Energy and mass circulation in the magnetosphere

Research Seminar on Sun-Earth connections

University of Helsinki, spring 2006

Minna Palmroth

Space Research, Finnish Meteorological Institute

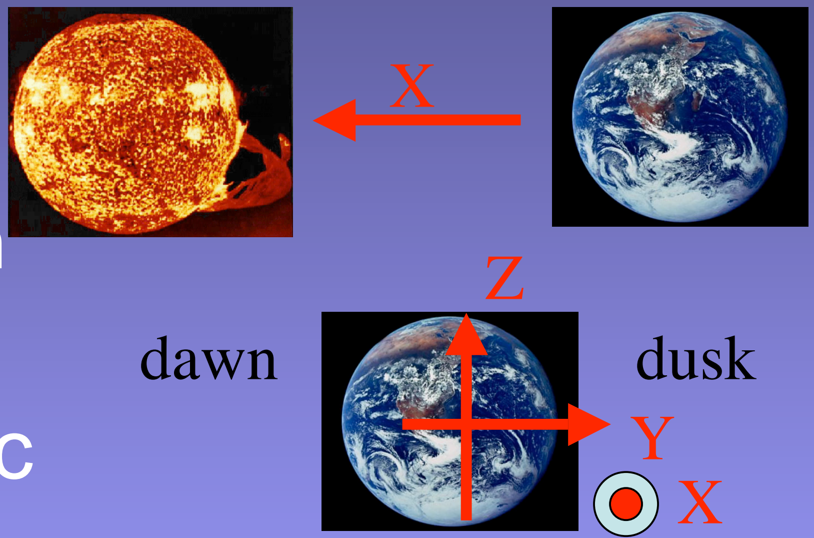
Helsinki, Finland

Lecture overview

1) General about energy and mass transfer
   - Earlier picture, current research
     - Main point in observations
2) Quantifying energy transfer
   - Earlier picture: Proxies, estimates
   - NEW: Use simulations!
   - NEW: Hysteresis in power input?
     - Main point in simulations

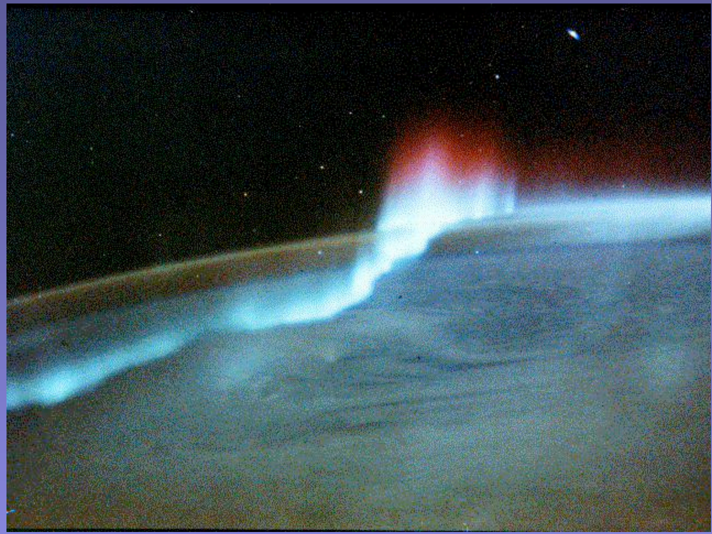
Nomenclature and definitions

- Coordinate system:
  - X towards Sun, Z usually towards magnetic pole (North Hem.), Y completes
- IMF: Interplanetary Magnetic Field
  - Solar magnetic field carried by solar plasma



