The Complete Disturbance
How Does it All Fit Together

Janet Kozyra (University of Michigan)

The Sun & Earth form a complex system with many interacting components that are themselves complex systems

Our ability to predict future states of this system have a direct benefit to a society increasingly reliant on technologies that are affected by the space environment (see D. Baker lecture).

Focus is on the interactions not the individual pieces.

The global system is dynamical and nonlinear.

There is a constant exchange of mass, energy and momentum across its open boundaries and between elements that drives it far from equilibrium.

Unlike systems in general , *complex* systems have the potential to produce unstable behaviors.

The Sun & Earth form a complex system which has characteristic properties

Prediction is difficult based on knowledge of components alone

What we measure is actually the integrated response of the entire interconnected system which can be nonlinear and unstable.

 - nonlinear: response is not the linear superposition of responses to individual processes

Disney's WALL-E (http://adisney.go.com/ disneyvideos/animatedfilms/wall-e/

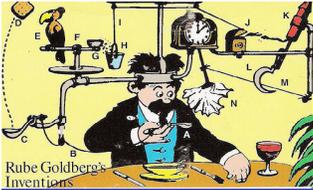"The whole is greater than the sum of the parts "

Negative and Positive Feedbacks Develop

A particular disturbance can trigger multiple nonlinear feedbacks between system components, which can amplify, cancel out altogether, or even change the nature of the expected response.
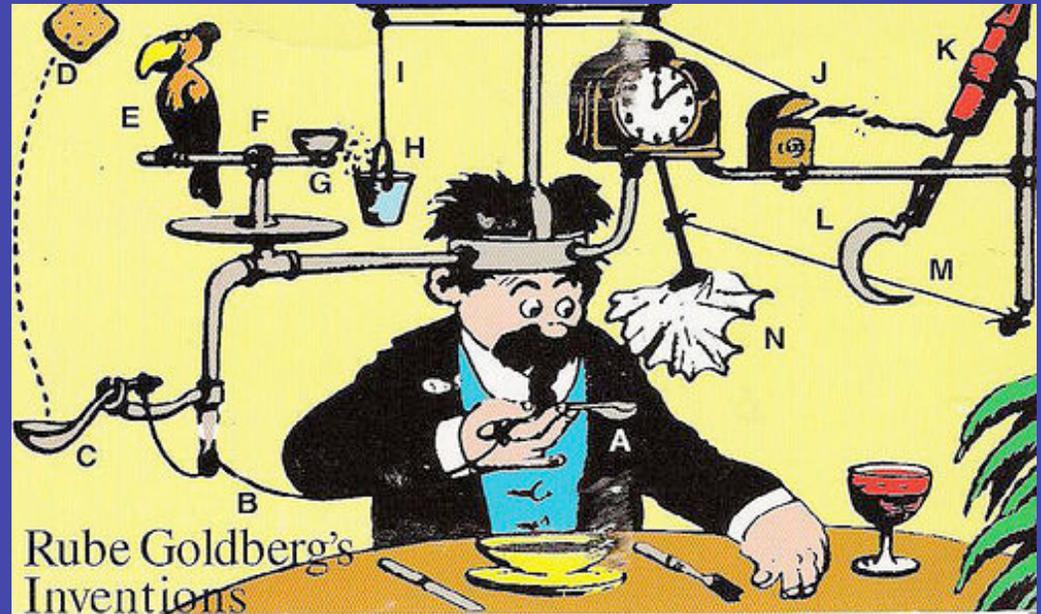
http://en.wikipedia.org/wiki/Rube_Goldberg_machine

"Simple cause & effect are rare."

Example

Solar Wind Electric Field → Increases polar cap potential drop (Φ_{pc}) enhances convection

Reduces reconnection rate, $\Phi_{pc,}$ & outflows

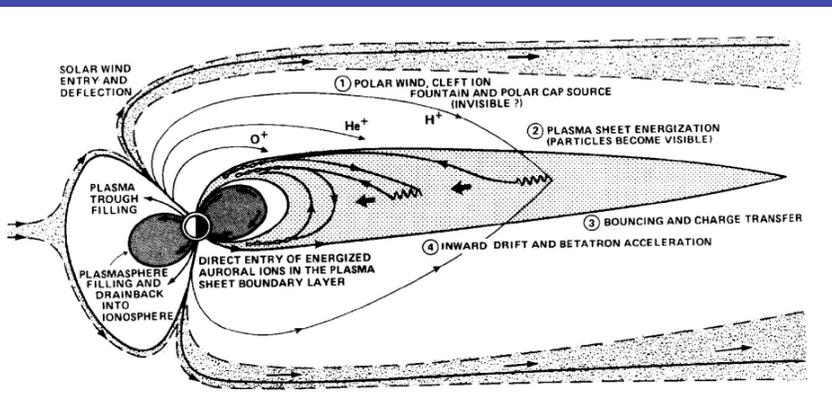Greater centrifugal acceleration of upflows

Mass Loading of Convection

Mass-loading slows convection

More ionospheric outflow

Chappell et al., 1987

Higher O+ content of plasmasheet

Winglee et al., [2002], Lotko, [2007]

History Matters

Preconditioning – a condition that must exist before something can occur

- Example: Northward IMF drives efficient capture of solar wind plasma triggering formation of superdense & cold plasma sheet material. If southward IMF closely follows, this material is delivered into the inner magnetosphere, acts as a source population for the ring current, and produces a more intense storm [c.f., *Thomsen et al.*, 2003].

Memory

- Example: the neutral atmosphere is a key element in system memory. Lot of inertia and long time-scales. Preserves the history of recent energy inputs. Introduces solar cycle and seasonal effects.

Initial Conditions – Small changes in initial conditions can produce significant changes in system state

http://www.aps.org/publications/apsnews/200406/butterfly–effect.cfm

"Butterfly Effect"

Emergent Features Appear

The source of phenomena can be contained in the interactions and not in the components themselves

No new components but unexpected features appear

One example of strong candidate for emergence:
- Great Red Auroras

Still from "The Mummy", Universal Pictures, 2008

"Science of Surprise"

Emergence? Great Red Auroras

The great red aurora of 10-11 February 1958, the 13th largest magnetic storm in recorded history. Snow appeared red in Alaska and radio communications between the US and other parts of the world were disrupted.   Photo credit: Bert Vorchheimer

Great red auroras occur *only* during extreme magnetic activity. Features [c.f. *Vallence-Jones*, 1992]:

❖ Red auroral displays of unusual brightness (> 100 kR of 630 nm light)

❖ Extend to exceptionally low MLATs

❖ Cover up to 95% of the sky in places

Observations suggest these aurora are produced by 10-20 min bursts of large fluxes of soft electrons (10s to 100s eV) [c.f., *Robinson et al*., 1985; *Shiokawa et al*., 1997]. Source unknown.

For reasons not understood:

❖ Auroral precipitation softens in energy during intense storms [c.f., *Hecht et al*., 2008]

Summary: Complex System Properties

✓Prediction is difficult based on knowledge of components alone

✓Negative and Positive Feedbacks are Integral to System Behavior

✓Small changes in initial conditions can affect the final state

✓History Matters

✓Emergent Features Appear

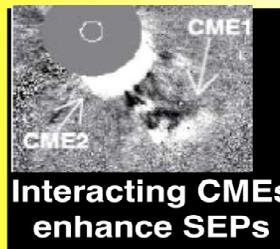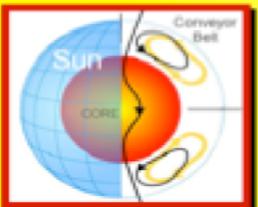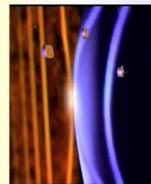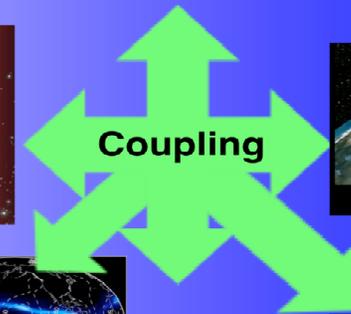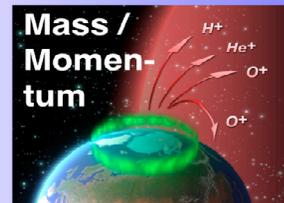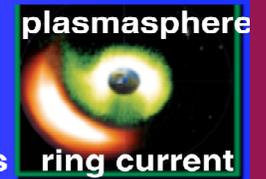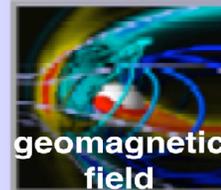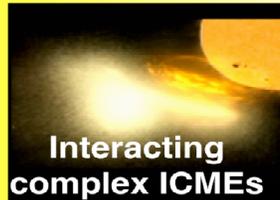Consequences:

•Interactions between components often define the system response Not contained in the individual pieces

•Clear cause and effect appears only when these effects are disentangled.

•For these cases, cannot break system into smaller digestible pieces for study

Summary of interacting components?

Preconditioning Initial Conditions Memory Feedbacks Nonlinearity Instability Emergence

Cross-scale coupling

Active Regions

Interacting complex ICMEs

Open Magnetic Flux

High speed streams

Super Active Regions

CME deflection by coronal holes

Solar Dynamo

Interacting CMEs enhance SEPs

Solar Flares

Solar energetic particles (SEP)

Solar wind energy input

geomagnetic field

plasma sheet

radiation belts

plasmasphere

ring current

Mass / Momentum

Coupling

Electrodynamic

plasma-neutral

Ionosphere-Thermosphere Mesosphere

highly structured ionosphere

Chemical-Dynamical

Polar Vortex

atmospheric waves

Global Electric Circuit

TLE

cosmic rays

System is Multi-Scale & Couples between Scales

Space Weather Scales
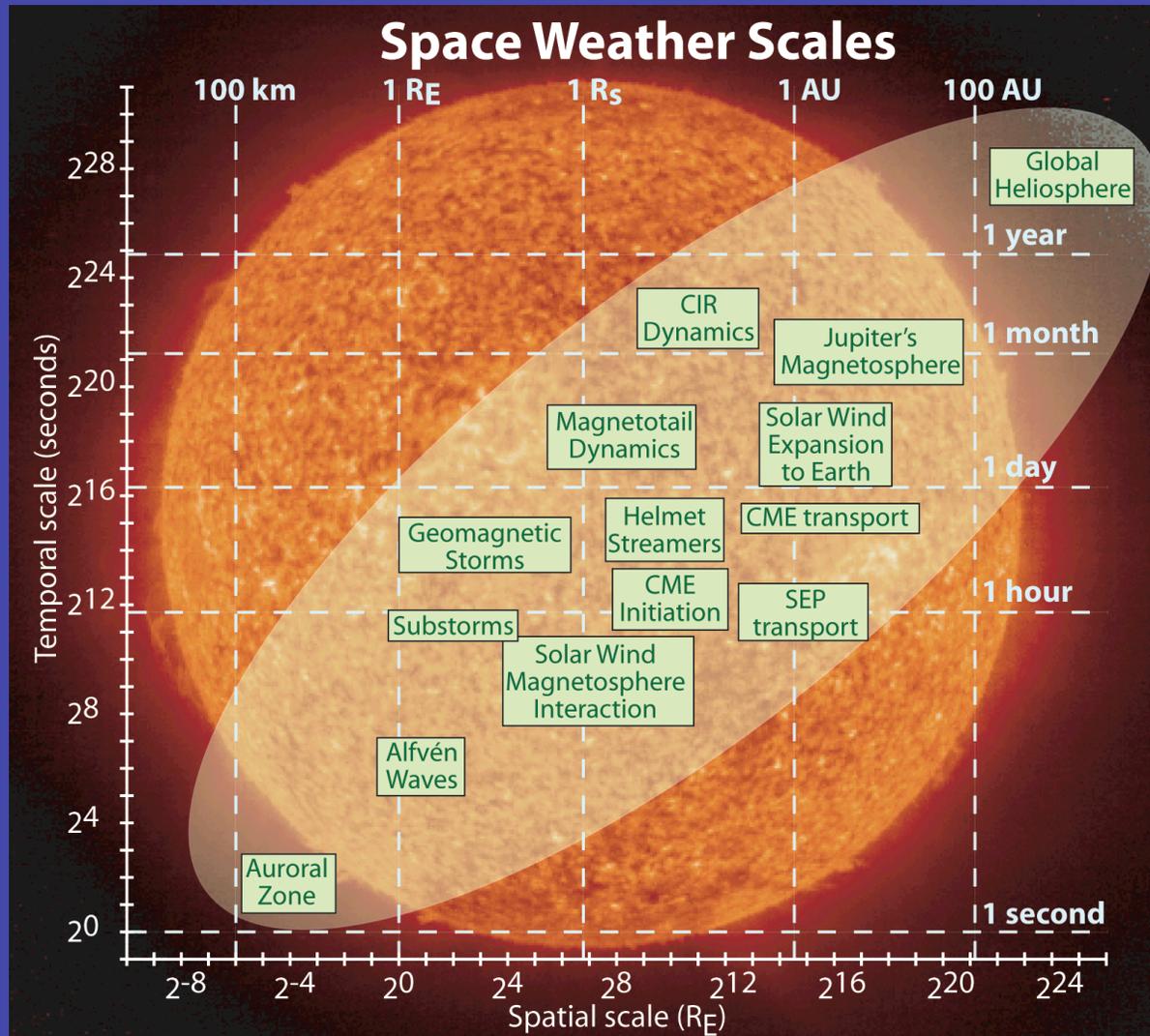
Processes operating at one scale can influence phenomena at other scales.

