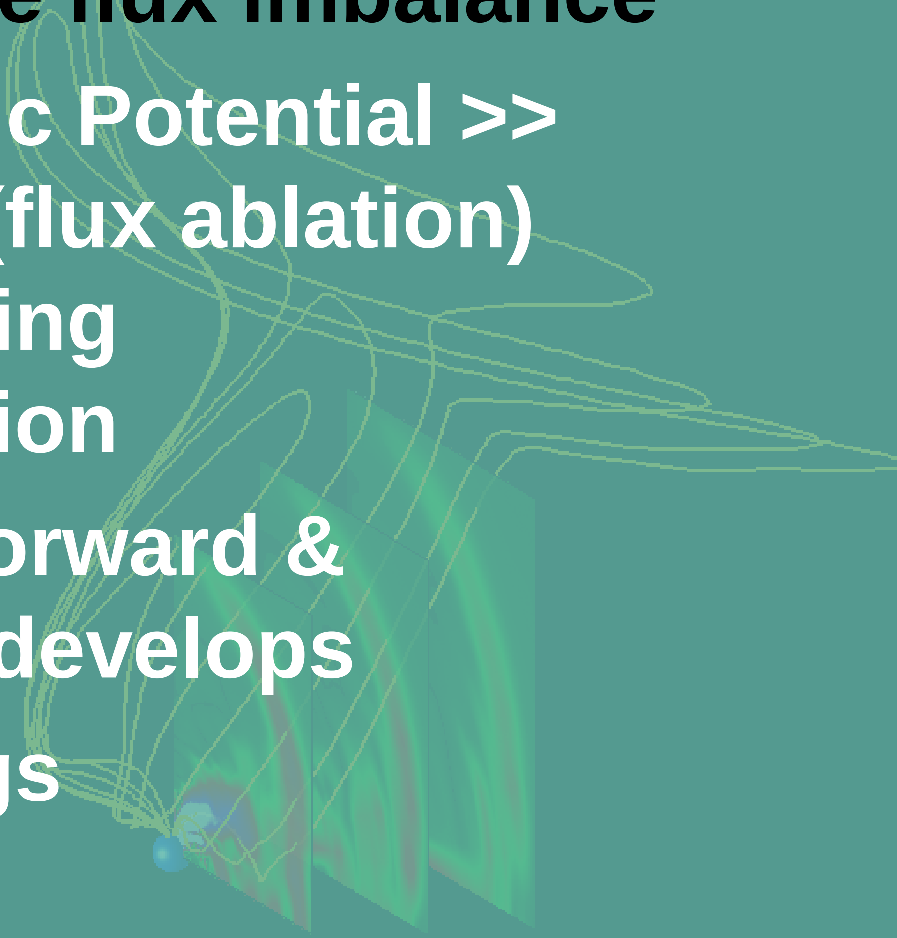



Chapman-
Ferraro
Dungey-
Alfvén
Isn’t this a remnant
of the C-F system?
IMF = 0
IMF Bz = -30

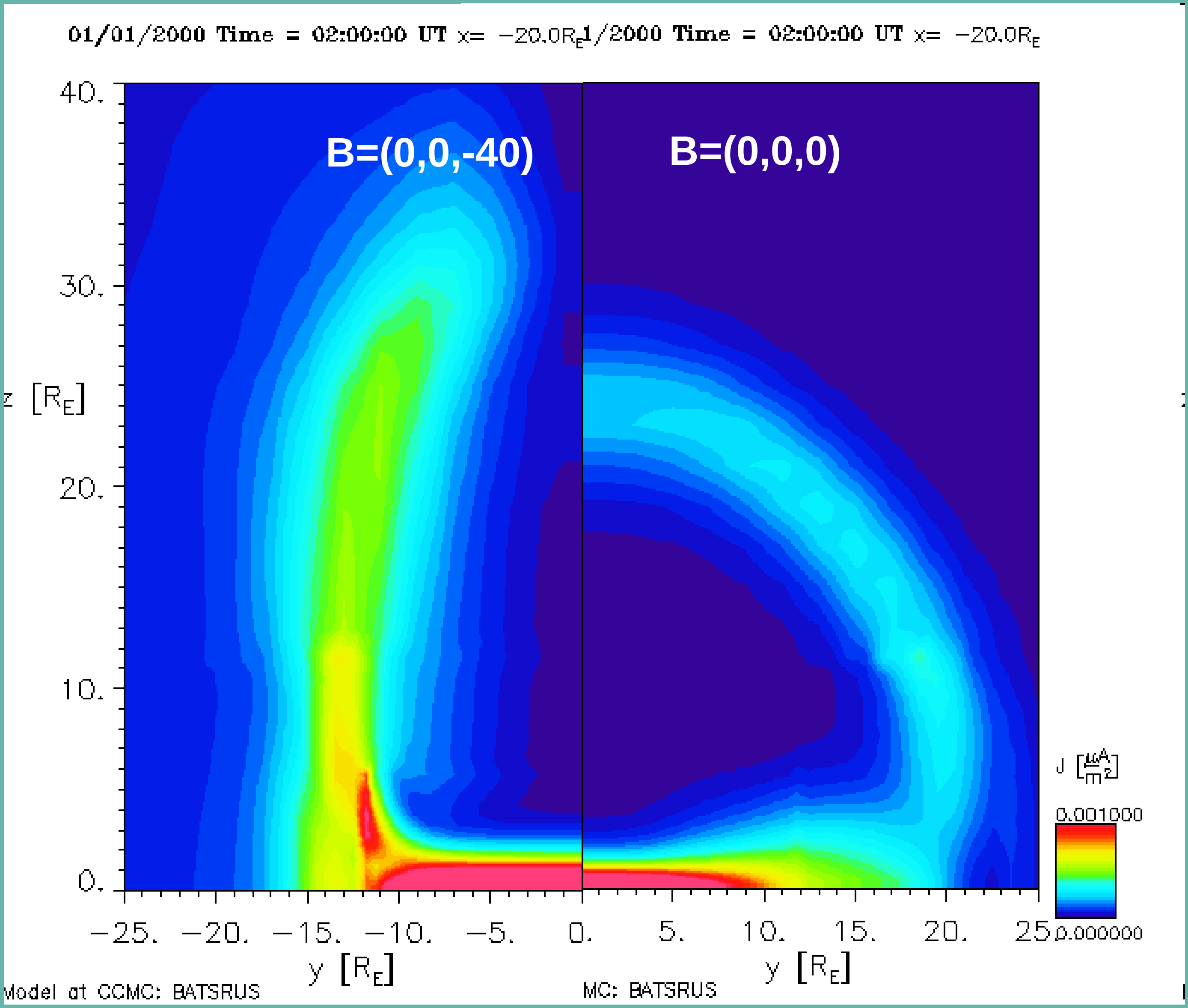

Subsolar Reconnection Current System
No
Magnetopause Segment
Magnetosheath Segment
Bow-Shock Segment
C-F Current System
Magnetopause
Magnetosheath
Bow Shock
x
Southward IMF
erg/cc−sec
−5.00E−11
−3.00E−11
−1.00E−11
1.00E−11
3.00E−11
5.00E−11