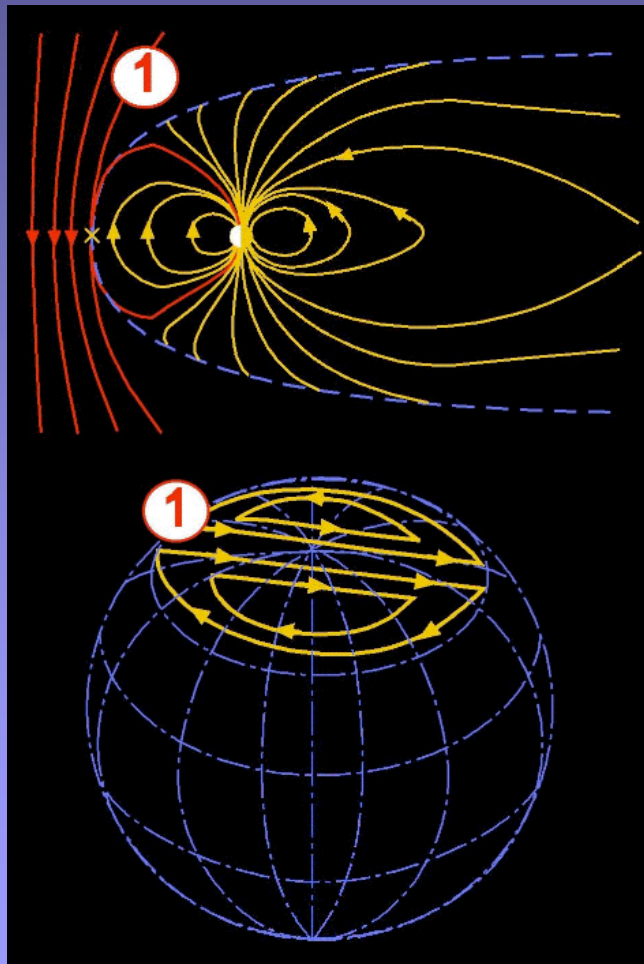
Motivation

- Solar energy fuels all dynamical features in near-Earth space
- Energy from
  - Reconnection (Dungey, 1961)
    - Details: next lecture
  - Viscous processes at magnetopause (Axford&Hines, 1961)
- Relative contributions (estimated) ~90%/10% (Kamide&Baumjohann, 1993)



Anecdote:
Reconnection vs. viscous interaction

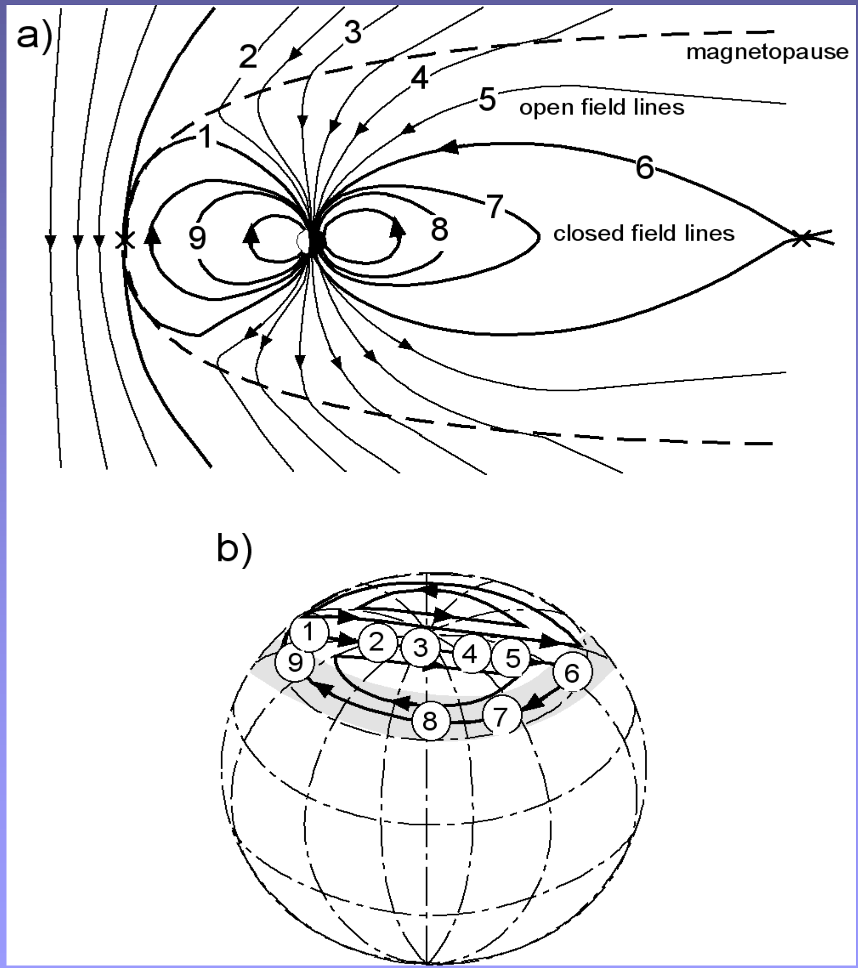
- Both start convection, philosophy different
- Reconnection:
  - Solar wind electric field maps along open field lines to ionosphere, electric field together with magnetic field cause field line motion (~90% of transferred energy)
- Viscous interaction at m'pause
  - Viscous forces drag field lines, field line motion together with magnetic field causes electric field over polar cap (~10% of transferred energy)