Image credit: T. Gombosi, CSEM, U of Mich

Energy moves through the system at a wide range of scales

Where is the Earth in this picture?

stills from the "zoom" movie
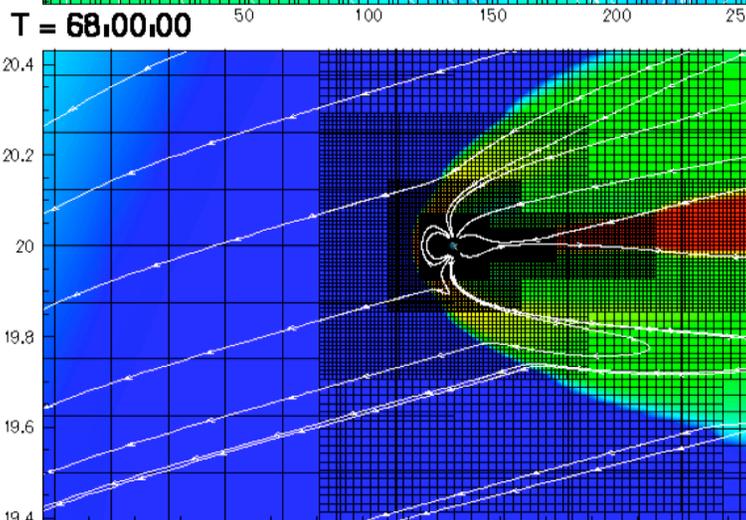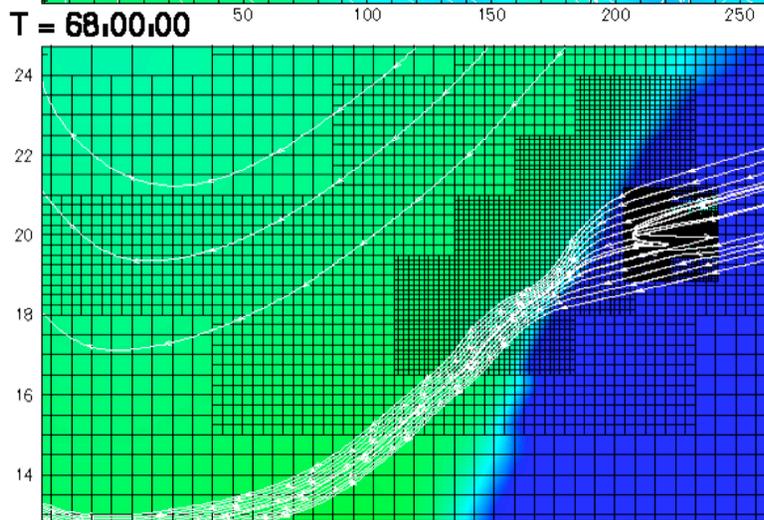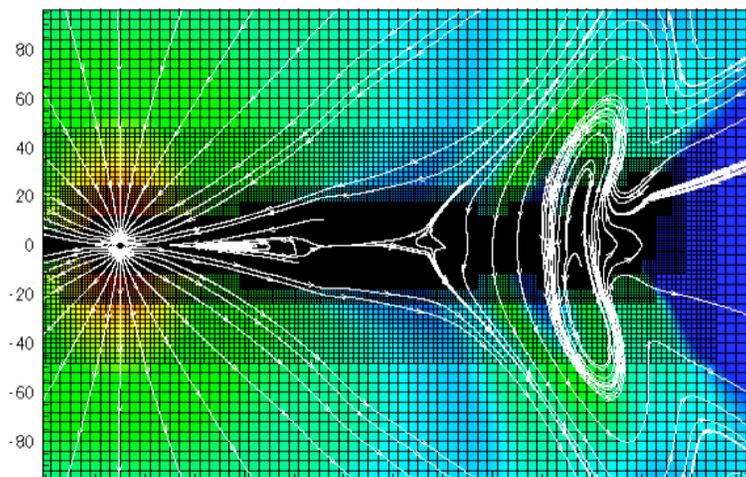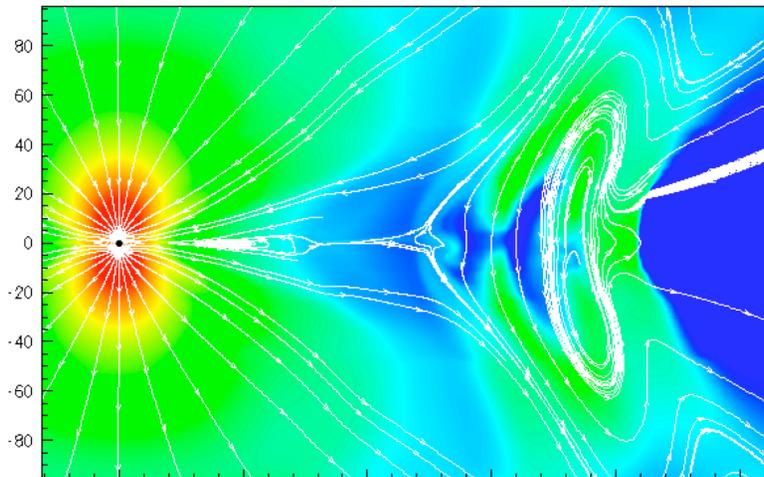
- Scales
  - ICME few 100 Rs
  - Magnet osphere few tenths Rs

< 0.1% of solar wind particles and <10% of the interplanet-ary electric field pene-trate into geospace

Internal Geospace Processes

System Processes

- ✓ Preconditioning
- ✓ Memory
- ✓ Nonlinearity
- ✓ Feedback Loops
- ✓ Instability
- ✓ Emergence

Main Coupling Processes

- ✓ Mass / Momentum
- ✓ Plasma - Neutral
- ✓ Chemical - Dynamical
- ✓ Electrodynamic

Cross-scale
Interactions

Active Electrodynamic Coupling

Impose unstruc-tured magneto-spheric FAC

Existing conduc-tivity gradients result in iono-spheric contribu-tions to FACs

$$\bar{E}$$

$$\Sigma \left| \begin{array}{l} \nabla\Sigma>0 \\ \bar{E}\cdot\nabla\Sigma>0 \\ J_{\parallel}\downarrow \end{array} \right. \qquad \begin{array}{l} \nabla\Sigma<0 \\ \\ J_{\parallel}\uparrow \end{array}$$

$$X$$
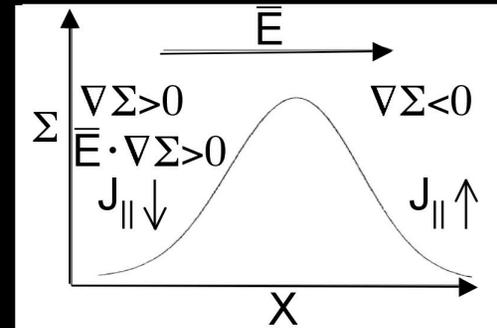
Enhance joule heating & precipitating energy flux

Create small-scale structures in FACs, E-fields
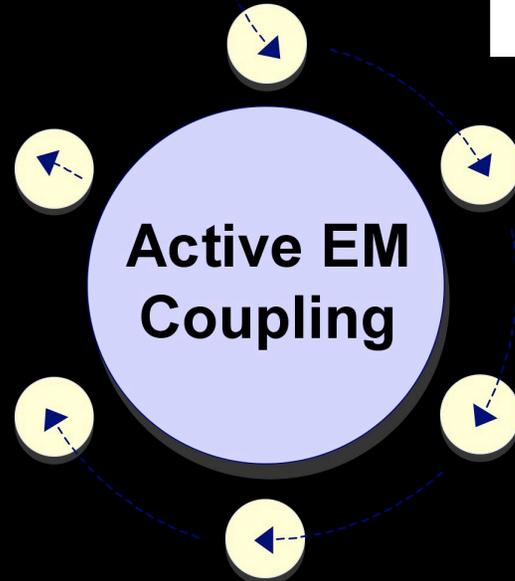
Active EM Coupling

Alfven waves carry FAC infor-mation back to magnetosphere

New FACs evolve with associated precipitation

Dynamically-changing conductivity gradients generate new FACs, launch Alfven waves upward

Active electrodynamic coupling is central to the behavior of the Sun-Geospace system, yet the self-consistent patterns of electric fields, currents, and conductivity have never been measured.

Sojka et al., 2006; Sojka & Zhu, 2006; Lotko, 2007

Ion-Neutral Coupling

Highly strutured plasma environment.
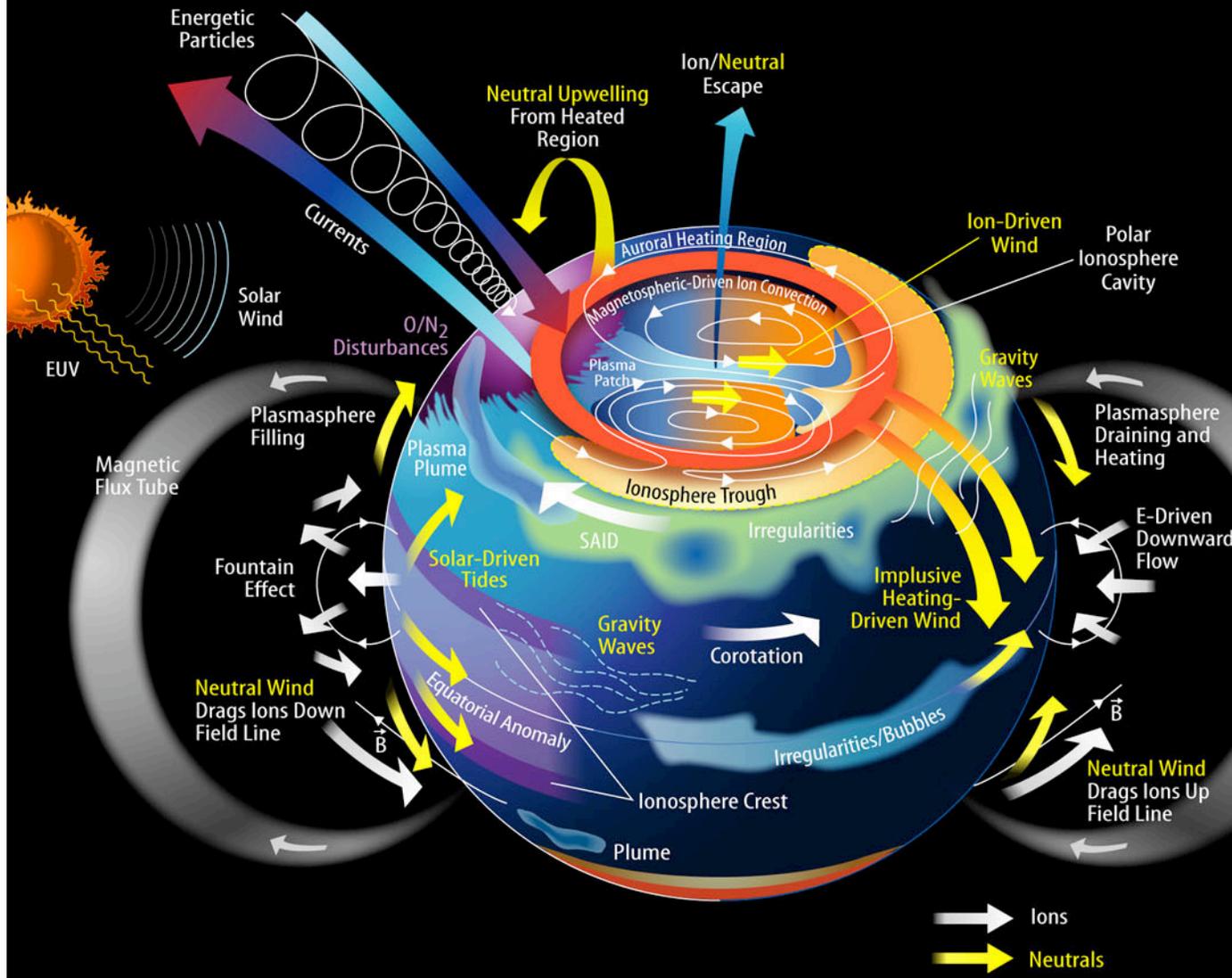
- **Strength of the interaction proportioal to Ne which is controlled by auroral precipitation, solar EUV, chemistry, and transport**
- **Neutral winds spread local heating globally.**
- **Heating produces waves that propagate vertically and horizontally.**
- **Neutral winds:**
  - **alter the chemistry of the ITM by advecting chemical constituents**
  - **drag the ions across field lines at low altitudes creating E fields, which alter winds at high altitudes.**
  - **Seed instabilities at low latitudes.**
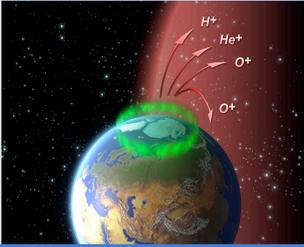
Mass / Momentum Coupling

Ionospheric Outflow: 2-Step Process

Outflows (which involve many independently-driven processes are best correlated with solar wind Pdyn fluctuations: Reason Unknown [c.f. Pollock et al., 1988; Moore et al.,1999]

Observed at FAST

r = 0.721 → Ion Outflow ← r = 0.855

Poynting Flux ← r = 0.634 → Electron Precipitation (Magnetosheath)

r = 0.743

r = 0.888 → ELF/VLF Waves (Heating) ← r = 0.741

Inferred

Ion Upwelling

Another "upwelling" process: horizontal transport of enhanced Ne patches

Ion Scale Height Increase

Electron Scale Height Increase – Ambipolar Field

Joule Dissipation

Electron Heating/Ionization

→ Causal   ⇨ Possibly Causal   ⇨ Correlated

Outflow: Acceleration to > escape velocity

Upwellling: Increase in scale height

After Strangeway et al., [2005] as summarized in Moore and Horwitz, 2007 and Lotko, 2007