Properties of the Dungey-Alfvén Magnetosphere

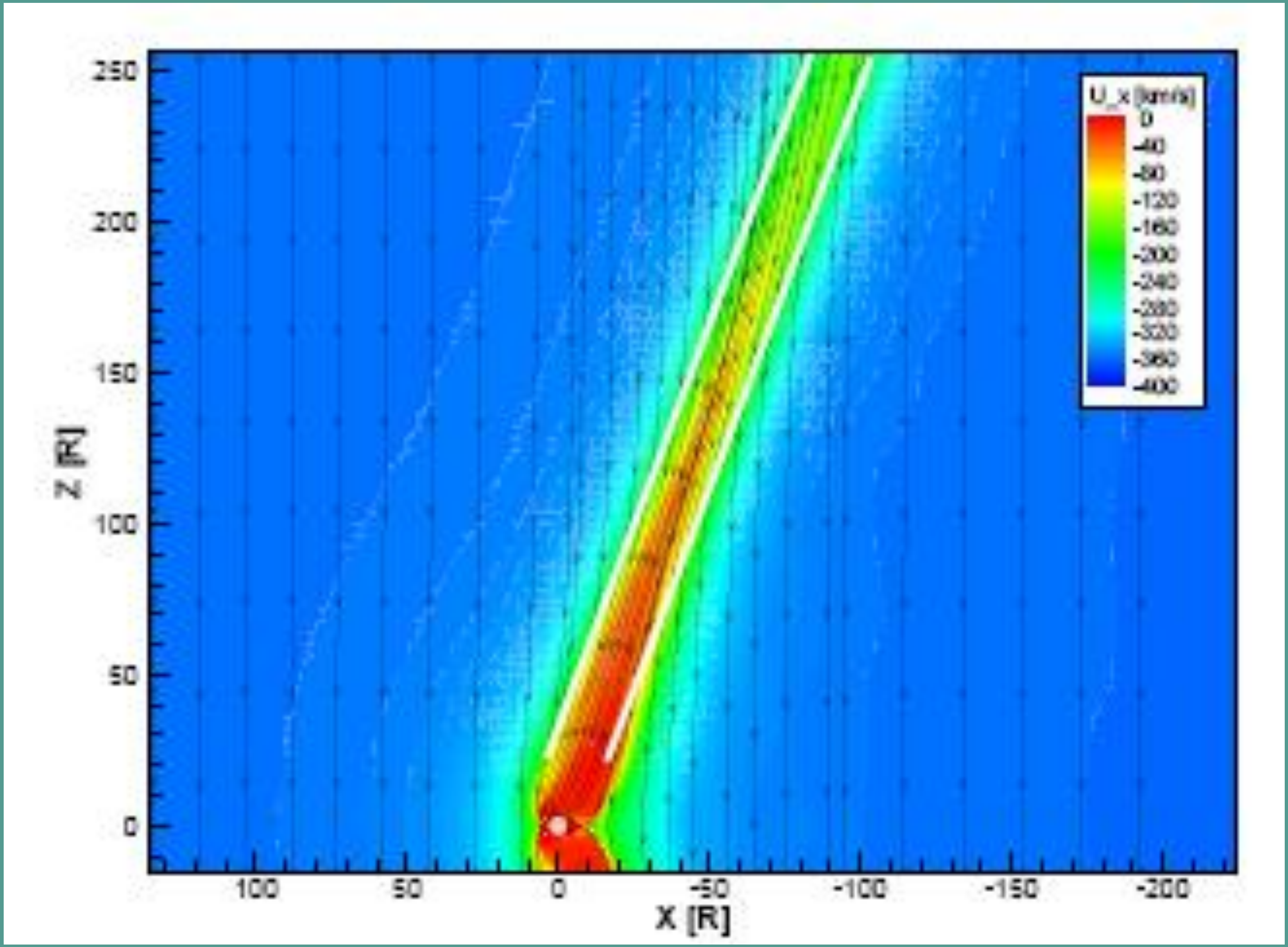
- **Huge dayside-nightside flux imbalance**
- - Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)
  - Dayside field weakening
  - Magnetospheric erosion
- - Cusps migrate equatorward & reconnection dimple develops
- - Tail morphs into wings



Tail Morphing into Wings



Ridley (2007) Alfvén Wings



Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**

  - Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)