After Dungey, 1961

Dungey picture (1961)

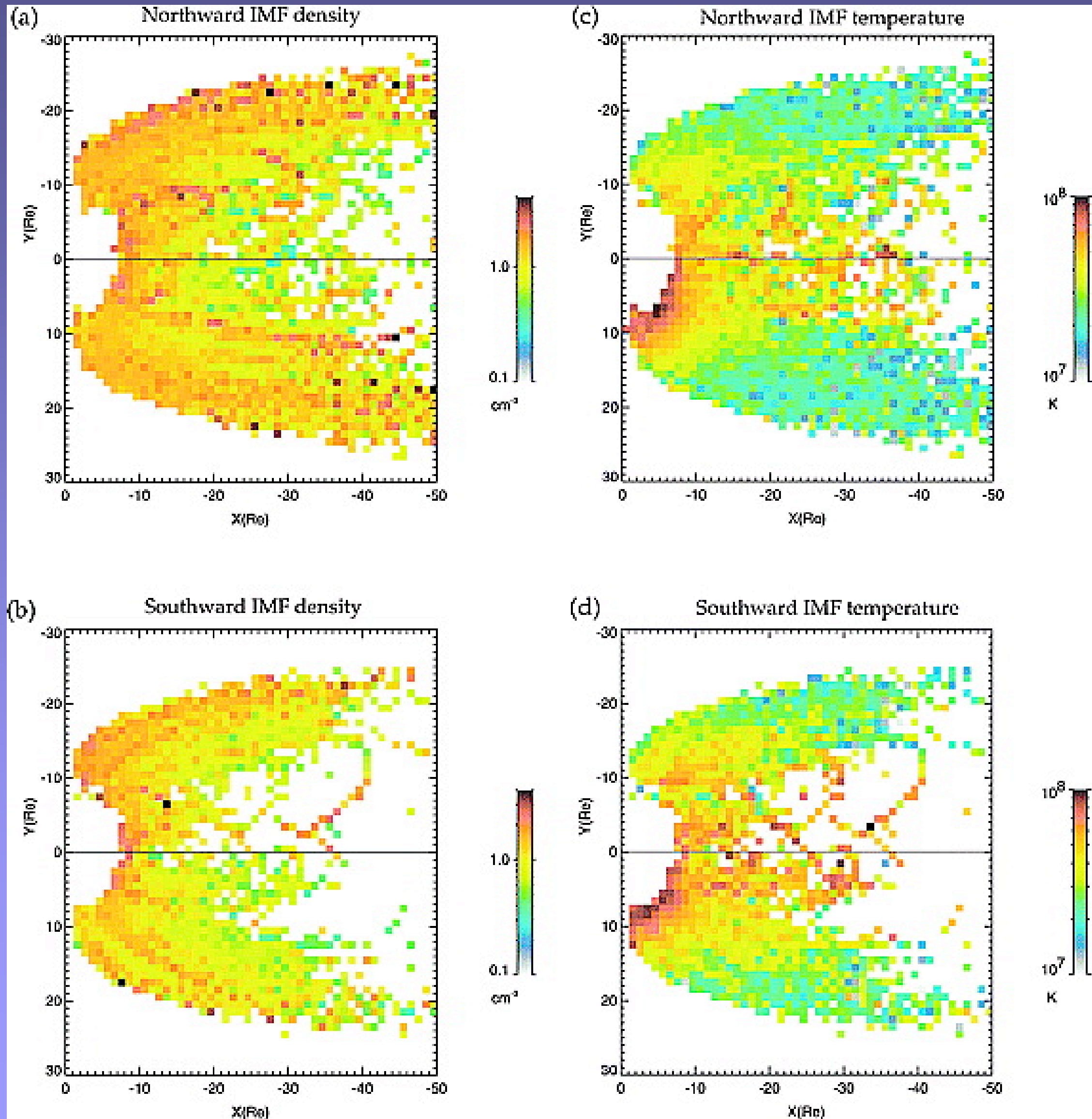
- Southward turning starts energy and mass entry at magnetopause
  - start of global convection
  - particle on open field line falls to closed field lines (plasma sheet) after tail reconnection
  - acceleration at reconnection line
    - Nightside aurora