Chemical-Dynamical Coupling

auroral particles

NO

NO   NO

NO

NOx

solar particles

radia-
tion
belt

NOx   NOx

NOx
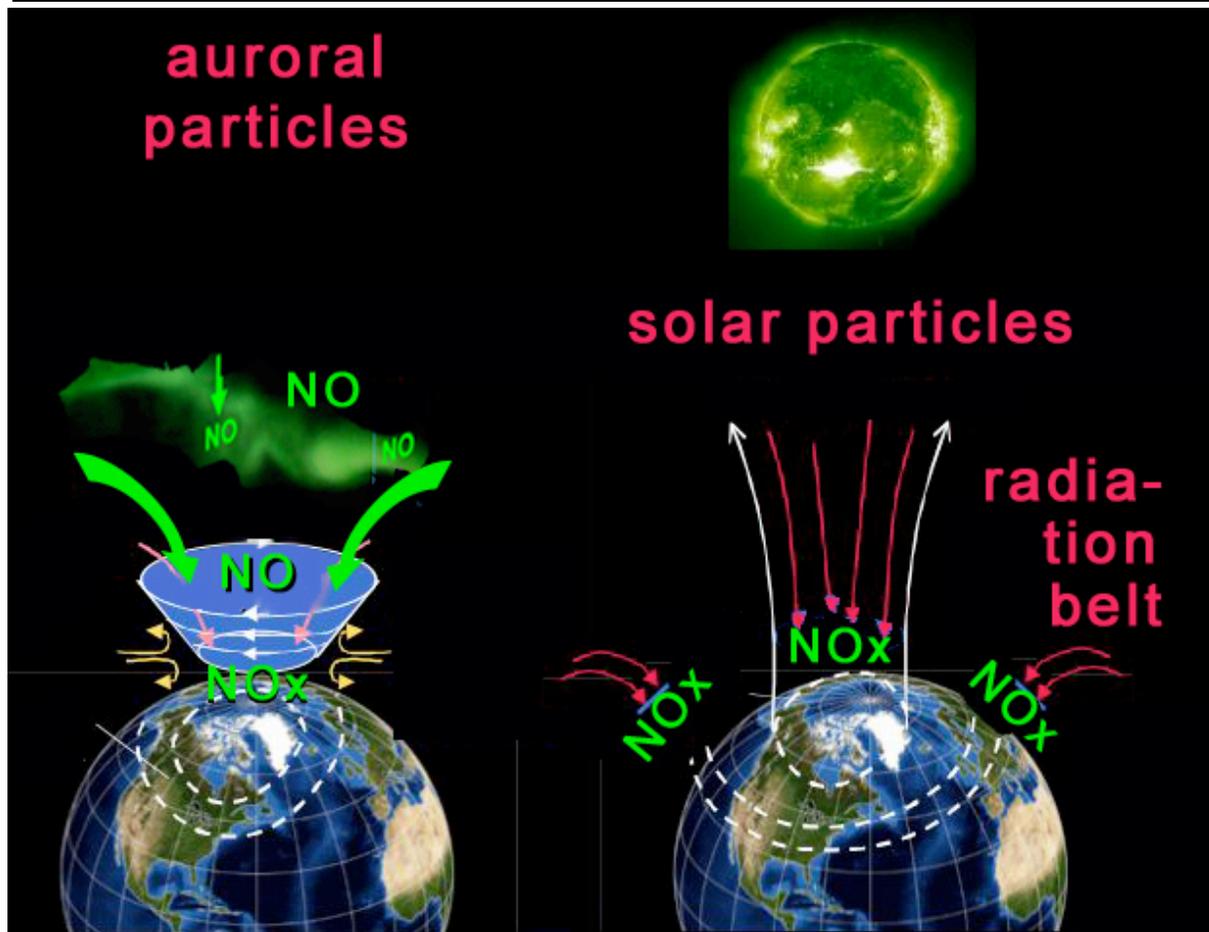
Interesting example of coupling between
stratospheric meteorology and space weather.
[c.f., *Randall et al*., 2006]. Peaks in NOx descent associated
with high speed stream activity [*Kozyra et al*., 2006].

- Upper and lower atmosphere iconnected through chemistry and dynamics.

- Transport of trace and reactive species results in redistribution in atmospheric heating --> dynamical changes

- Energy and momentum also transported by atmospheric waves, such as tides, planetary and gravity waves.

- These waves are forced by the absorption of sunlight in the lower atmosphere, orography, non-linear wave-wave interactions and by latent heat release in clouds.

Have a feel for geospace as a complex system, now look at interaction sun-to-Earth

1) Define the elements of the sun-Earth system.

2) Look at the energy budget during a space weather disturbance

3) Explore energy inputs to geospace and how they depend on the IMF and other solar wind parameters

4) Track geo-effective drivers (and driver combinations) back to their solar sources. Allows us to identify key processes in the Sun's magnetic variability that most dramatically effect Earth. Find links between solar evolution and both short- and long-term variations in the geospace-atmosphere environment. Refine our definitions of geo-effectiveness.

Geospace Stormtime Energy Budget

- Geospace processes are powered by the sun and solar wind
- Dominant energy input is associated with magnetic merging
- Converted to plasma sheet flows and heating
- Energy is dissipated in:
  - Ring current
  - Auroral particle precipitation and joule heating
- Plasmoids carry energy back to the solar wind

Energy Budget - 17-21 April 2002 Storms

E (ergs) of Solar eruption		E (ergs) at 1 AU intersecting Geo-space cross-section		E (ergs) dissipated in Geospace		E (ergs) radiated to space from the atmosphere	
4/15 & 4/17 CME	----------	Kinetic Energy [3]	7.3×10^{25}	Ring Current[4]	1.0×10^{24}	5.3 μm NO cooling[6]	1.4×10^{24}
E_P 4/21 CME[1]	5.0×10^{30}	ε param-eter[3]	3.2×10^{24}	Joule & Particle[3]	2.5×10^{24}		
E_K 4/21 CME[1]	1.8×10^{32}			Plas-moids[5]	1.2×10^{23}		
4/21 SEP[2]	3.2×10^{31}						

[1] Emslie et al., JGR, [2004]

[2] Mewaldt et al., JGR, [2005]

[3] AMIE technique [G. Lu, NCAR]

[4] RAM model [M. Liemohn, UM]

[5] Energy loss due to plasmoids was based on estimate of 1E22 ergs dissipated per substorm [Ieda et al., 1998] and approximately a dozen substorms indicated by the AL index during 17-20 April 2002.

[6] Mlynczak et al., JGR, [2005, 2006]

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Homework Question: Under typical solar wind conditions, which is greater, the kinetic or magnetic energy and energy flux?

[1] Emslie et al., JGR, [2004]

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Energy Input from the Solar Wind into Geospace

- No direct observations

- Knowledge of energy input based on:
  - Proxies
  - Numerical Experiments with MHD models

Some basics about magnetic reconnection related to Geospace energy input

Image Credit: ESA

plasma inflow

Jet ← | o | → Jet   Large-scale

inflow

Ion-scale

Electron-scale
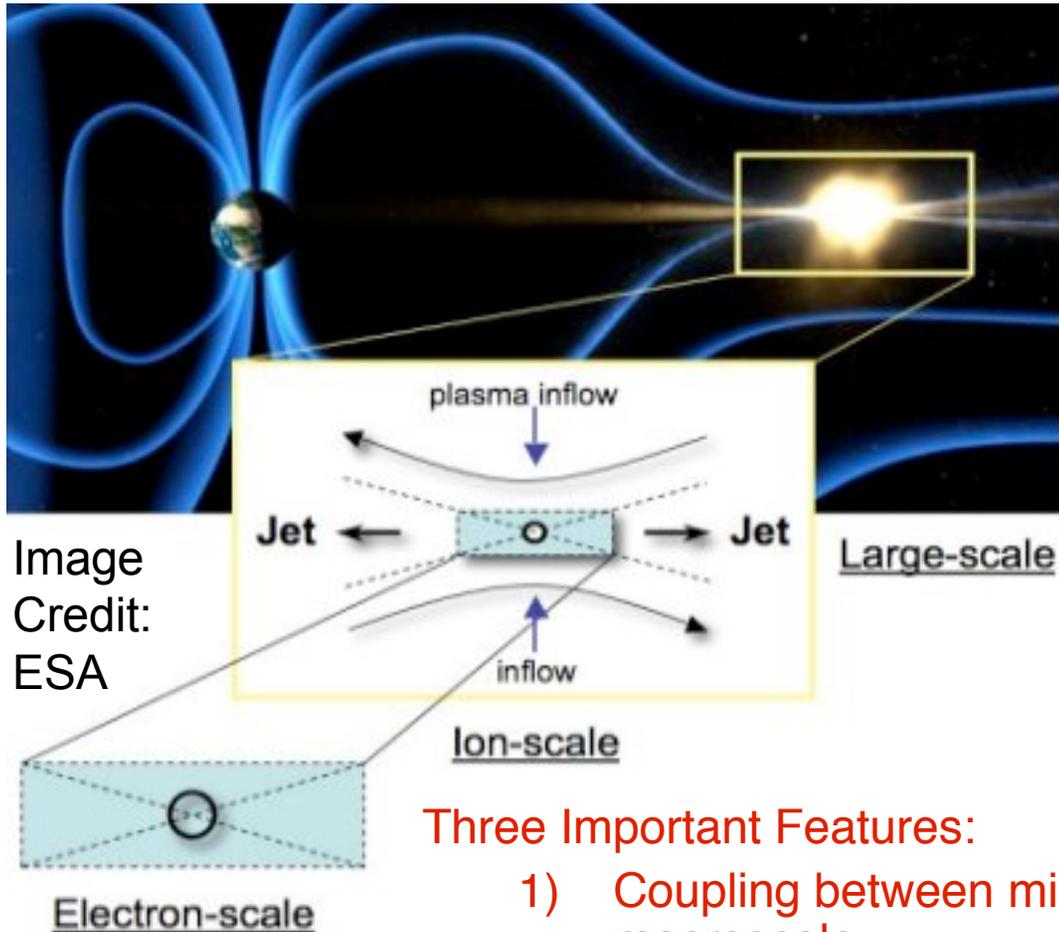
DEFINITION [*Vaivads et al., Space Sci Rev*, 2006]:

"Magnetic reconnection is a physical phenomenon where:

1) microscopic *(electron and ion gyroradii)* local processes cause a macroscopic change in magnetic topology so that earlier separated plasma regions become magnetically connected,

2) on macroscopic *(MHD)* scales the system relaxes to a lower energy state converting magnetic field energy to kinetic energy of charged particles"
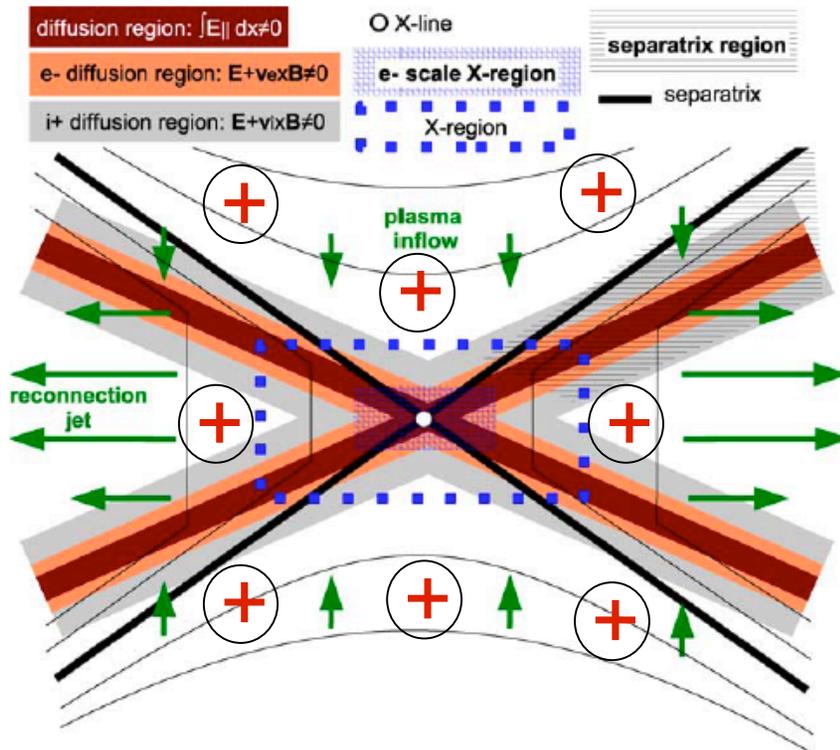
Three Important Features:

1) Coupling between microscale and macroscale
2) Mixing of previously unconnected plasmas
3) Conversion of magnetic to particle energy

Vaivads et al., 2006

X-line: Line along which magnetic field lines from two different topological regions interconnect. In a 2D projection, reduces to a point. Separator, Merging line.

E_{tan}: Electric field locally tangent to the X-line. Determines the transport of magnetic flux to the x-line and the reconnection rate.

Separatrix: Surface that separates flux tubes with different topology. 2D projection is a line.

Separatrix Region: Broader region around the separatrix where microphysical processes are important.

Diffusion Regions: All regions in the separatrix region where topological changes take place. In these regions $\int E_{\parallel}\, ds \neq 0$. Only near the x-line do previously separated field lines become interconnected.

Electron (Ion) Diffusion Regions: Regions in the separatrix region where "frozen-in-flux" condition is broken. Near the x-line, the ion diffusion region is called the X-region and the electron diffusion region is called the electron scale X-region.

Guide Field Reconnection: B $\neq$ 0 along the x-line. In this case $E_{tan} = E_{\parallel}$. Leads to general definition of reconnection $\int E_{\parallel}\, ds \neq 0$, integral is taken along a field line in the reconnection region [c.f., Vaivads et al., 2006].
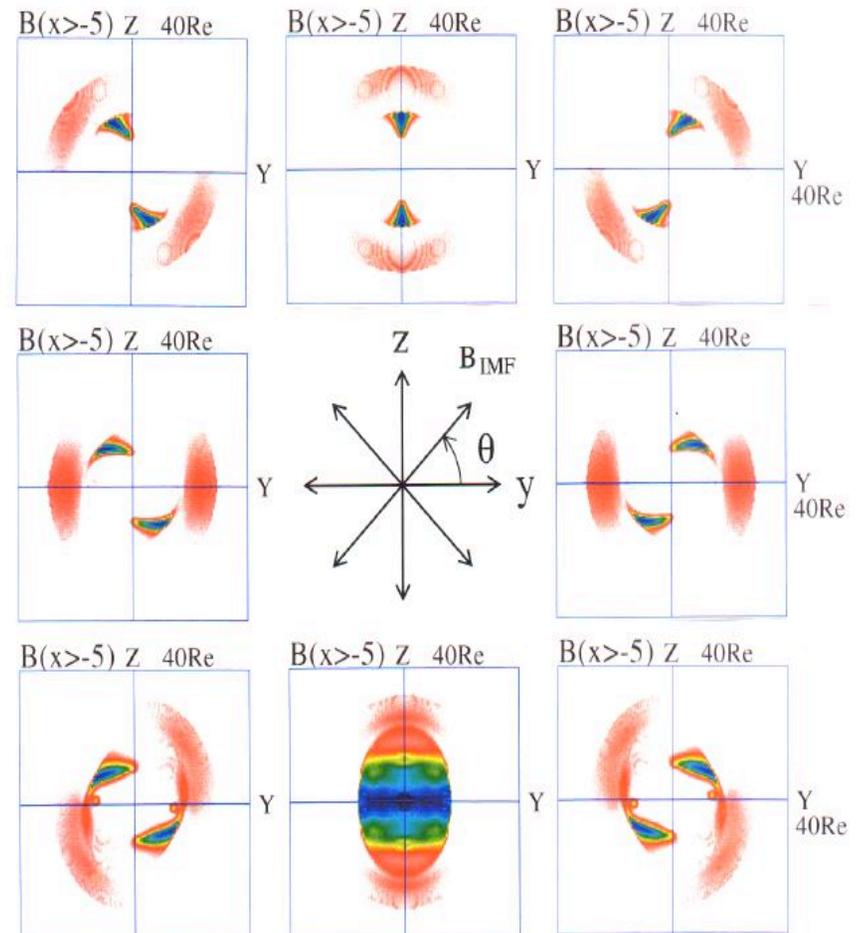
Anti-Parallel Reconnection vs IMF orientation

- Anti-parallel merging regions for purely horizontal IMF By are located at the high latitude magnetopause on the nightside but move to the high-latitude dayside region equatorward of the cusp and to increasingly lower latitudes with increasing southward IMF component [*Crooker*, 1979; *Luhmann et al.*, 1984; *Ogino et al.*, 1986; *Laitinen et al.*, 2007].