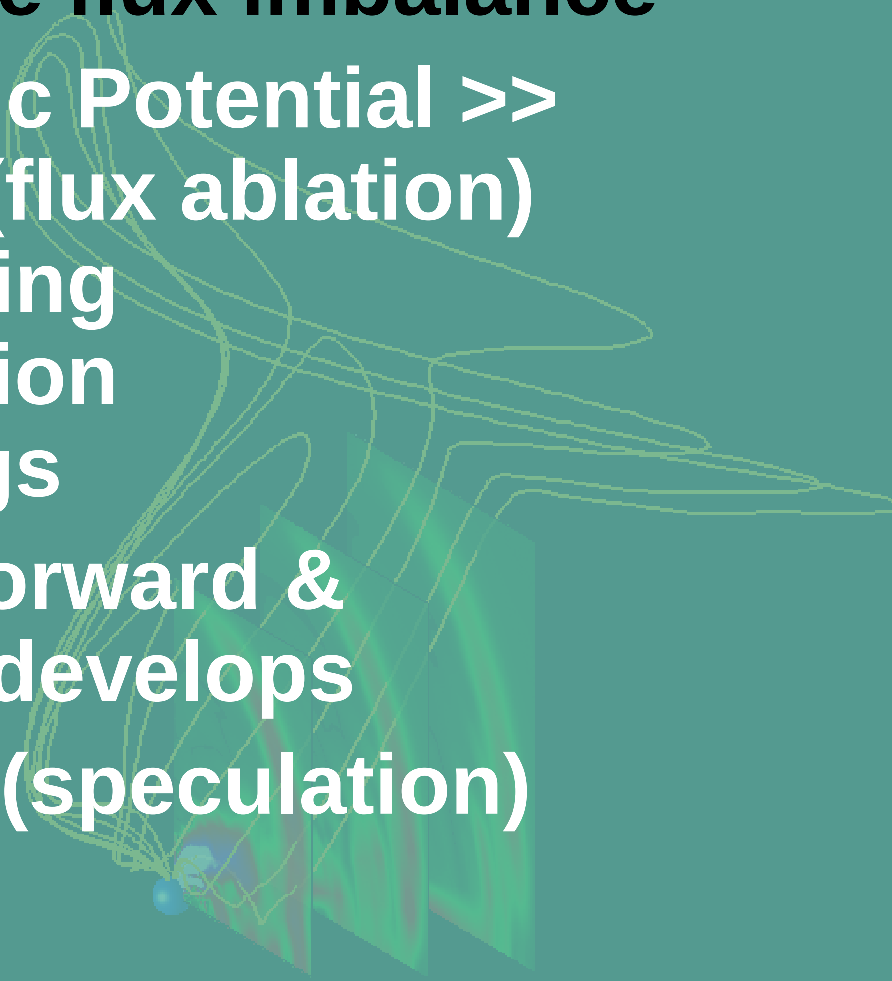
  - Dayside field weakening

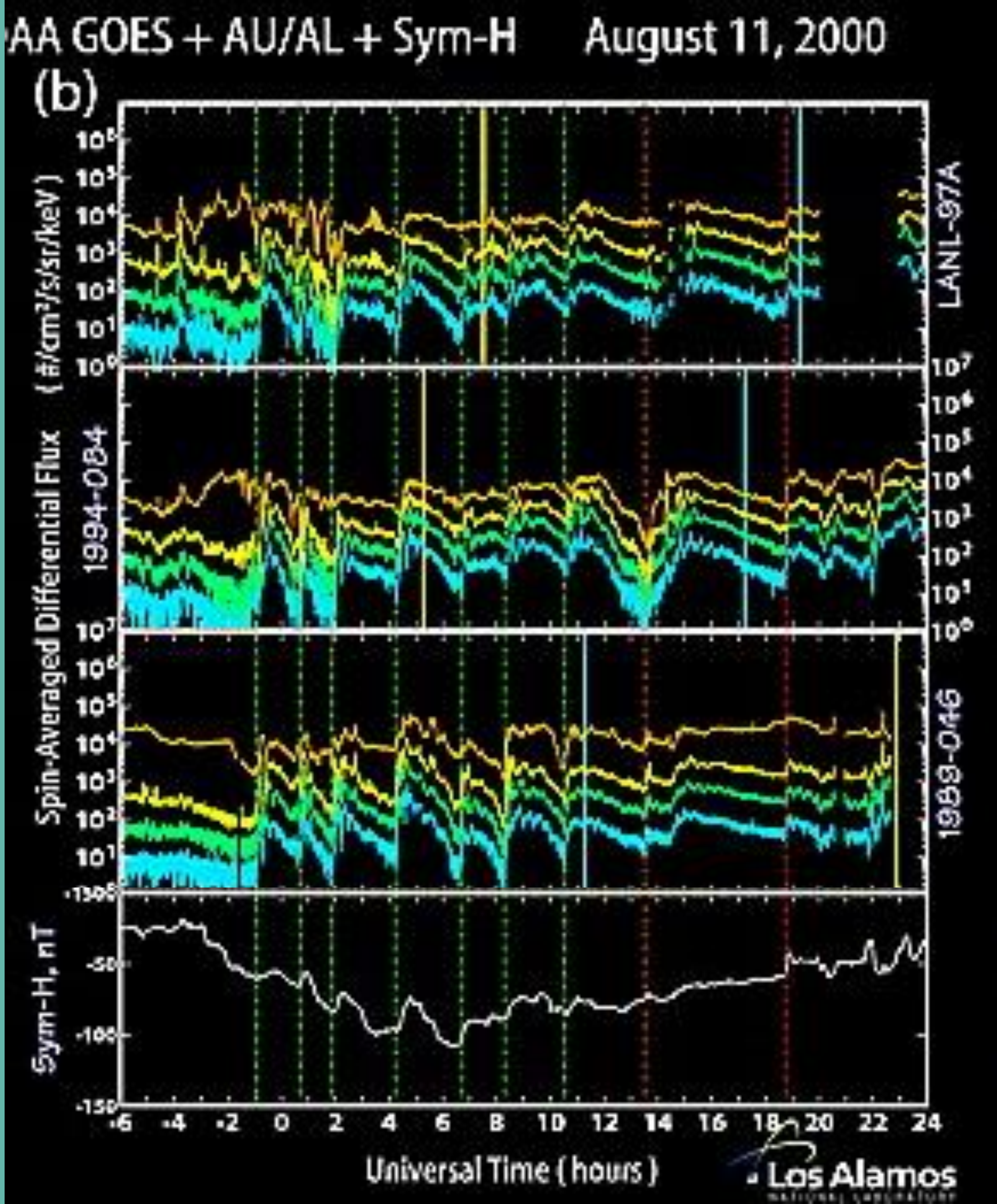
  - Magnetospheric erosion

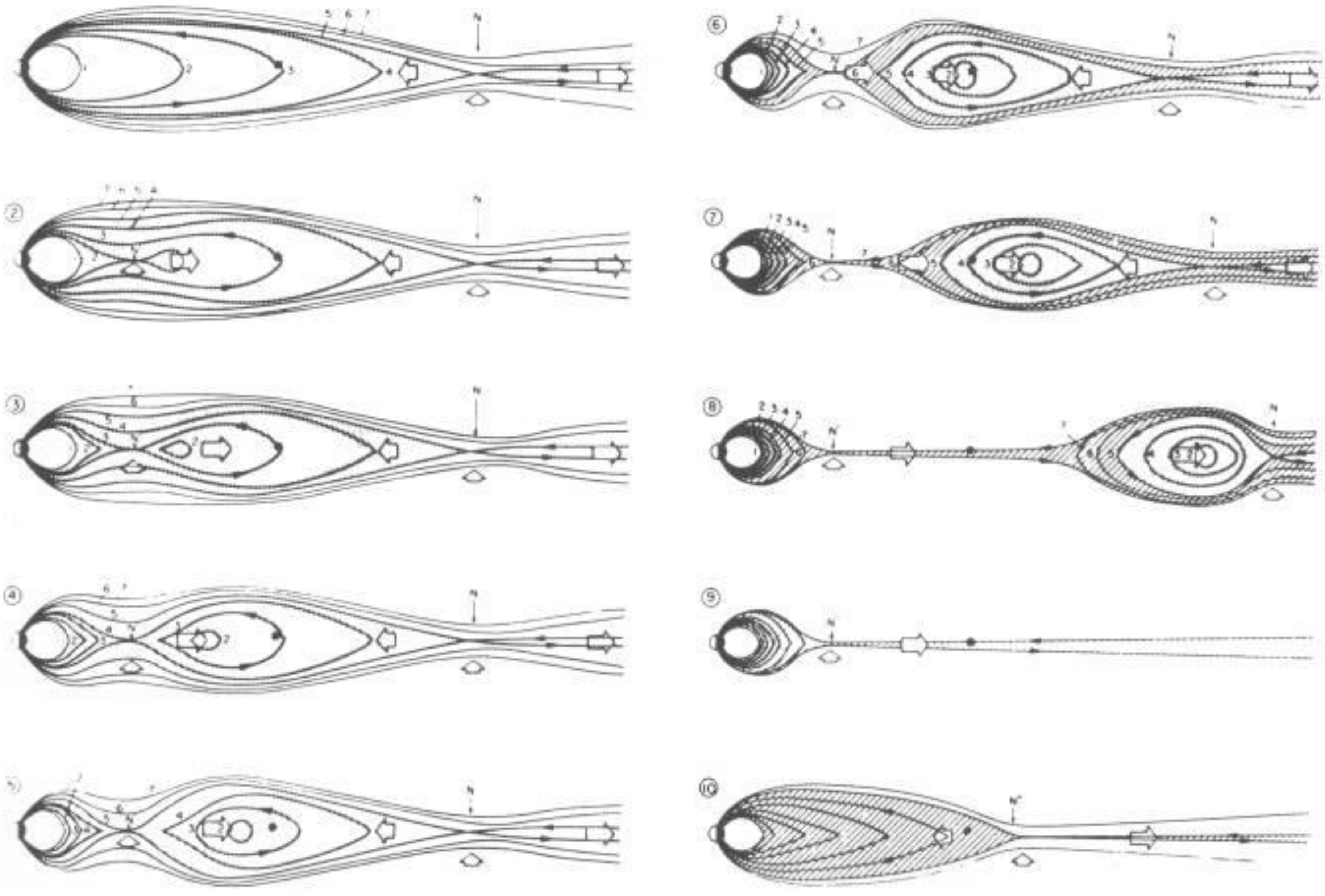
  - Tail morphs into wings

  - Cusps migrate equatorward & reconnection dimple develops

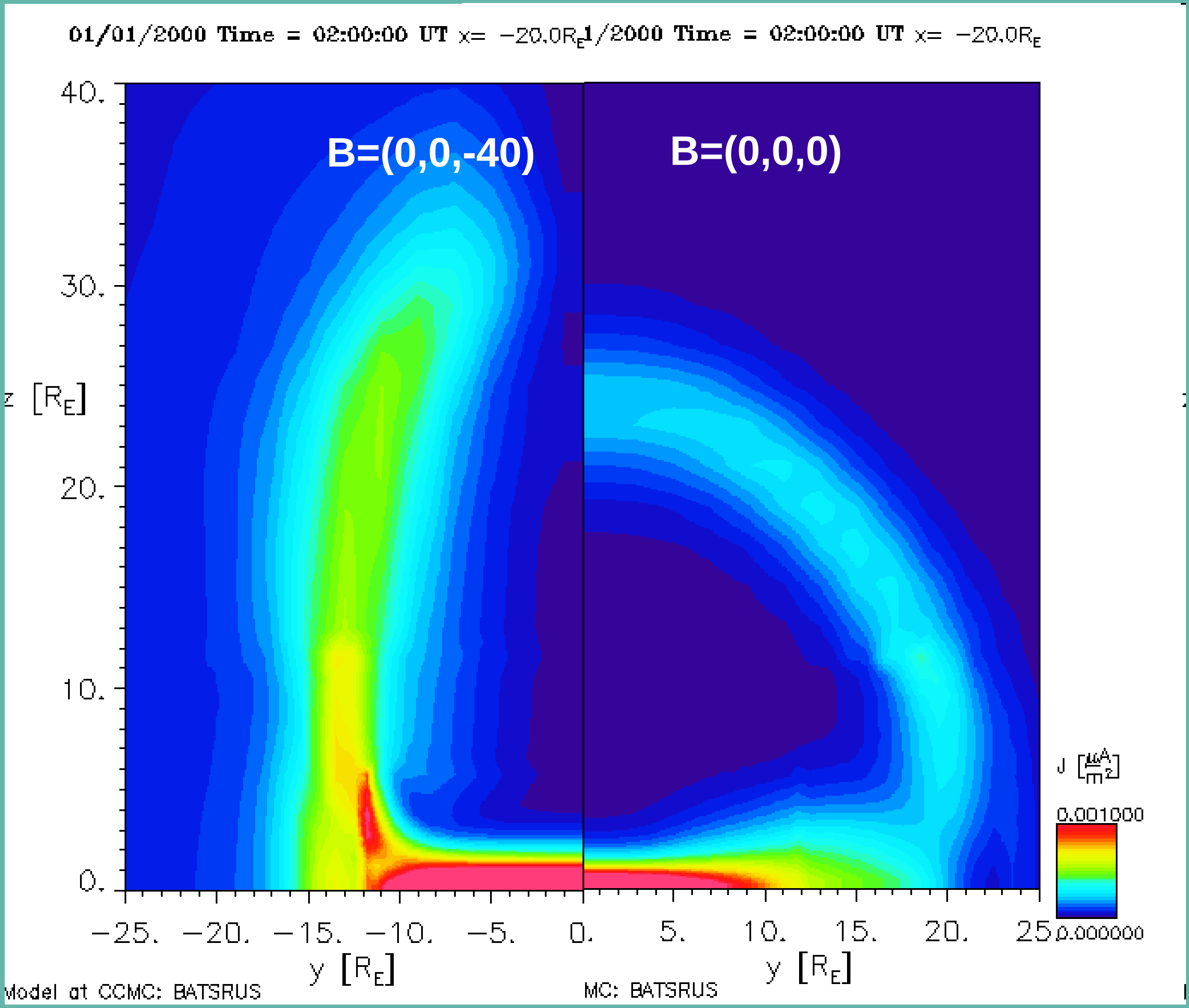
  - Sawtooth substorms (speculation)