After Dungey, 1961

Observations disagree with Dungey

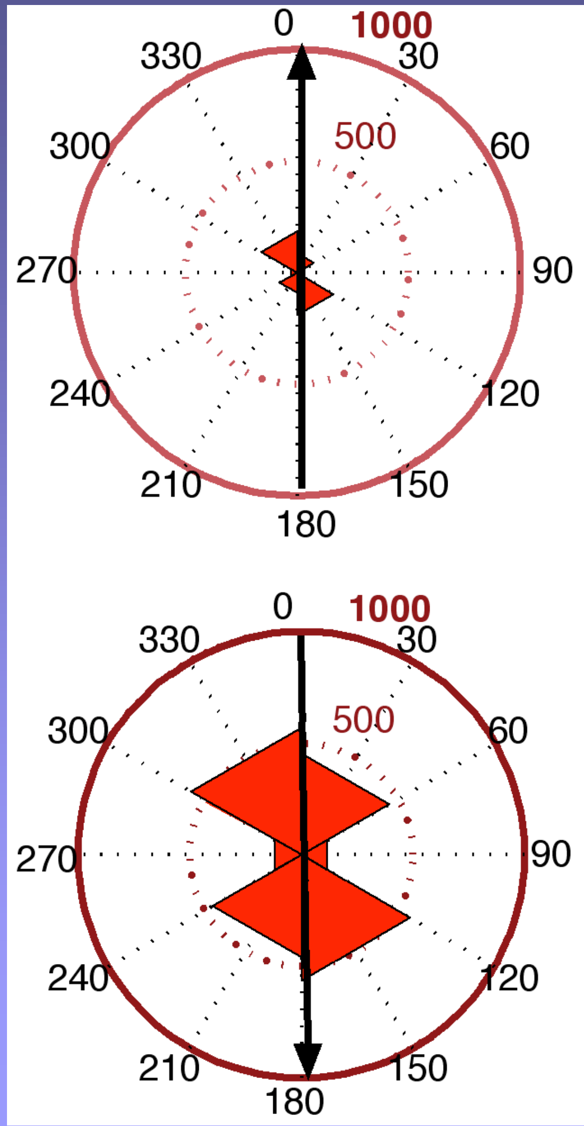
- Plasma sheet is
  - Hot (acceleration) but virtually *empty* during southward IMF
  - Cold and *dense* during northward IMF
    - Disagreement with entry of mass and energy during southward IMF
- => points to dominant mass entry during northward IMF?
- Energy still transfers during southward IMF!
  - E.g., Palmroth et al., (2003)



Wing and Newell (2002)

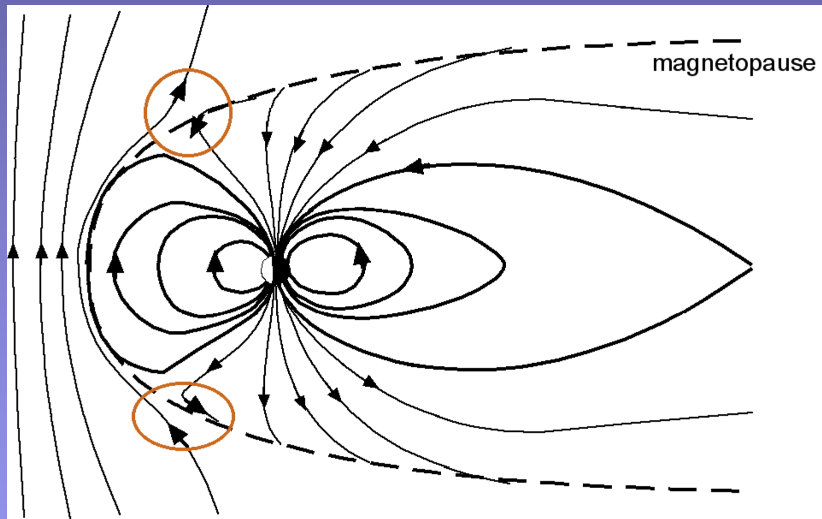
Observations disagree with Dungey

- Plasma sheet is
  - Hot (acceleration) but virtually *empty* during southward IMF
  - Cold and *dense* during northward IMF
    - Disagreement with entry of mass and energy during southward IMF
- => points to dominant mass entry during northward IMF?
- Energy still transfers during southward IMF!
  - E.g., Palmroth et al., (2003)