- This means that two high-latitude merging regions drive magnetospheric convection, one in each hemisphere, rather than the single sub-solar reconnection region during purely southward IMF.

- Anti-parallel merging regions are shifted to the dawnside in the northern hemisphere and duskside in the southern hemisphere for IMF By <0 and the reverse for IMF By >0.

Weak field anti-parallel merging regions

Rotation of incoming IMF
Projection of minimum B region   B=5.0nT

http://center.stelab.nagoya-u.ac.jp/web1/simulation/mhd3d01/fig02.jpg

Component Reconnection

Zero tilt, Bz = -3nT, Pdyn = 2 nPa

Reconnection Component

Magnitude increases as angle between fields increases toward anti-parallel.

B_{SH}/B_{BL}

B_{rec}/B_{BL}
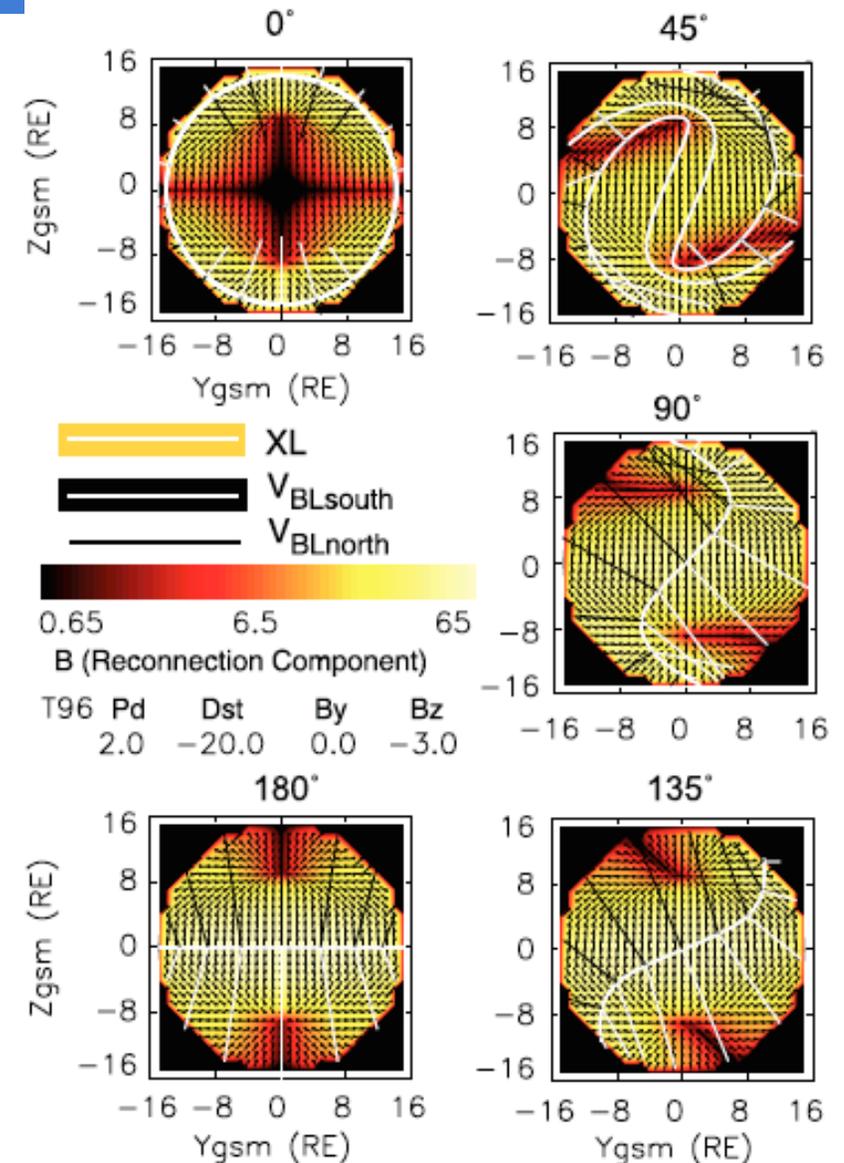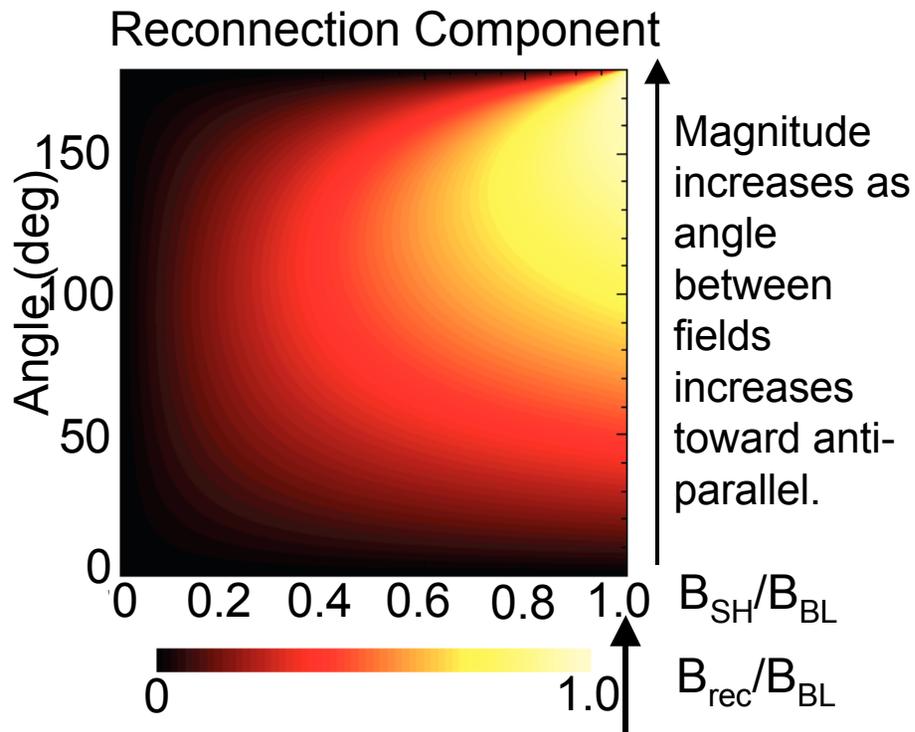
- Component (low shear) Reconnection [c.f., Moore et al., 2002]: No requirement for anti-parallel reconnection in MHD equations [Cowley, 1976]. X-line is normal to the line along which the two fields have equal and opposite components (called reconnecting component). Different than guide field which parallel to the x-line. Rate goes to zero with the reconnecting components

Moore et al., 2002

Some Unknowns & Controversies

No observations of total energy input due to reconnection. Critical information for understanding sun-Geospace interaction.

$E_{||}$ distribution in separatrix region and its spatial and temporal variation: Largely unknown. Some information from simulations. Important in order to understand topological changes in the broader separatrix region and how they relate to the global changes in the magnetic field structure.

How magnetic energy conversion is distributed throughout the separator region and near the x-line: Observations so far are unable to resolve this. Some suggested mechanisms for example are: particle acceleration [c.f., Nagai et al., 2001] and particles interacting with slow shocks [Petschek, 1964]

Vaivads et al., Space Sci Rev, 2006

What you will see in the next slides is that solar wind energy input to the magnetosphere through reconnection (in MHD experiments) takes place over a much broader region than the X-line.

Solar wind energy input, GUMICS, x>0

Magnetopause = streamline
Total energy flux through surface

Varies with IMF-direction

Magnetic energy
Blue = dissipation
Red = production

$$E = B \times v \neq 0, \ \mu_0 S = E \times B \Rightarrow S \perp B$$

Scales with Pdyn

$\nabla \cdot S > 0$

$\nabla \cdot S < 0$

separator line

Magnetic shear angle — 170° — 135°

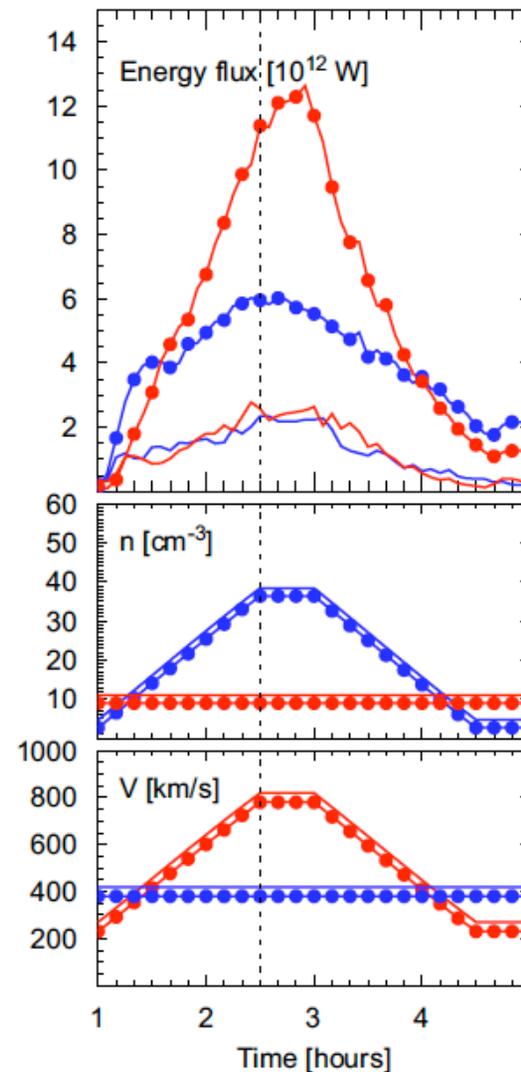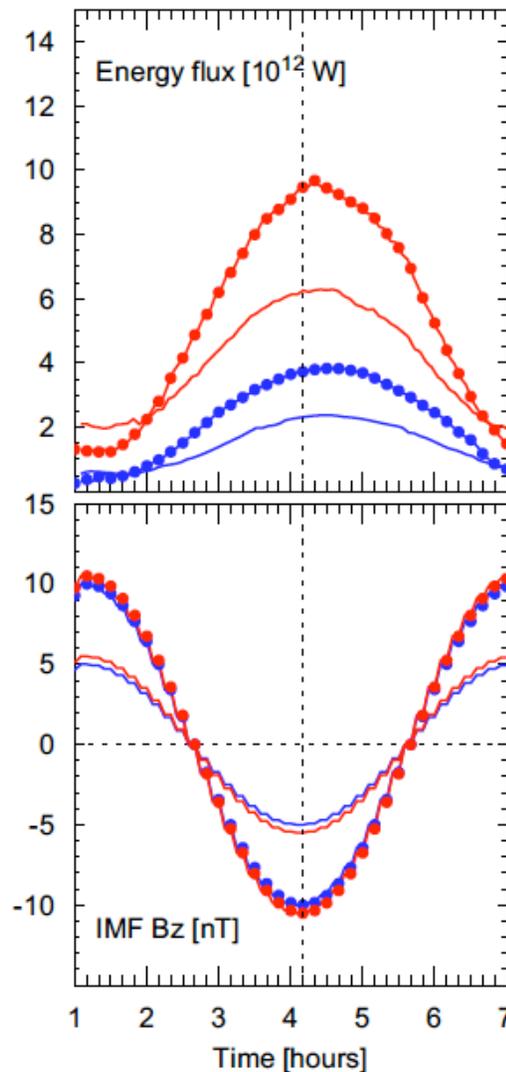Pulkkinen et al., 2007, 2008; Laitinen et al., JGR, 2007

Energy Input - Dependence on Solar Wind parameters & IMF

High P (8 nPa)

Low P (2 nPa)

⊸⊶ High B

—— Low B

GUMICS-4 MHD Simulations [Pulkkinen et al.,JASTP, 2007, 2008; Palmroth et al., 2006]

P= 1-10 nPa by varying:

- V_{sw} only

- n_{sw} only

  clock angle

⊸⊶ - Bz (157.5^0)

—— +Bz (22.5^0)

Controlled by reconnection efficiency which depends on IMF, IEF, solar wind density, velocity, pressure

Energy Input - Dependence on Solar Wind parameters & IMF

	Southward IMF	Northward IMF	Dynamic Pressure
Energy Input	controlled by: • IMF orientation and magnitude • Solar wind velocity (more important) and density	• Orientation of IMF is more important than magnitude. • Larger for high speed, low IMF strength • Smaller for low speed, high IMF strength	• Input scales with dynamic pressure • More strongly controlled by solar wind velocity than density for the same pressure

[Pulkkinen et al., JASTP, 2008]: Overall -- Energy input in simulations controlled by reconnection efficiency with solar wind parameters in order of importance being clock angle and Vsw, followed by B magnitude andNsw.