AA GOES + AU/AL + Sym-H August 11, 2000
(b)
Spin-Averaged Differential Flux (#/cm²/s/sr/keV)
LANL-97A
1994-084
1989-046
Sym-H, nT
Universal Time (hours)
Los Alamos

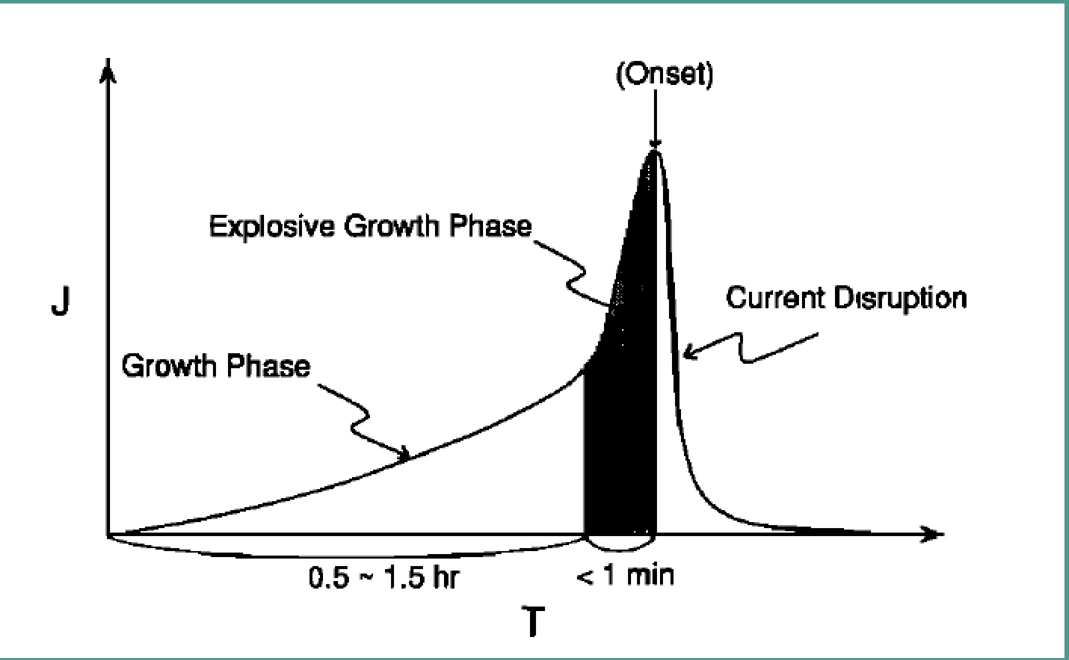


Hones Conceptual Substorm Model


01/01/2000 Time = 02:00:00 UT x= −20.0R_E
1/2000 Time = 02:00:00 UT x= −20.0R_E
B=(0,0,-40)
B=(0,0,0)
z [R_E]
40.
30.
20.
10.
0.
−25. −20. −15. −10. −5. 0. 5. 10. 15. 20. 25
y [R_E]
y [R_E]
J [μA/m²]
0.001000
0.000000
Model at CCMC: BATSRUS
MC: BATSRUS