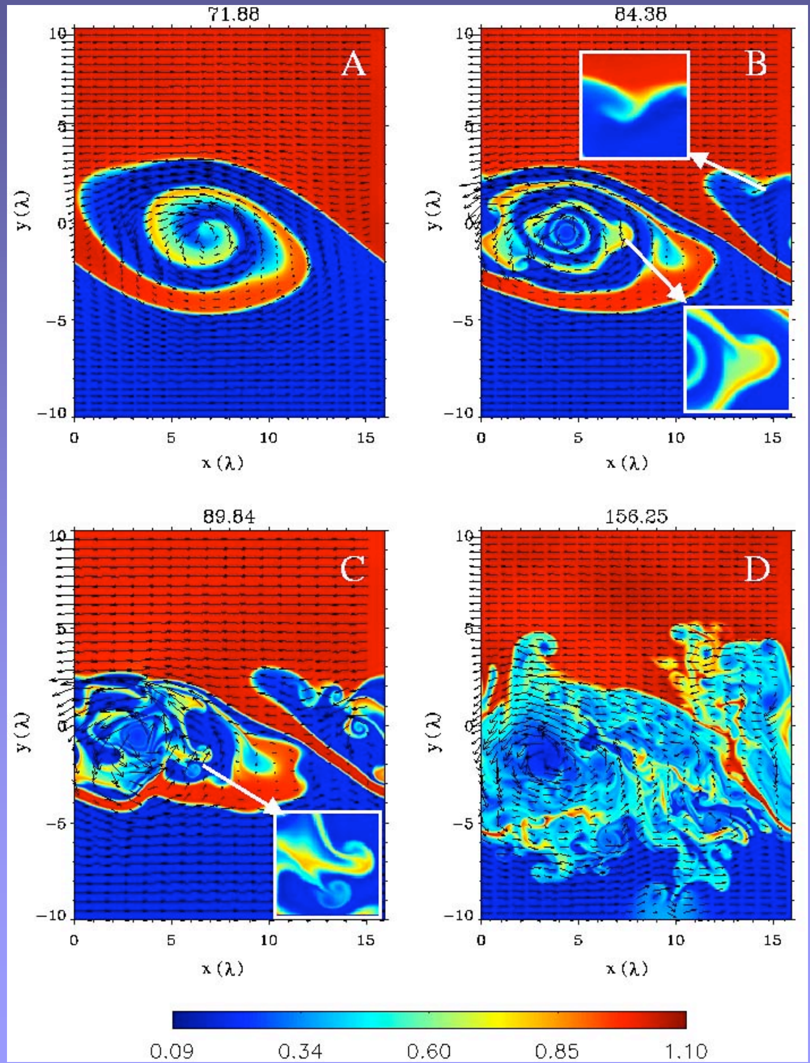
Mass transfer during northward IMF

- 2 possibilities (at least)
  - Behind-cusp reconnection
    - Mass enters through open field line but is not accelerated earth- or tailward (lack of tail reconnection)
  - Kelvin-Helmholtz instability at magnetopause
    - Fast solar wind flow creates waves at magnetopause, waves twine and reconnect
- Relative contributions unknown
  - active research topic



Mass transfer during northward IMF

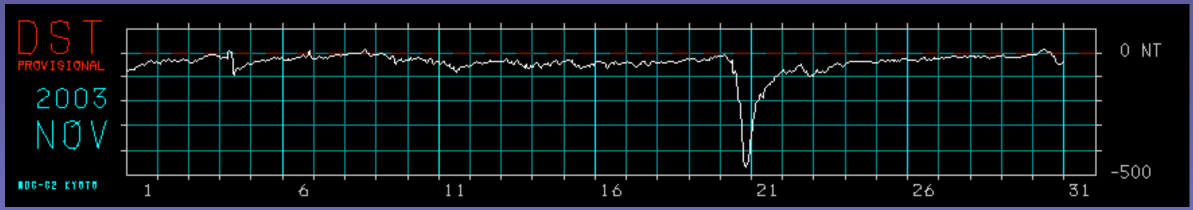
- 2 possibilities (at least)
  - Behind-cusp reconnection
    - Mass enters through open field line but is not accelerated earth- or tailward (lack of tail reconnection)
  - Kelvin-Helmholtz instability at magnetopause
    - Fast solar wind flow creates waves at magnetopause, waves twine and reconnect
- Relative contributions unknown
  - active research topic