Energy input varies in a manner similar to proxies (like epsilon) but is considerably larger

History matters. Energy input depends on both present & recent IMF

clock angle 10^0 steps   IMF Bx = 0
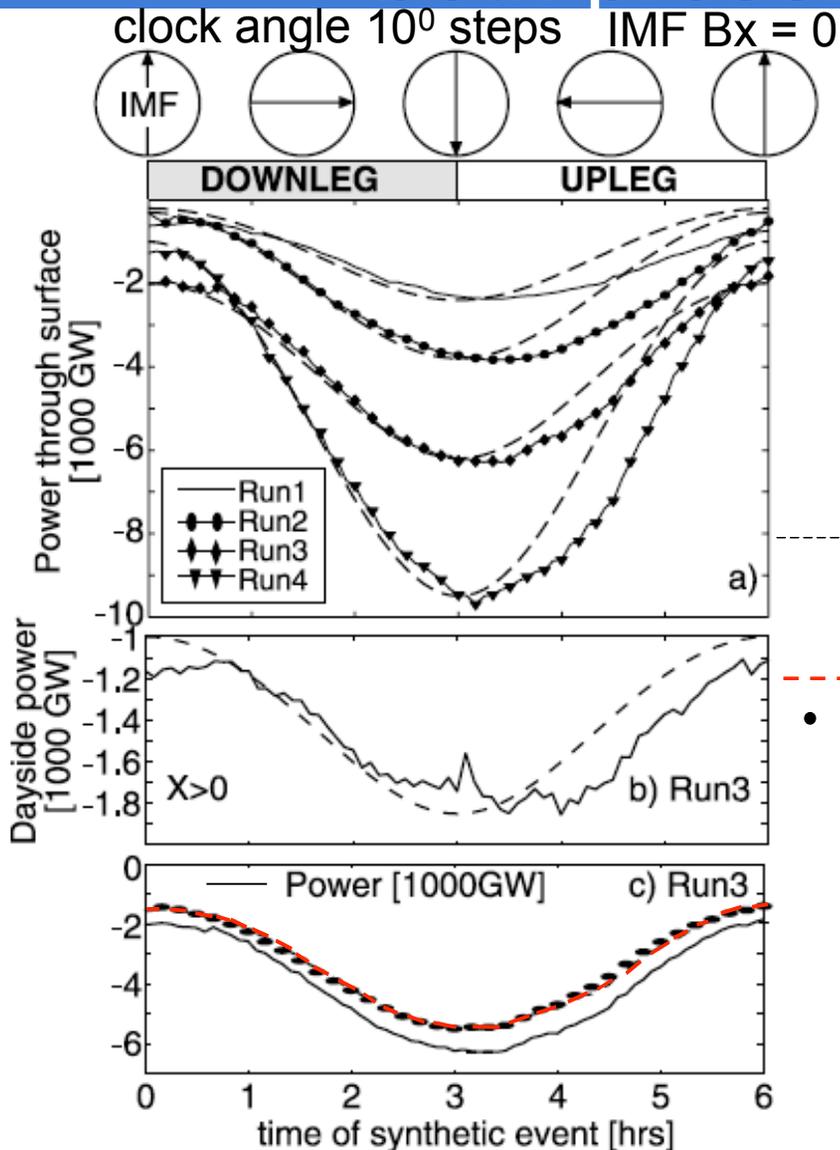
Power calculated from total thermal, kinetic and electromagnetic energy flux through magnetopause surface to x=-30 R_E.

Result: Power input proportional to $\sin^2(\theta/2)$, when the clock angle rotates from north to south. On the return rotation (south to north) the power input remains enhanced longer than given by $\sin^2(\theta/2)$.

----- scaled $\sin^2(\theta/2)$

- - - Poynting flux

• Poynting flux using E and B from Δt before through surface from Δt after 03:00 RT

[Palmroth et al., GRL, 2006]

Characteristic Time Lags & Hysteresis

Table 1. Synthetic Run Parameters and Time Lag of Hysteresis

| #	$|IMF|$, nT	p_{dyn}, nPa	Time Lag, min
1	5	2	30
2	10	2	40
3	5	8	20
4	10	8	30

*The time lag computed by finding the best correlation for delayed upleg power transfer with the upleg sin2(θ/2)

The energy input *after* an interval of southward IMF is stronger than for the same conditions *before* the southward IMF interval.

After the IMF rotates to a new value, there is a change in reconnection within 10-15 minutes [Laitinen et al., 2007] and a response in the energy input through the magnetopause within 20-40 minutes [*Palmroth et al.*, 2006].

This time delay can be comparable to the time between significant IMF rotations (for example, in high-speed streams).

What causes the hysteresis?

θ = 150°

θ = 210°
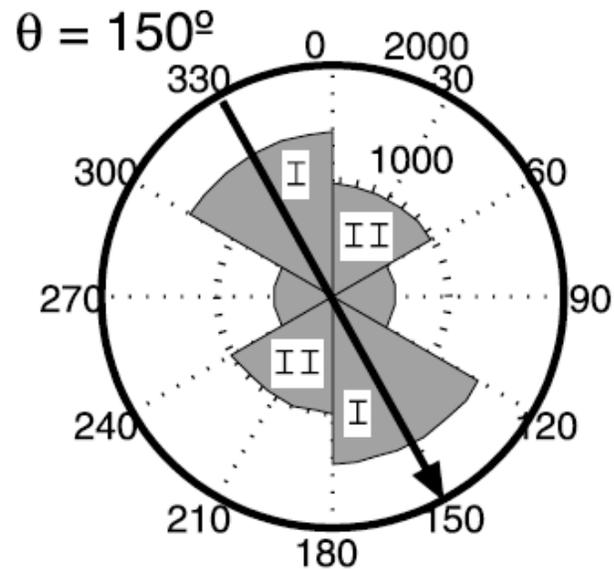
Input power from run #3 integrated over x and plotted vs azimuth angle radially from 0 to 2000 GW at the outer circle. Clock angle marked by arrow.
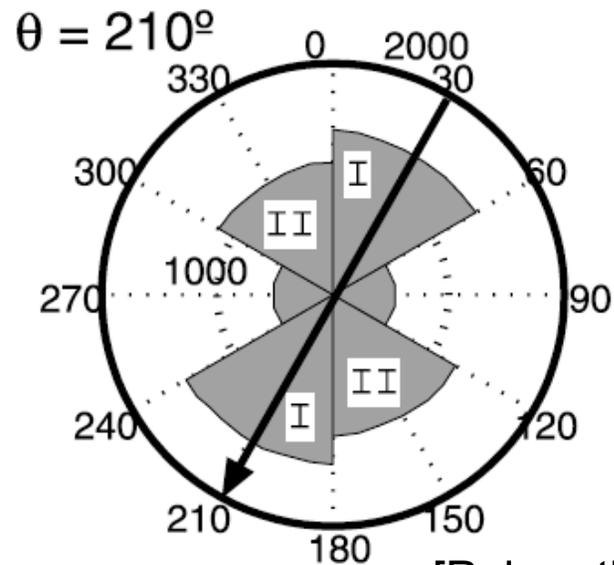
Cause of Hysteresis: Power input remains high in regions associated with recently visited clock angles (region II). Reason not yet known.

[Palmroth et al., GRL, 2006]

Energy input also depends on dipole tilt

- Dipole tilt varies with UT and season. It defines the geometry between the internal geomagnetic field and IMF

- Controls the polar cusp location [Zhou and Russell 1997].

- Shifts reconnection away from the sub-solar point [c.f., Maynard et al., 2002,2003; Park et al., 2006]. Reconnection rate is smaller because of increased magnetosheath flows [Park et al., 2006]

Projection of magnetic field magnitude for X > -15 R_E

(c) (X >-15R_E) Z 30R_E

Min B below sub-solar region

Y 30R_E

-30R_E

5 [nT] 0
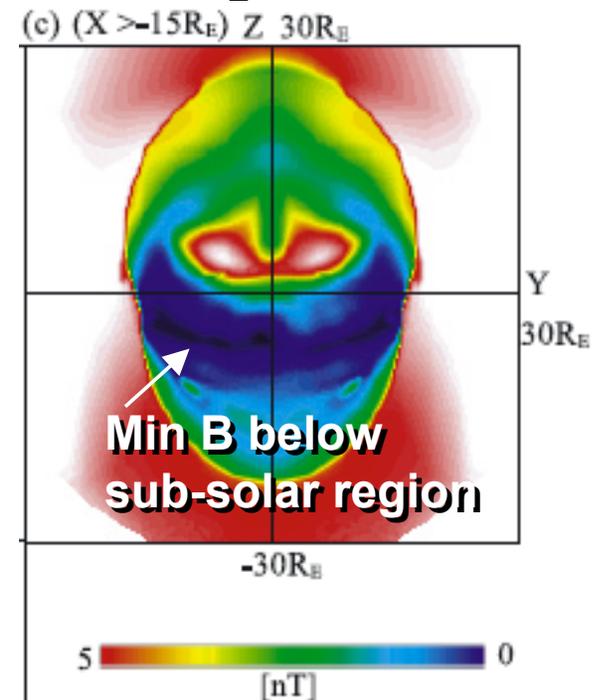
MHD simulation, purely southward IMF, 30° dipole tilt

Park et al., 2006

Dipole Tilt

Angle between the Earth's north dipole axis and the Z_{GSM} direction. Positive for tilts toward the sun

Question: How does the dipole tilt vary over a day and over the year? Does this mean that magnetic activity can have a UT dependence?
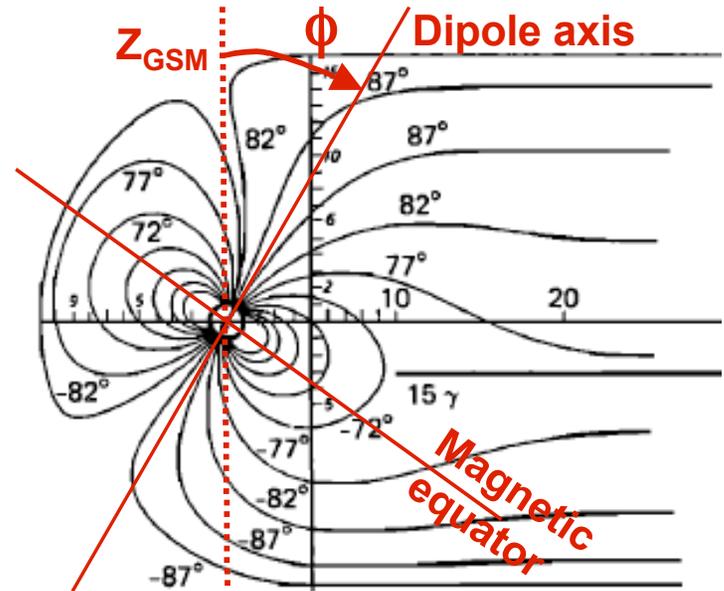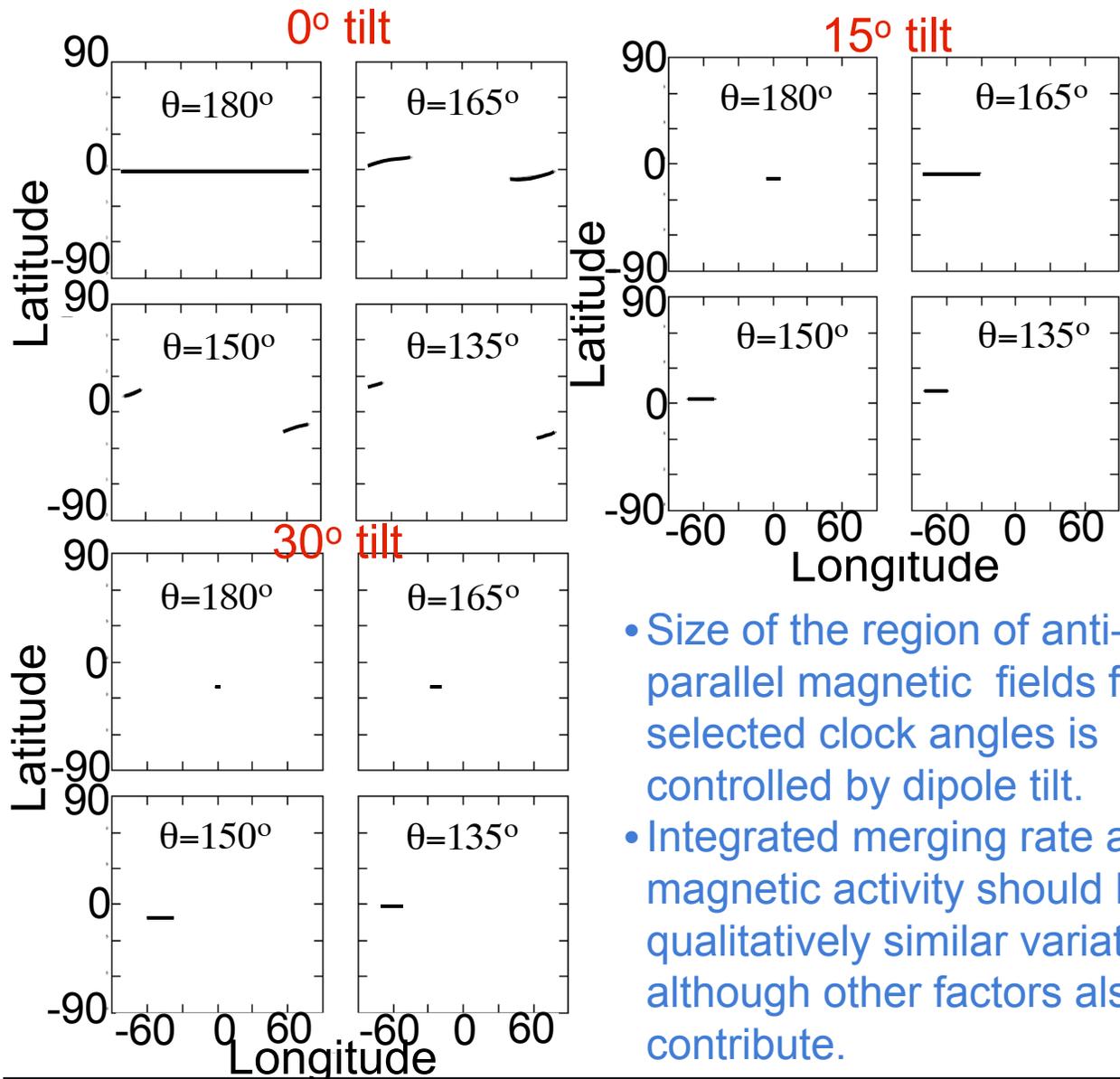
$$\Phi_{day} = 9.4 \cos \left[(UT - 17.29) \frac{2\pi}{24} \right],$$

$$\Phi_{year} = 23.4 \cos \left[(DOY - 172) \frac{2\pi}{365.25} \right],$$

$$\Phi_{tilt} = \Phi_{year} + \Phi_{day}.$$

Shue et al., GRL, 2002

Shue, PhD Thesis, 1993; Nowada et al., Planet. Space Sci., 2009

Dipole tilt may effect anti-parallel merging

0° tilt

θ=180° θ=165°
θ=150° θ=135°

Latitude (90, 0, -90) vs Longitude (-60, 0, 60)