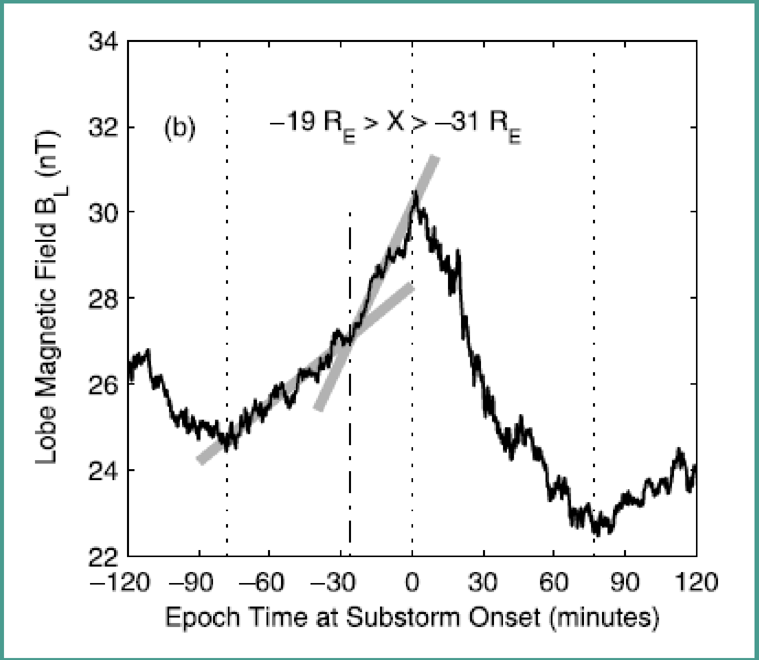
Regular Substorms

Ohtani et al., 1992

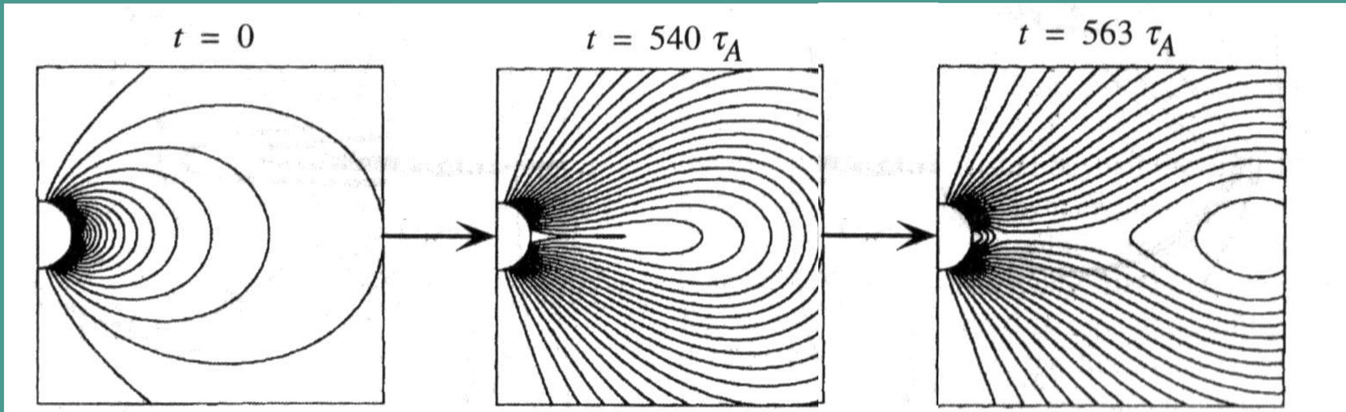


Sawtooth Substorms

Huang & Cai, 2009



CMEs

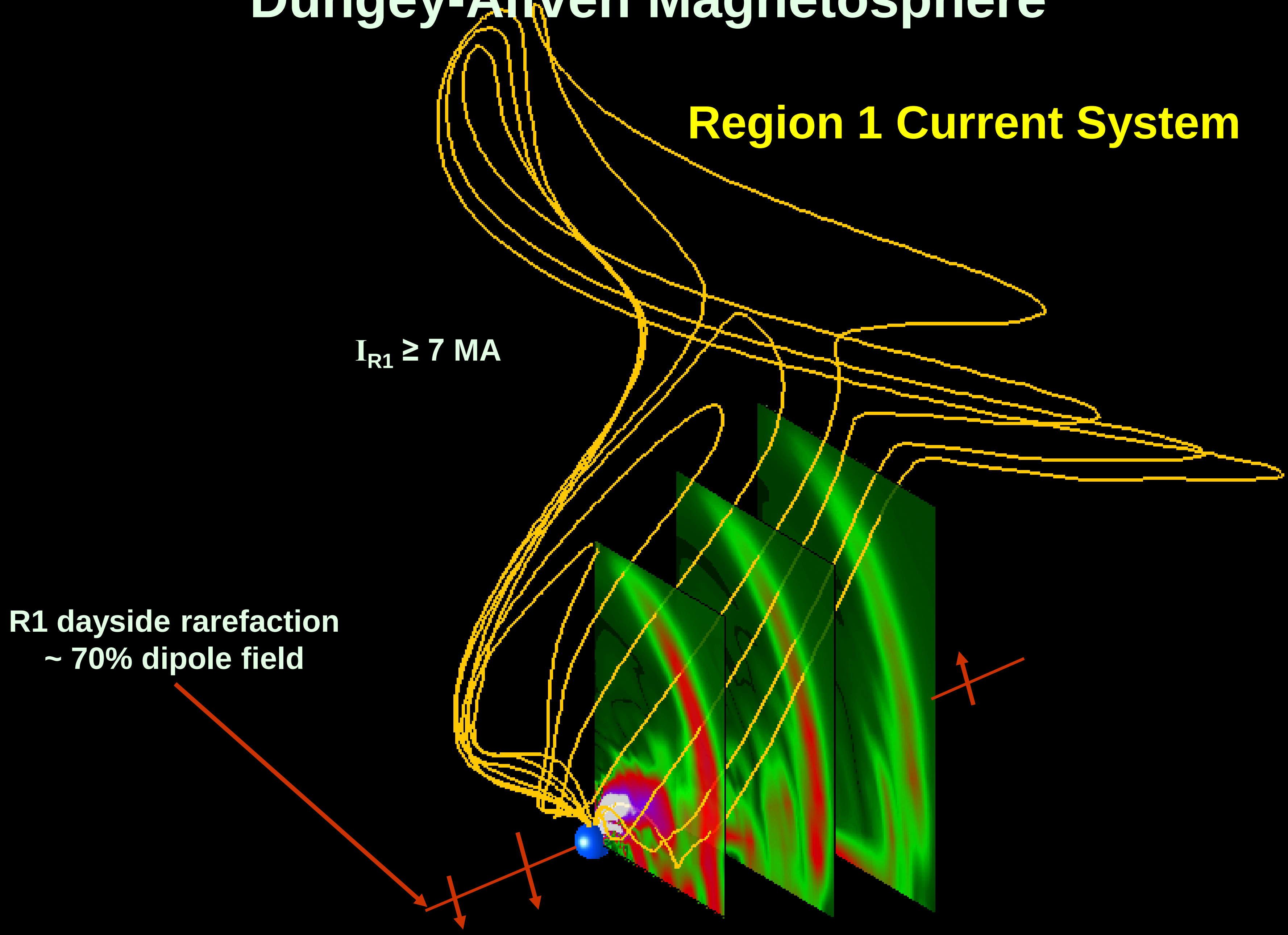


Mikic and Linker

Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
  - Trans-magnetospheric Potential >> Transpolar Potential (flux ablation)
  - Dayside field weakening
  - Magnetospheric erosion
  - Tail morphs into wings
  - Cusps migrate equatorward & reconnection dimple develops
  - Sawtooth substorms
- **Force reversal and amplification**

Dungey-Alfvén Magnetosphere

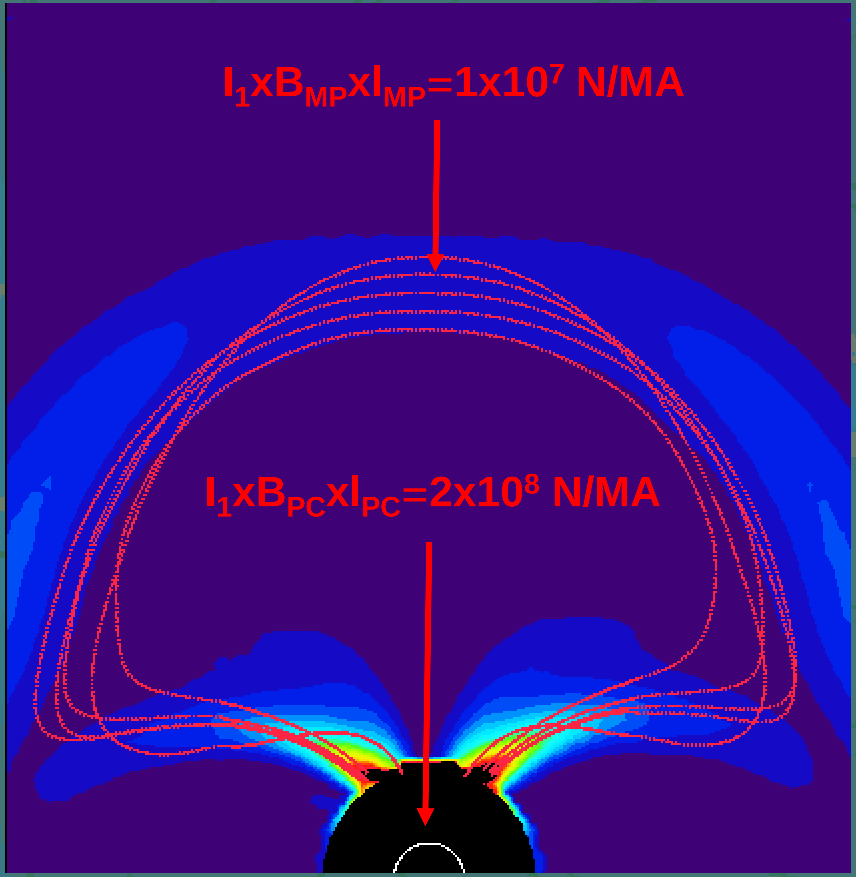


Magnetic gradient pushes Earth toward the Sun.

Region 1 Force Amplified by Dipole Interaction

Back of the envelope estimate

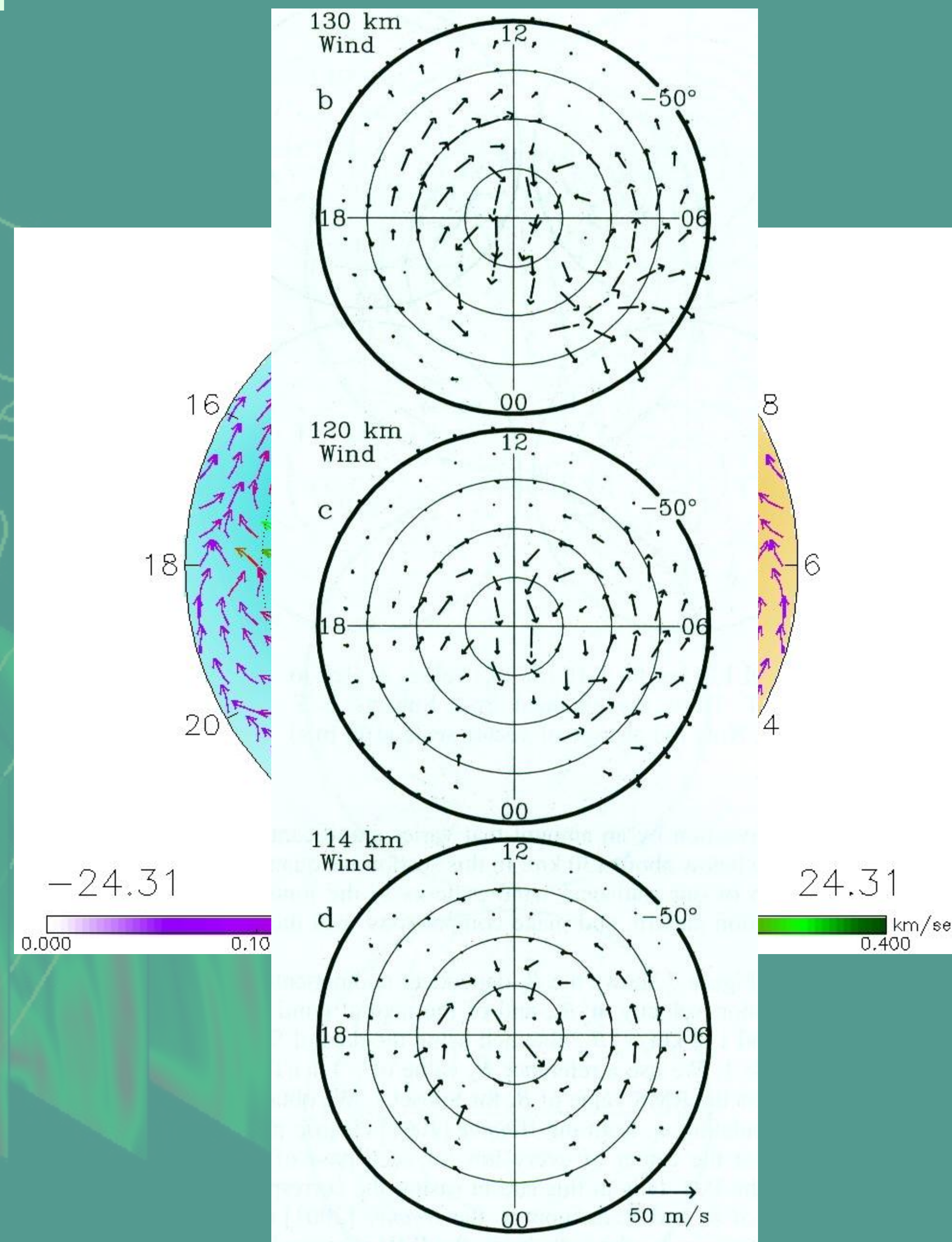
BATSRUS/CCMC



i.e., roughly an order of magnitude bigger

Atmospheric Reaction

- **Region 1 current gives the J in the JxB force that stands off the solar wind**
- **And communicates the force to the ionosphere**
- **Which communicates it (amplified) to the neutral atmosphere as the flywheel effect**