15° tilt

θ=180° θ=165°
θ=150° θ=135°

Latitude (90, 0, -90) vs Longitude (-60, 0, 60)

30° tilt

θ=180° θ=165°
θ=150° θ=135°

Latitude (90, 0, -90) vs Longitude (-60, 0, 60)

Neutral Line Length (0°, 40°, 80°, 120°, 160°) vs Clock Angle of IMF, θ (180°, 160°, 140°)

0° tilt
15°
30°

- Size of the region of anti-parallel magnetic fields for selected clock angles is controlled by dipole tilt.
- Integrated merging rate and magnetic activity should have qualitatively similar variations although other factors also contribute.
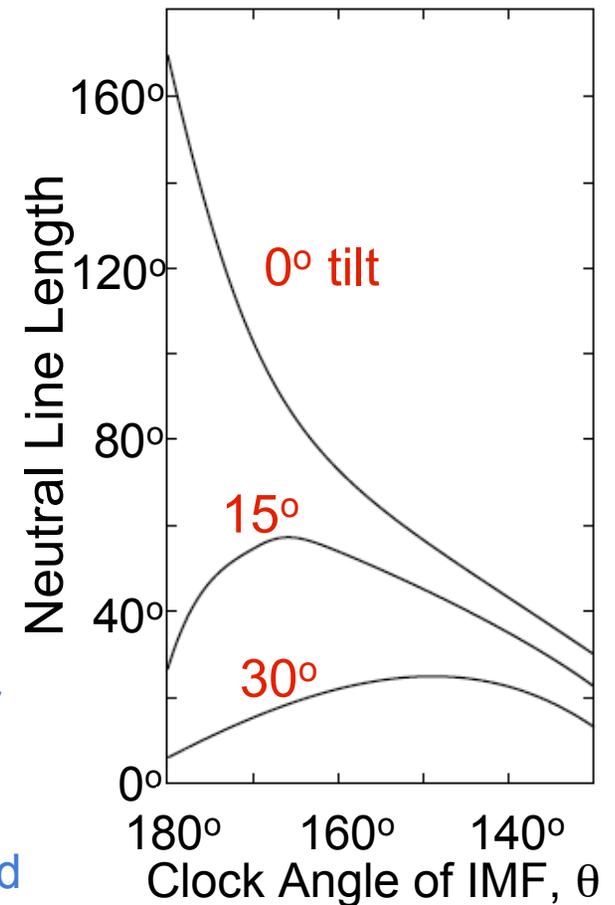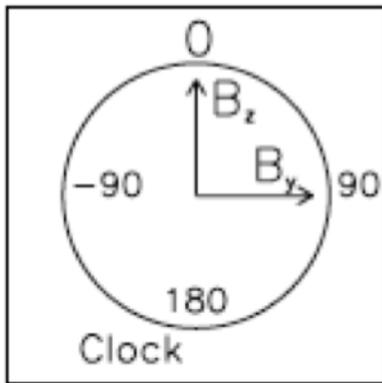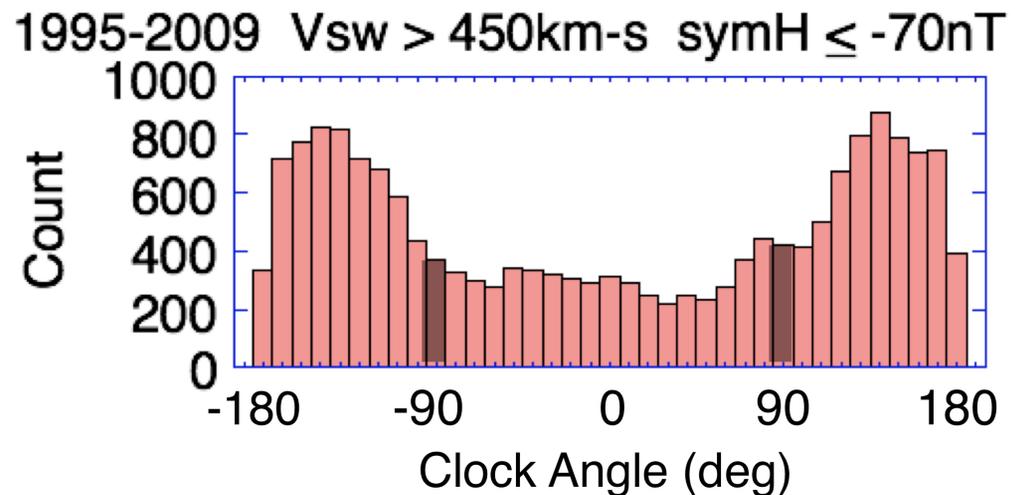
Russell et al., GRL, 2003

Geospace Response is strongly dependent on IMF Direction

- Reconnection happens where
  - IMF is ~anti-parallel to the magnetospheric field and convection drives the fields together.
  - Component reconnection in the sub-solar region can also play an important role.

- The orientation of the IMF has a major impact on
  - magnetospheric configuration
  - plasma populations
  - resulting magnetic activity.

- Allow solar wind mass and energy to enter the magnetosphere

- Results in large-scale circulation of plasmas and field lines results.

- Provides energy that powers all types of magnetic activity.

Direction of IMF during Active Times

1995-2009 Vsw > 450km-s symH > -30nT

1995-2009 Vsw > 450km/s -30 ≥ symH > -70nT

1995-2009 Vsw > 450km-s symH ≤ -70nT

Clock Angle (deg)

Oblique IMF is most common orientation
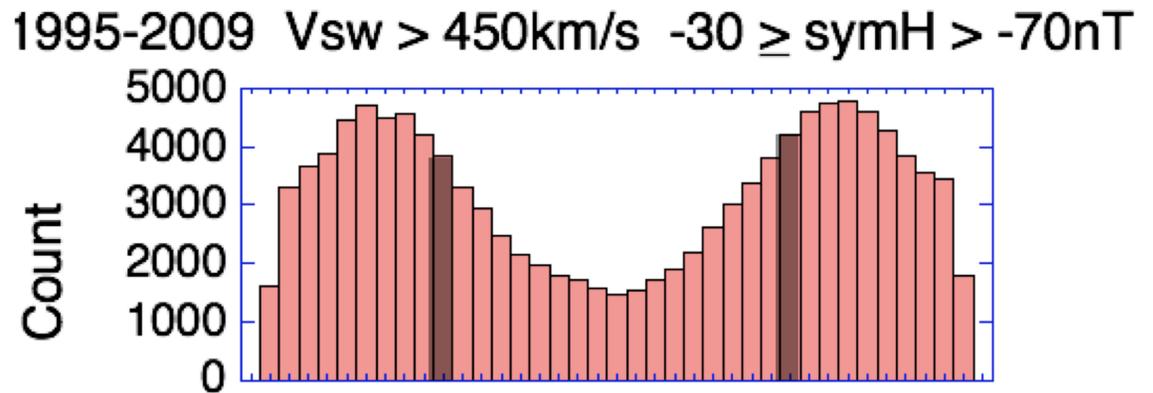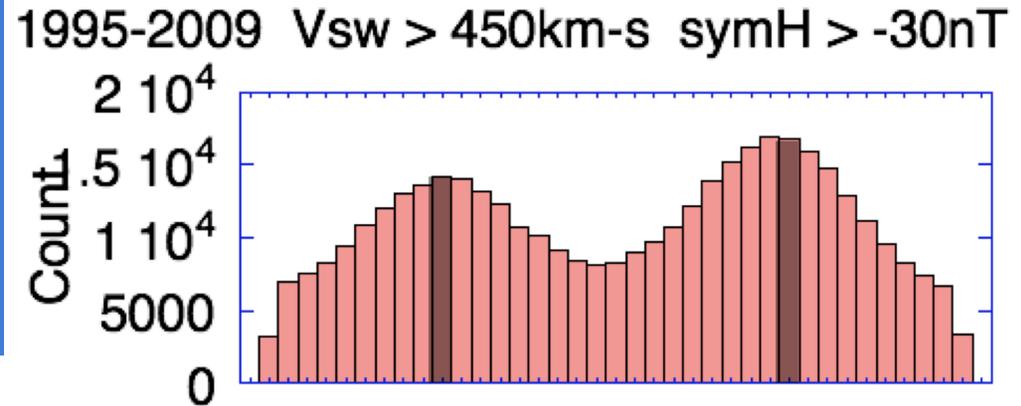
Effects of IMF Direction on the Geospace System
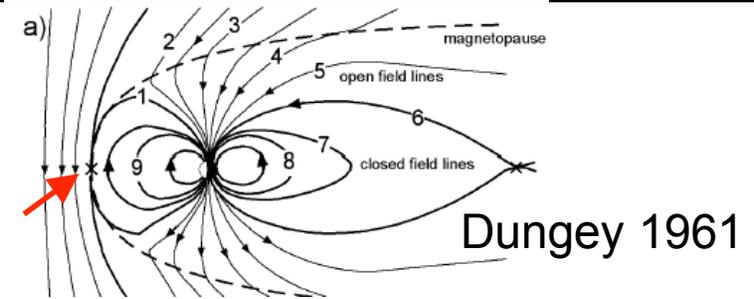
Southward IMF *Unique feature:* most effective solar wind energy transfer	Subsolar anti-parallel merging region. Reconnection rate is greatest here where magneto-sheath flows are slowest [c.f., Park et al., 2006].	 Dungey 1961
Northward IMF *Unique feature:* enables capture of large amounts of solar wind plasma [c.f., Li et al., 2008]	Poleward-of-cusp merging. Solar wind/magnetosheath capture occurs when merging takes place either simultaneously in both hemispheres or sequentially.	Reiff 1982
Oblique IMF (strong IMF By with small $\pm$Bz) *Unique feature:* multiple merging regions operating simultaneously	Five merging regions: • 2 anti-parallel high-latitude (cusp null) • 2 poleward of cusp (x null) • 1 sub-solar (component merging)	 Tanaka, 2007 Com-plicated convec-tion
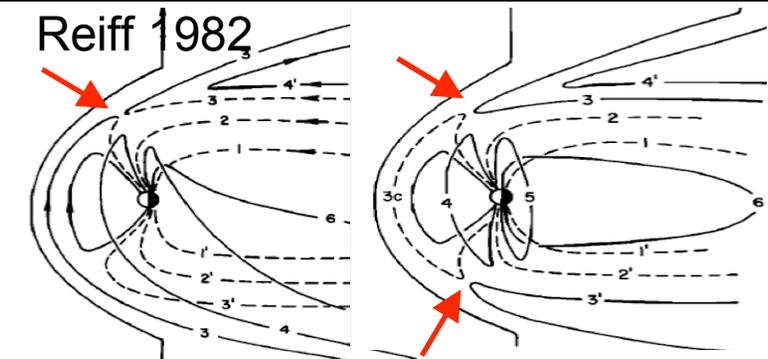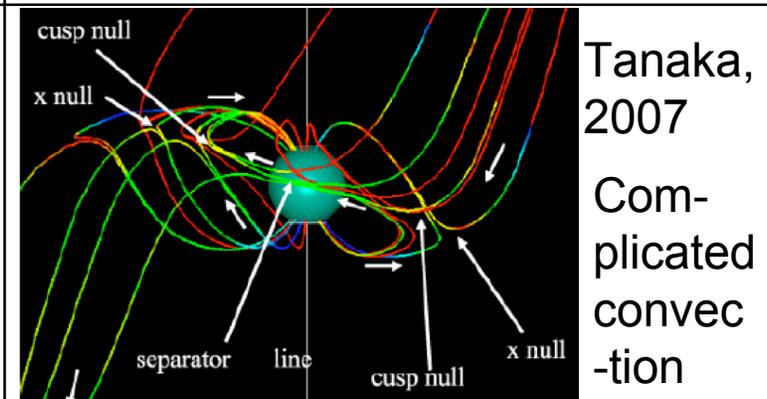
How does Southward IMF drive the geospace system?
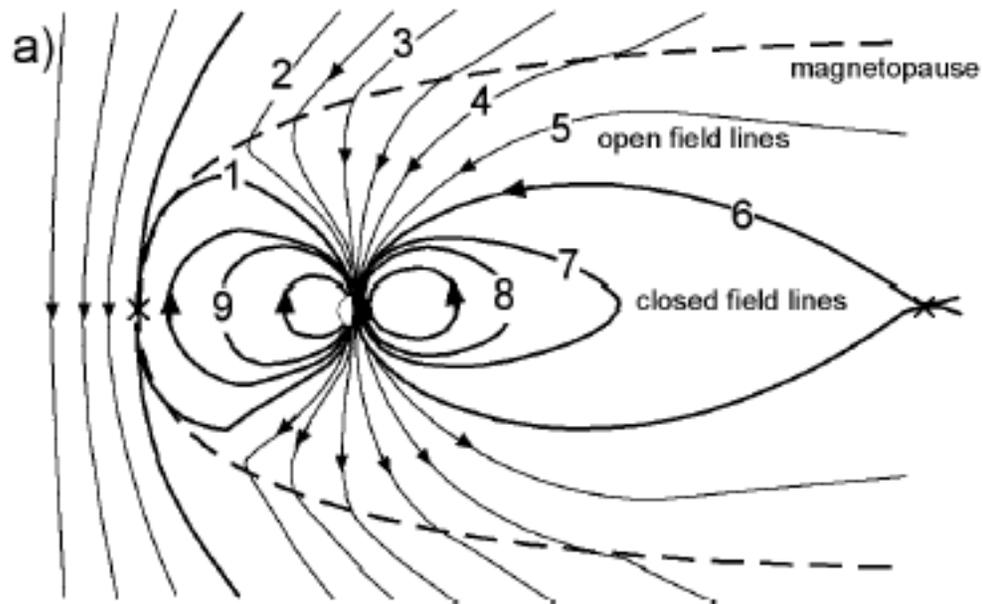
a) 2-cell convection pattern. Drives anti-sunward convection over the polar cap
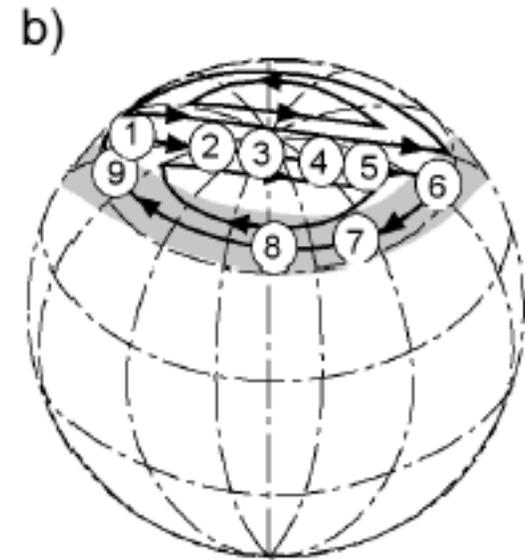
b) After Dungey [1961]. Figure from Palmroth [2003]

Treated in more detail in V. Vasiliunas lecture

Geospace Response - Southward IMF

[c.f., Gonzalez et al., 1994, and references therein]

- Strong long-lived dawn-dusk electric fields associated with the passage of strong southward IMF by the Earth are the primary cause of magnetic storms.