Richmond et al., 2003

Properties of the Dungey-Alfvén Magnetosphere

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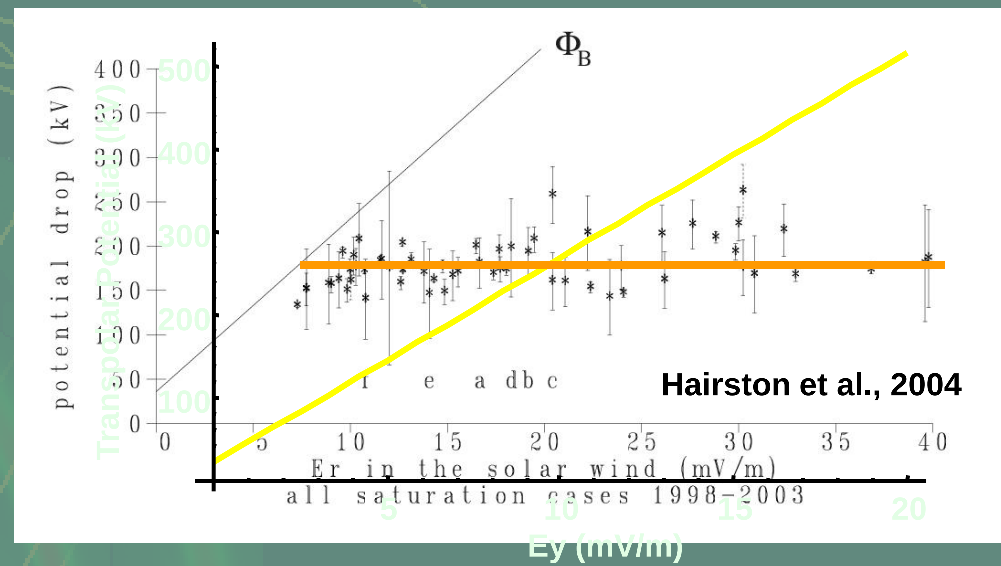
- **Force reversal and amplification**
- **Transpolar potential saturation**

Transpolar Potential Saturation

Instead of this

You have this



The Hill SW-M-I Coupling Ansatz

$$\Phi_H = \frac{\Phi_R \Phi_I}{\Phi_R + \Phi_I}$$

Where:

Φ_H is the Hill transpolar potential.

Φ_R is the potential from magnetopause reconnection.

Φ_I is the potential at which region 1 currents generate .
 a significant perturbation magnetic field at the reconnection site.

$$\Phi_R = \frac{57.6 E_{sw} F(\theta)}{P_{sw}^{1/6}}$$

Linear regime (small E_{SW})

$$\Phi_I = \frac{4608 P_{sw}^{1/3}}{\xi \Sigma_o}$$

Saturation regime (big E_{SW})

Ridley (2007) Alfvén Wings

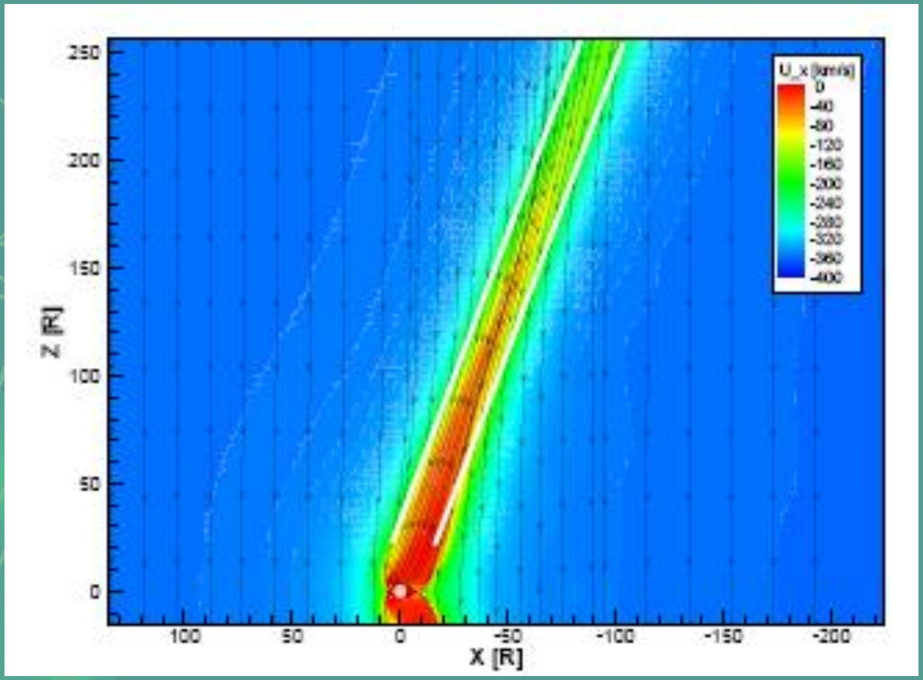
Electric field in Alfvén wings (Neubauer, 1980)

$$E_A = \frac{2\Sigma_A}{2\Sigma_A + \Sigma_P} E_{sw}$$

where

$$\Sigma_A = \frac{1}{\mu_o V_A \sqrt{1 + M_A^2}}$$

$$\Phi_A = E_A \pi R_{ms} \varepsilon_r$$



Extreme limit

$$\Phi_A = \frac{1300 P_{sw}^{1/3}}{\Sigma_P}$$

Compare Hill

$$\Phi_I = \frac{4608 P_{sw}^{1/3}}{\xi \Sigma_P}$$

The Hill model gives the Alfvén wing potential in the appropriate limit

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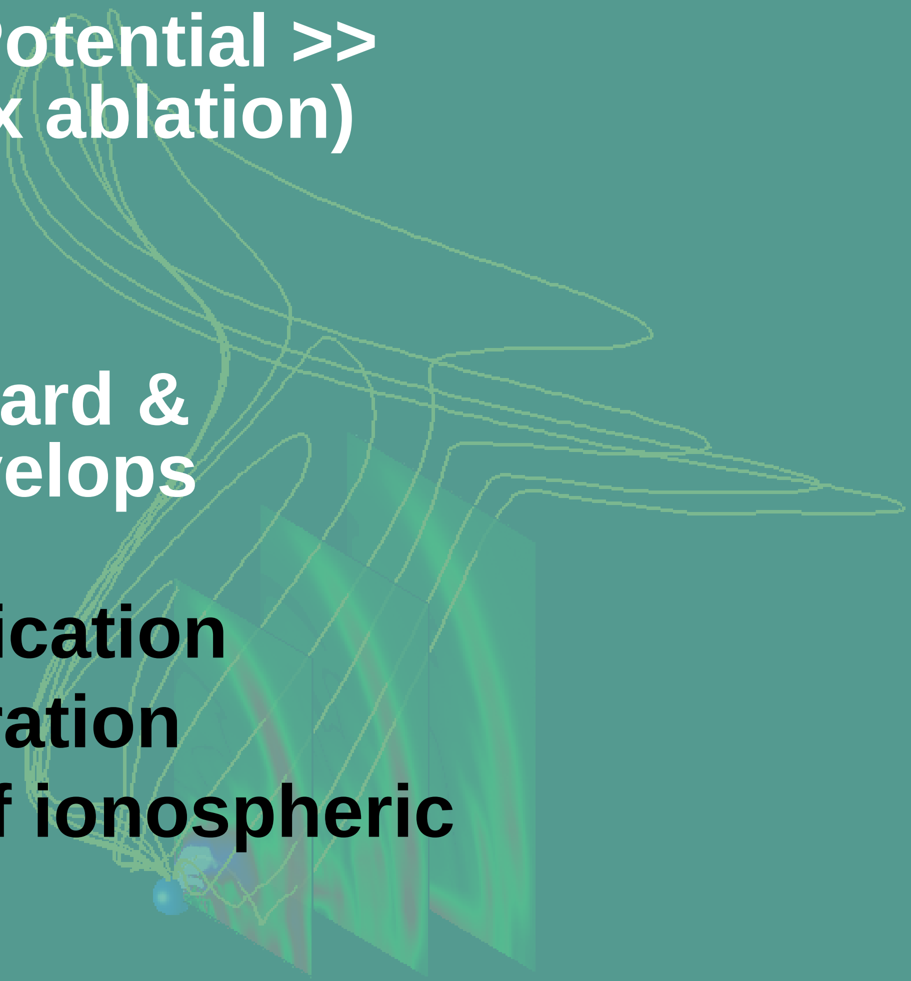
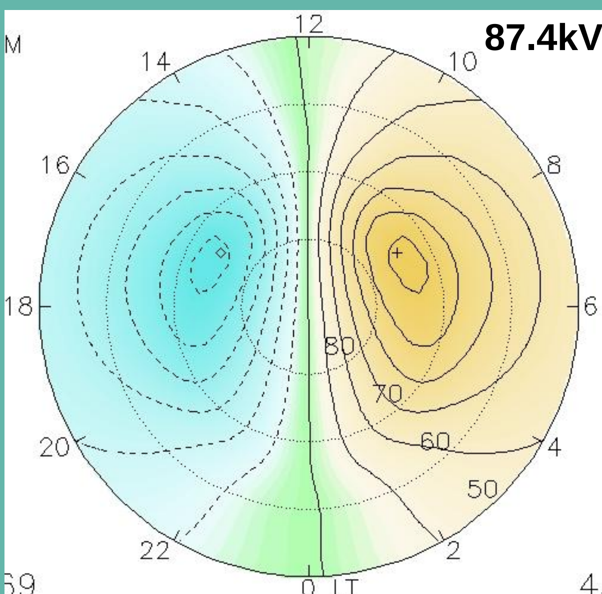
  - Sawtooth substorms
- **Force reversal and amplification**
- **Transpolar potential saturation**
- **System-wide regulation of ionospheric conductance**