- Energy is transferred to the magnetosphere via magnetic reconnection. [Treated in V. Vasiliunas lecture]

  - Efficiency of the energy transfer ~10% for strong magnetic storms [Gonzalez et al., 1989]

- Convects plasma deep into the inner magnetosphere.   Along the way it is adiabatically and non-adiabatically energized to form the stormtime ring current. [See M. Liemohn lecture later this week].

- Solar wind dynamic pressure enhances the geo-effectiveness.

Table 1. $(B_z, \Delta T)$ Thresholds for Storms at 80% Occurrence Level (ISEE 3 Interval: August 1978 to December 1979)

	Dst, nT	B_z, nT	ΔT, hours
Intense	−100	−10	3
Moderate	−50	−5	2
Small (typical substorm)	−30	−3	1

How does northward IMF drive the Geospace system?

Solar wind / magneto-sheath plasma captured on closed field lines.

4-cell convection pattern. Drives sunward convection over the polar cap
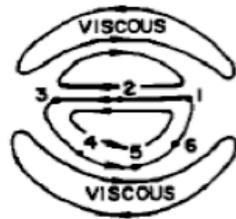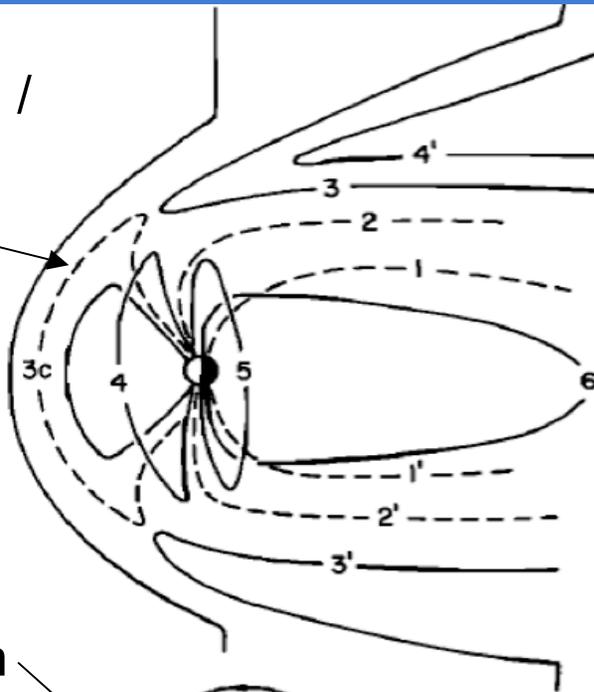
After Reiff, JGR, 1982

Simultaneous high-latitude reconnection

Sequential high-latitude reconnection

dipole tilt
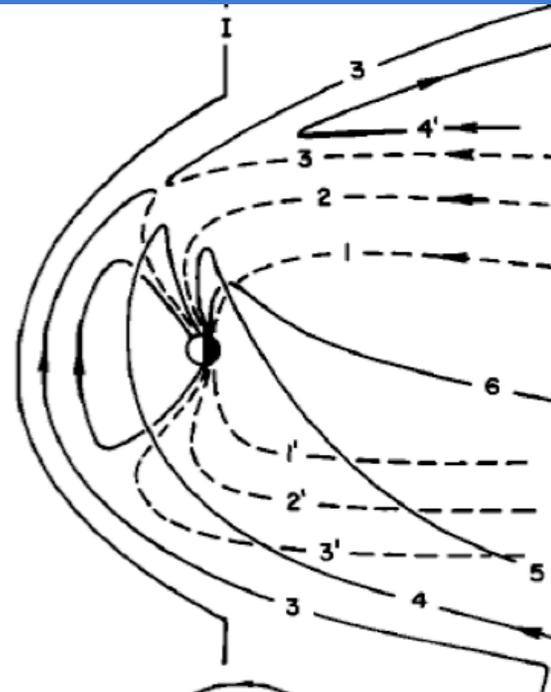
After Dorelli et al., JGR, 2007
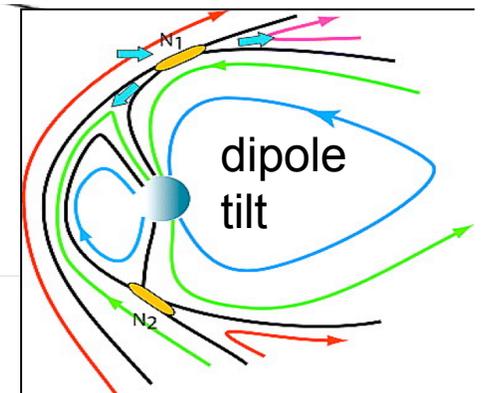
Geospace Response - Northward IMF

- During strongly northward IMF, simultaneous or nearly simultaneous double high-latitude reconnection results in a large rate of mass transfer from the solar wind into the closed field line region of the magnetosphere. [c.f., *Øieroset et al*., 2005, 2008; *Lauvraud et al*., 2006; *Li et. al.*, 2005, 2009; *Watanabe et al*., 2006; *Laitinen et. al.*, 2007

- This efficient mass transfer results in the formation of cold dense plasma sheets and the capture of stagnant solar wind plasma inside the dayside magnetopause.

- Some system effects:

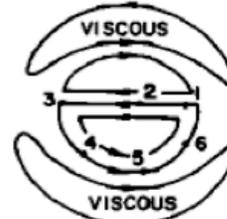 - Evidence that the addition of cold dense plasma to the dayside magnetopause region influences the reconnection rate [c.f., Borovsky and Denton, 2006; Borovsky et al., 2008].

  - Cold dense plasma sheet provides a particularly effective source population for the ring current that can be delivered to the inner magnetosphere during subsequent southward turnings of the IMF [c.f., *Thomsen et al*., 2003; *Lavraud et al*., 2005,2006]

How does oblique IMF drive the Geospace system?

Views from OPEN-GGCM

- **5 merging regions:** a sub-solar component and four anti-parallel high-latitude merging sites

- Shows field lines near the open-closed boundary

- Separator line is the 3D analogue of 2D x-lines.

- White arrows show B field direction

View from Sun
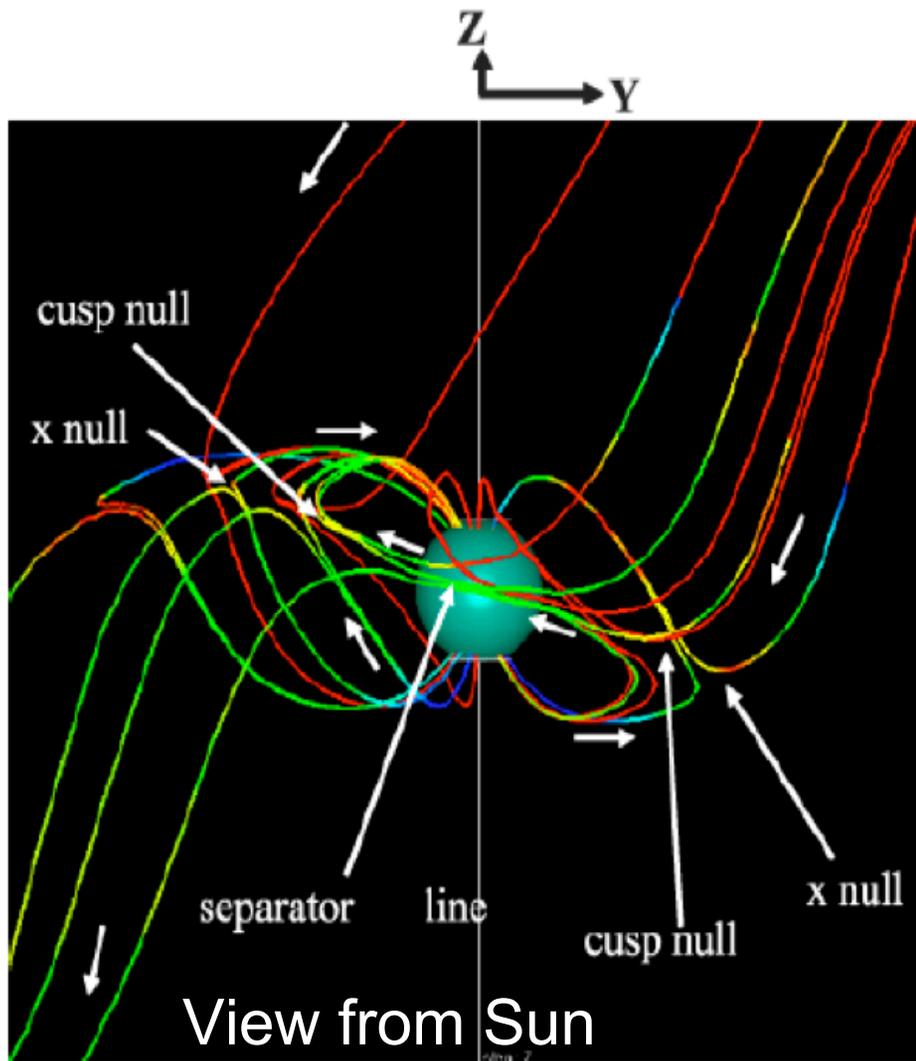
Tanaka, Space Sci Rev, 2007

Berchem, et al., JGR (2008)

component merging

— IMF
— open
— closed

$E_{||} = 0.5$ mV/m surfaces
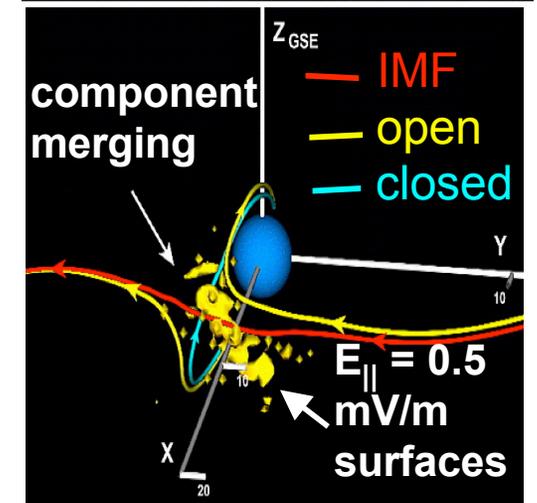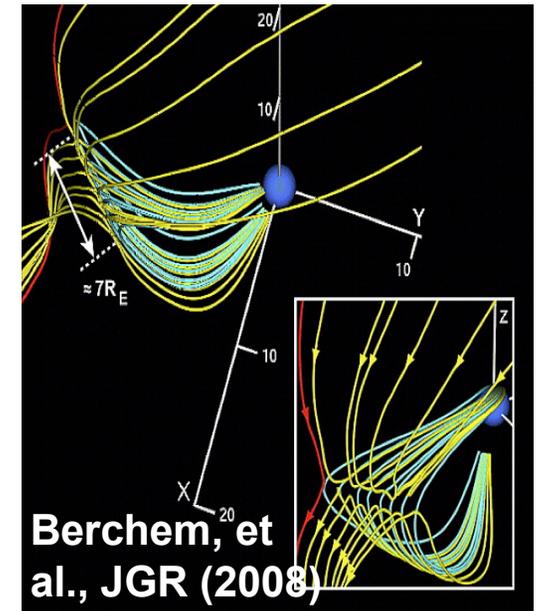
Convection patterns under oblique IMF