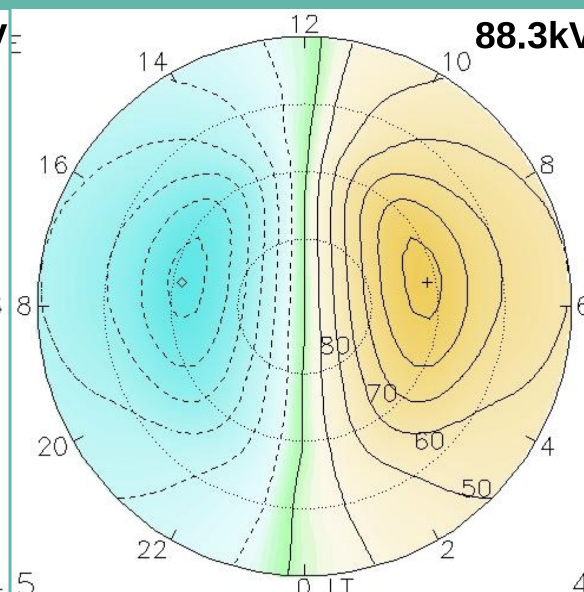


Weak Driving
IMF Bz = -5 nT
6 to 1 Summer to Winter Conductances

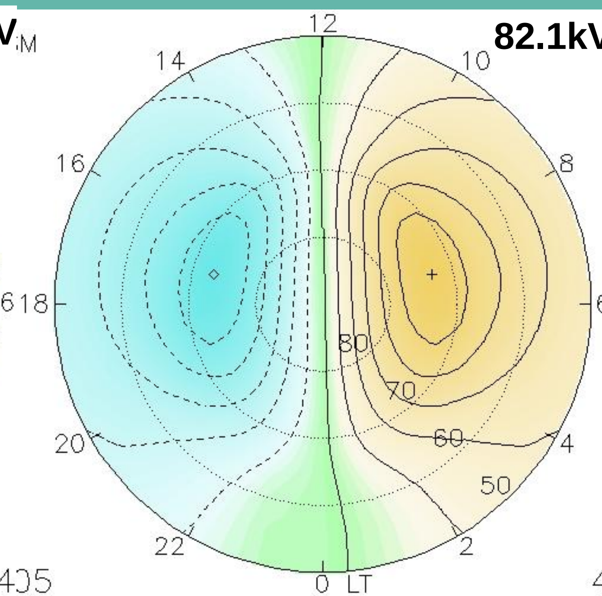
Summer



Spring/Fall

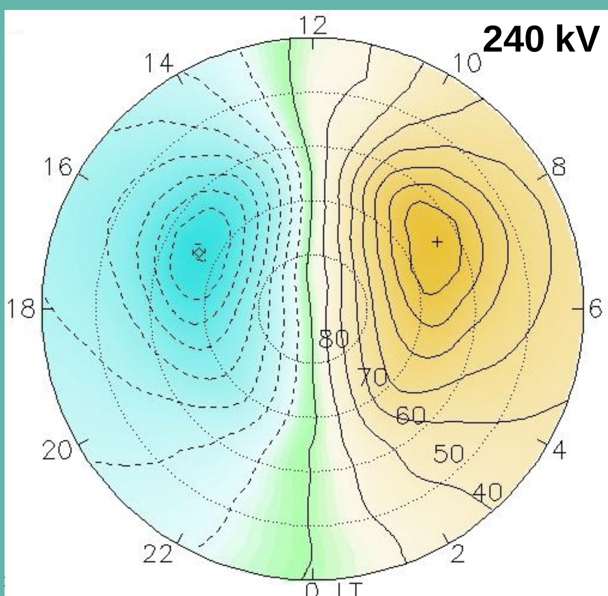


Winter

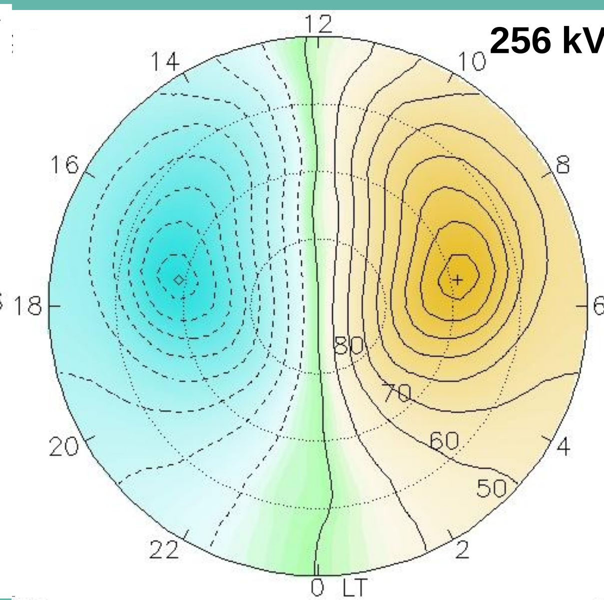


Strong Driving
IMF Bz = -30 nT
12 to 2 Summer to Winter Conductances

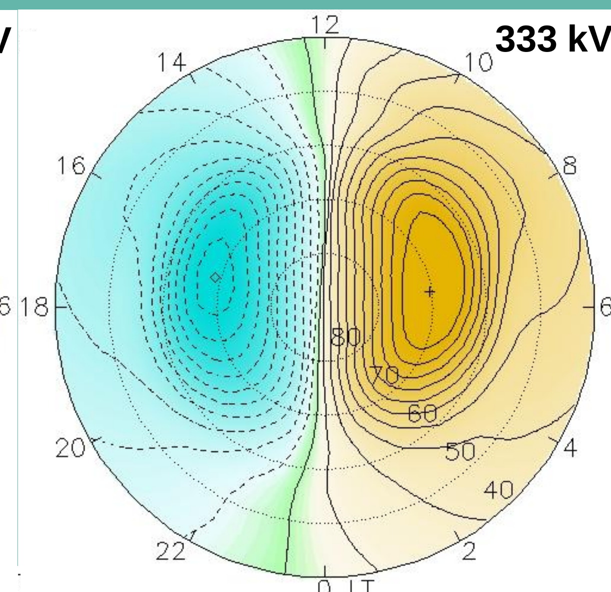
Summer



Spring/Fall

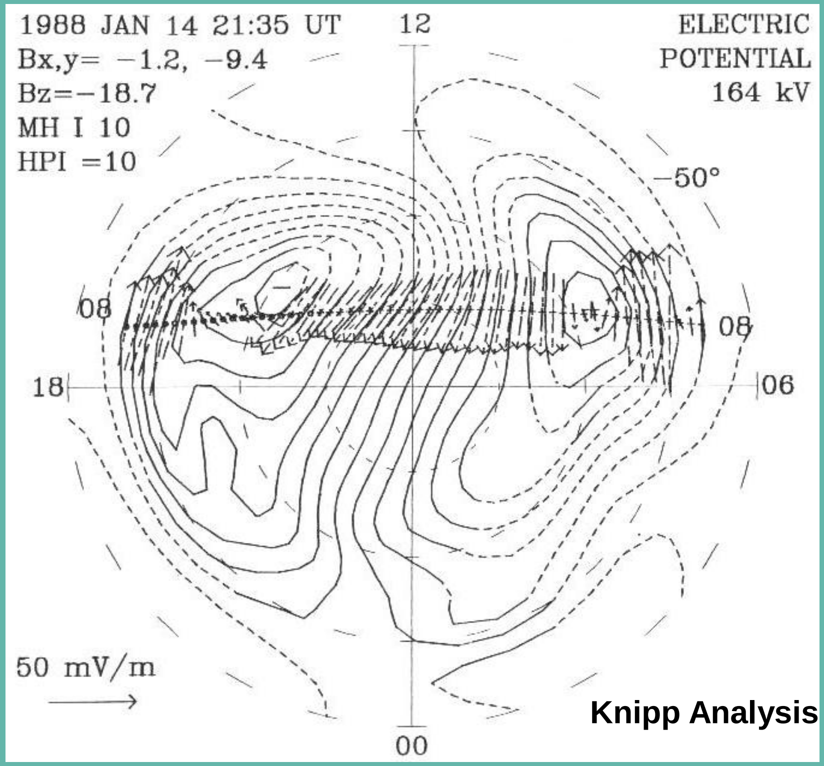


Winter

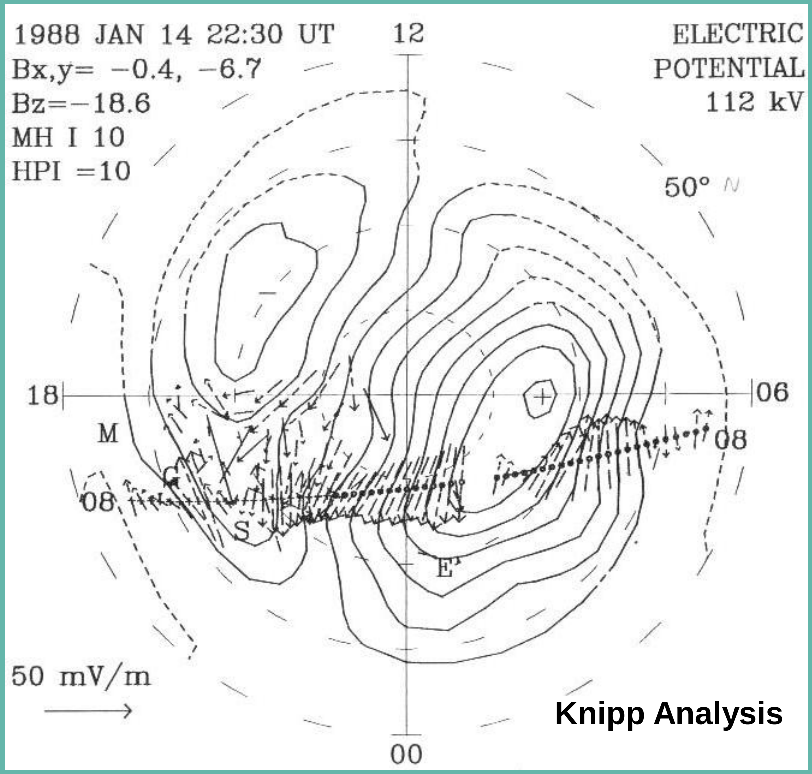


Interhemispheric Comparison
AMIE-Derived Potentials
1988 Jan 14 Storm

South/Summer



North/Winter



- Result: Counter to simulations, potential goes down in winter hemisphere!