IMF dominated by +By, small ± Bz

Sandholt, et al., GRL, 2001
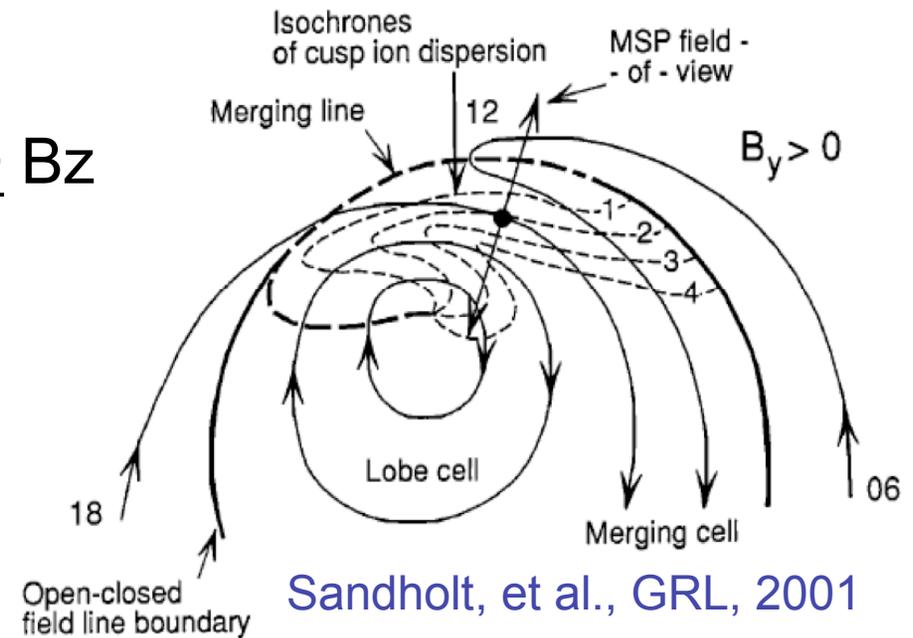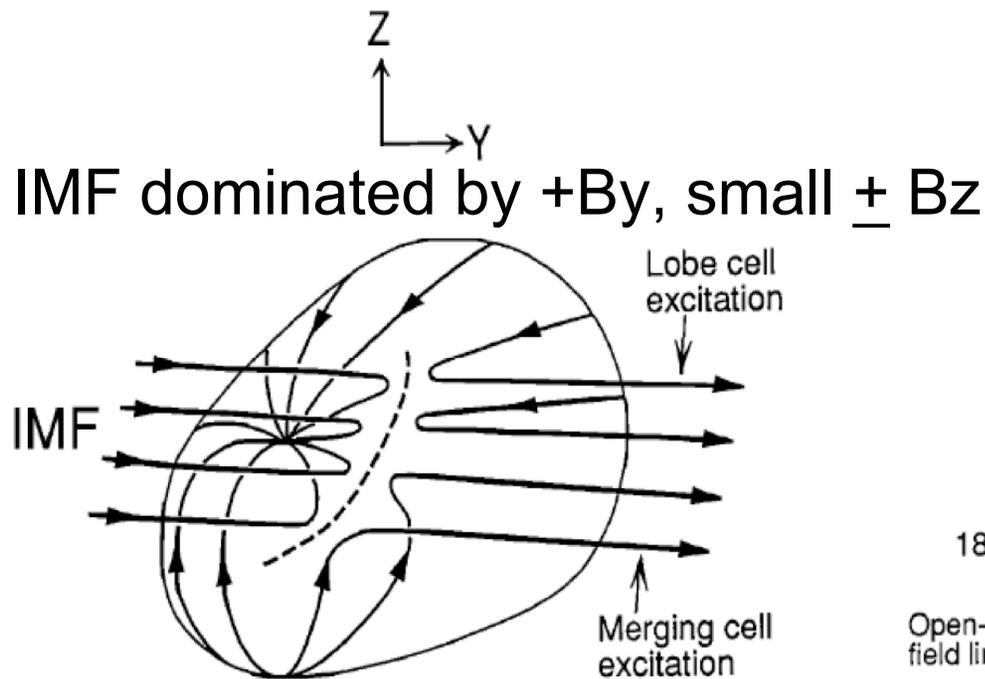
- Magnetic tension (resulting from kinks in the field lines introduced during the reconnection process) drags the field lines westward towards noon for negative IMF By and the reverse for positive IMF By.
- As field lines move in the dawn-dusk direction, they become less kinked and by the time they approach noon MLT they are moving largely tailward with the solar wind flow *[e.g., Smith and Lockwood, 1996]*.
- This initial dawn-dusk motion of the field line creates an east-west dispersion in the energy of precipitating ions [*Weiss et al*., 1995; *Wing et al*., 2001].

Visible evidence of the change of convection during oblique IMF compared to southward IMF
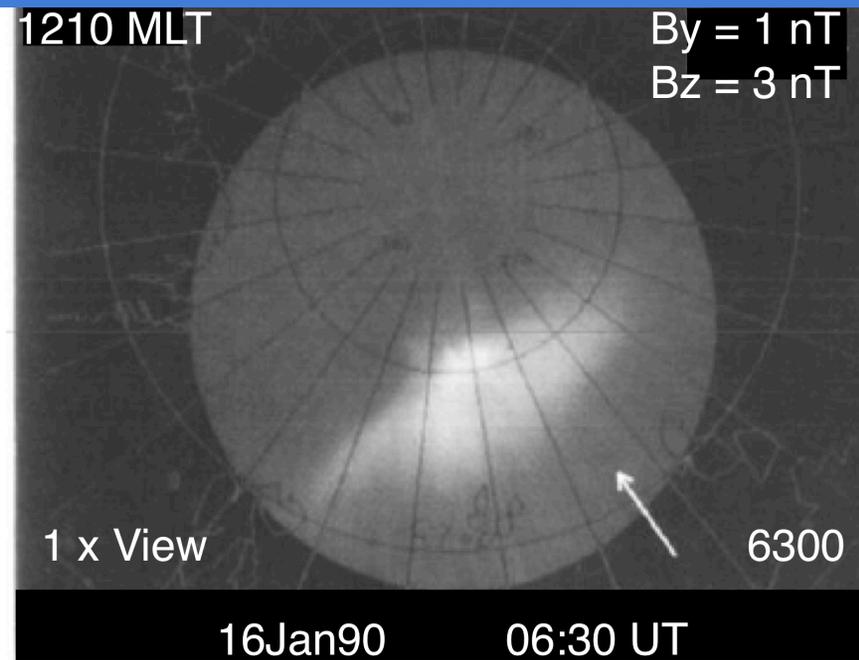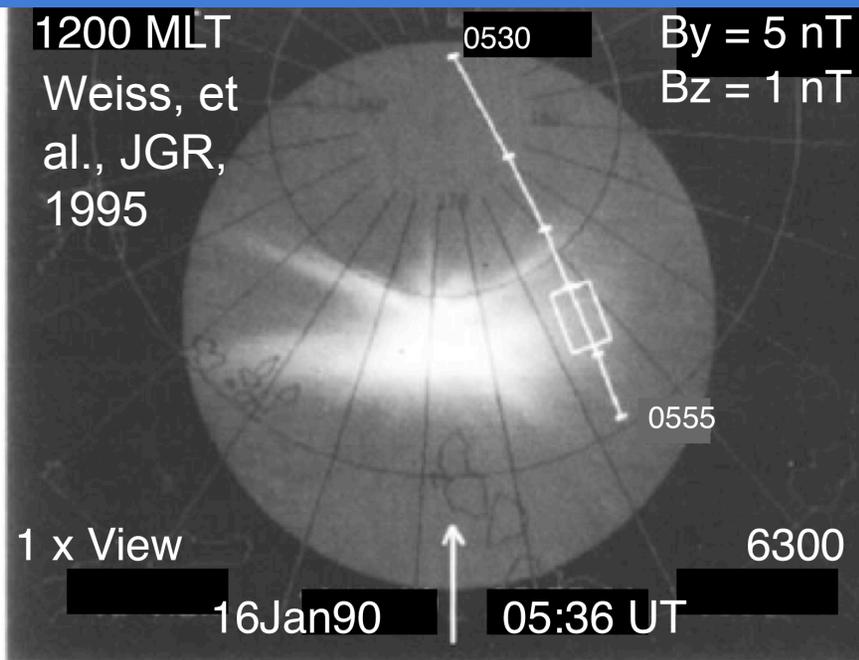
- Obliquely southward IMF conditions are statistically associated with the appearance of a cold dense ion population at geosynchronous orbit on the dawnside [*Lavraud et al*., 2006]. This is a separate population from the cold dense plasma sheet that appears near midnight after northward IMF intervals. Do multiple reconnection sites re-close open flux tubes to capture solar wind plasma?
- Oblique IMF is typical of high-speed streams, in which *fluctuating* magnetic fields from Alfven wave trains are superimposed on a Parker spiral IMF configuration --> Hysteresis and transition between states.

To summarize so far ….

- Energy input to geospace depends on (1) solar wind parameters, IMF strength and orientation and (2) dipole tilt.
- Each major IMF orientation (north, south, oblique) brings with it unique geospace consequences.
    - Southward IMF: Most effective solar wind energy transfer. Drives strong magnetic activity
    - Northward IMF: Captures large amounts of solar wind plasma on closed field lines. Produces cold dense plasma sheets which can be delivered into the inner magnetosphere if the IMF turns southward
    - Oblique: Multiple merging regions. Results in complicated convection patterns.
- Hysteresis occurs. Energy input depends on both present & recent IMF
- Simulations indicate that the magnetosphere takes 10-15 minutes to reconfigure and activate new merging sites. There is a time delay of 20-40 to reach maximum energy input after a change in the IMF.
    - Variations in solar wind and IMF parameters on shorter time scales (i.e.. In high speed streams and shocks) may mean the magnetosphere is in transition between known configurations a large part of the time

Trace back through system from geospace to Sun to identify geo-effective solar & heliospheric processes

Geoeffectiveness: Primary Parameters

Basic Parameters

- Simulations indicate that solar wind energy input controlled by:
  - IMF strength & orientation (pure IMF B_{south} most effective),
  - V_{sw}: high values intensify interplanetary electric field, drive strong shocks that accelerate solar particles
  - Dynamic pressure (V_{sw} more important than N_{sw} for a given pressure)

- Geoeffective solar wind disturbances
  - CMEs: Long-duration & strong IMF Bs. *Source:* solar eruptions
  - CIRs & HSS: Long-lived (up to ten days) intervals of high Vsw & fluctuating Bs. Typical IMF is oblique with small $\pm$ Bz. *Source:* Coronal Holes
  - Sheath regions: shocks, high P_{dyn}, high V_{sw}, compressed IMF Bs *Source:* propagation of solar ejecta through heliosphere

Geoeffectiveness: Modifying Factors

Modifiers

- **Solar Wind Density**
  - Correlated with plasma sheet density (ring current source) [c.f., *Borovsky et al.*, 1998]
  - Effects strength of ring current & magnetic storm
- **Low Alfven Mach no.**(high Bs, low Nsw)
  - Associated with saturation of the polar cap potential [*Ridley* 2005, 2007; *Kivelson and Ridley*, 2008]
  - Modifies magnetospheric response to extreme drivers
- **Northward IMF**
  - Efficient capture of solar wind plasma - can produce cold dense plasma sheet [c.f., *Li et al*, 2009]
  - If delivered to inner region by subsequent IMF Bs- amplifies ring current & storm intensity [*Thomsen et al.*, 2003]
  - Is this a factor in complex ICME ejecta?

Geoeffectiveness: Solar complexity

Super Active Regions (multiple eruptions)

- First CME clears path for rapid transit of subsequent CMEs [c.f., *Manchester et al.*, 2008]

- Previous CME still attached to AR provides scatter free pathway for SEP transit (CME Superhighway) [*Cane et al.*, 2005]

- Earlier eruptions precondition Geospace as new CMEs arrive

Open magnetic flux (Low latitude coronal holes)

- CHs deflect CMEs either toward or away from the Earth - deflected CME in 20 Nov 2003 superstorm closer to sun-Earth line [*Gopalswamy et al.*, 2009]

- CH-AR-Current Sheet (CHARCS) structures: intense storms associated with ARs close to the streamer belt and to growing low-latitude CHs [*Gonzalez et al.*, 1996].

- Distribution of low-latitude CHs controls geospace energy input during the declining phase of the SC. Can differ from cycle to cycle [*Gibson et al.*, 2009]
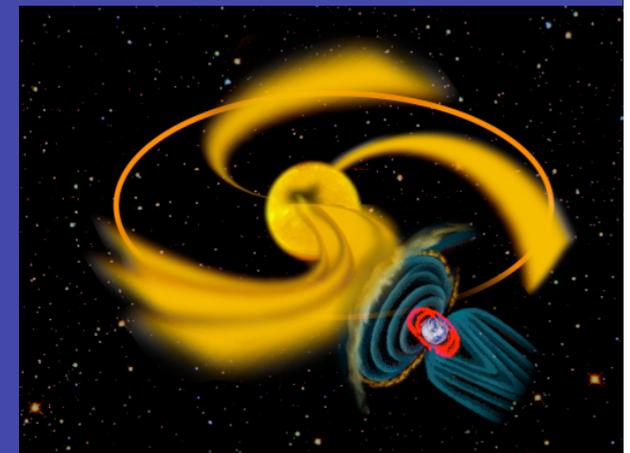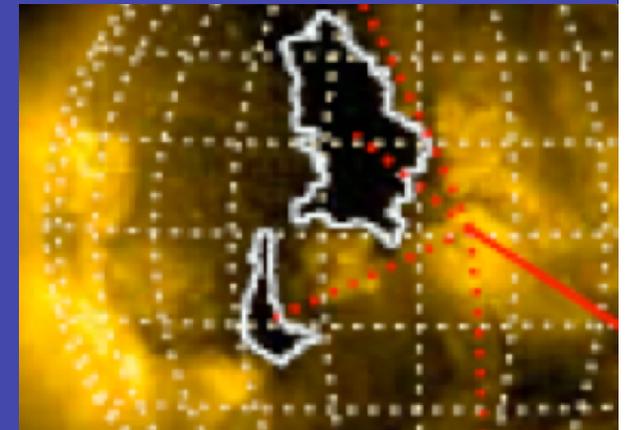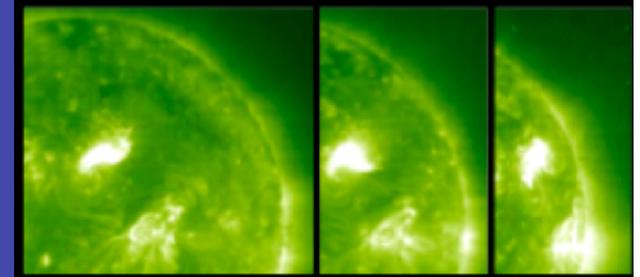
Geoeffectiveness: Solar complexity

CME-CME interactions

- Produce more efficient acceleration and stronger SEP events [*Gopalswamy et al.,* 2003]

- Produce omplex ICMEs that intensify storms [*Farrugia et al*., 2006]

Highly inclined CMEs with strong axial Bs - extremely geo-effective type of CME. Difficult to predict [*Gopalswamy et al*., 2005]

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