- Inference: Reality (?) is like equal conductance case.

Summary of the Properties of the Dungey-Alfvén Magnetosphere

- **Huge dayside-nightside flux imbalance**
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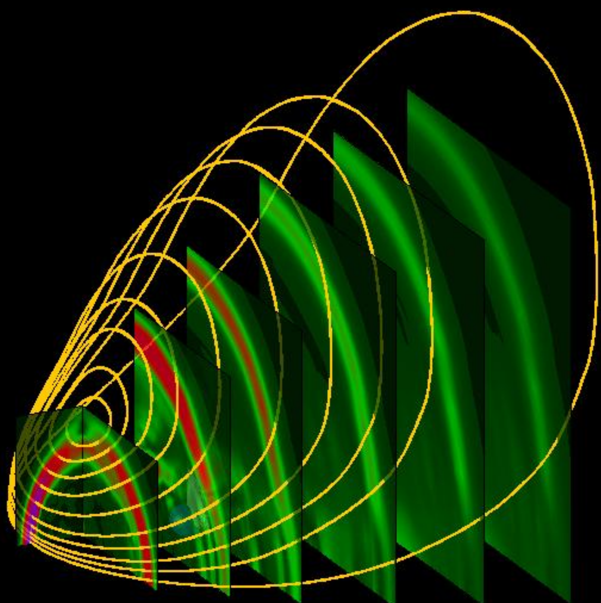
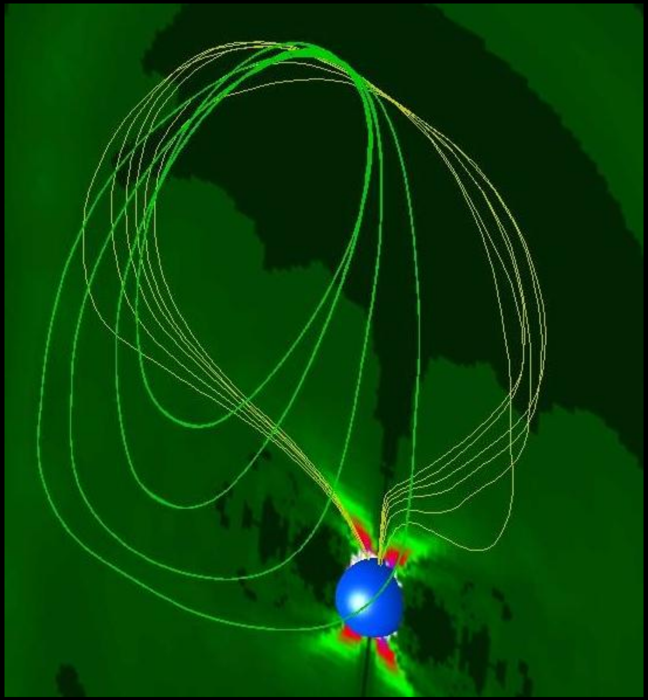
  - Dayside field weakening
  - Magnetospheric erosion
  - Tail morphs into wings
  - Cusps migrate equatorward & reconnection dimple develops
  - Sawtooth substorms (TPE-analogs to CEMs?)
- **Force reversal and amplification**
- **Transpolar potential saturation**
- **System regulation of ionospheric conductance**

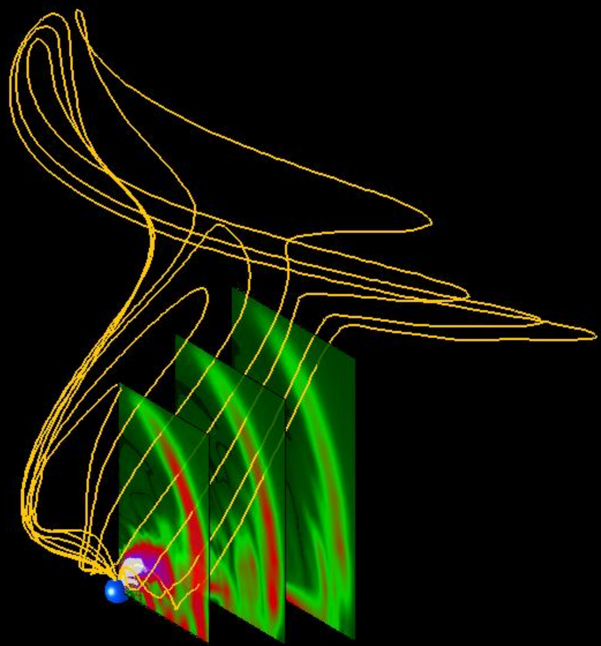
THE IDEAL

THE HYBRID

THE EXTREME







THE END