Matsumoto&Hoshino (web)

Association to space weather

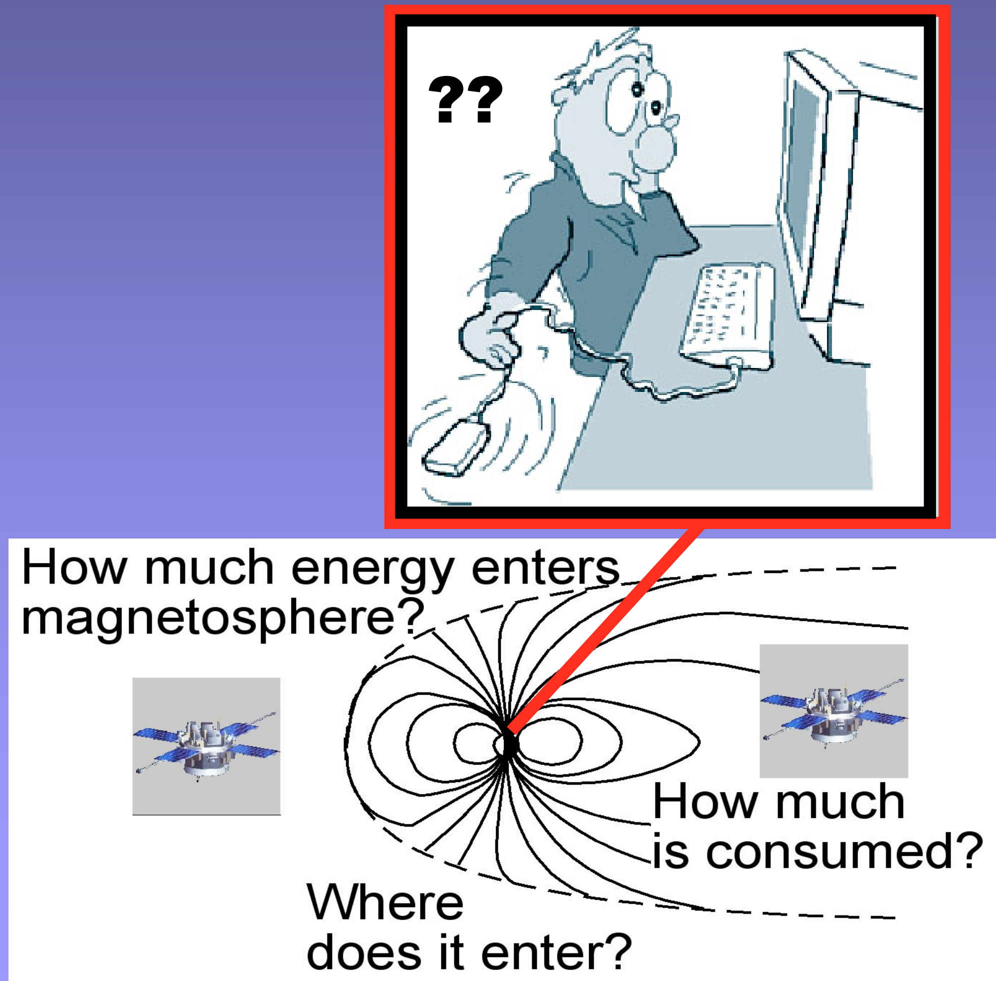
- Plasma sheet fills during northward IMF and accelerates during southward IMF
- The more there is plasma in the plasma sheet, the stronger is the ring current (and hence the magnetic storm) (Thomsen et al., 2003)
- The longer is the IMF northward before storm, the stronger is the storm?
  - This is a research exercise!



Aurora borealis at Athens, Greece, November 2003
© Anthony Ayiomamitis

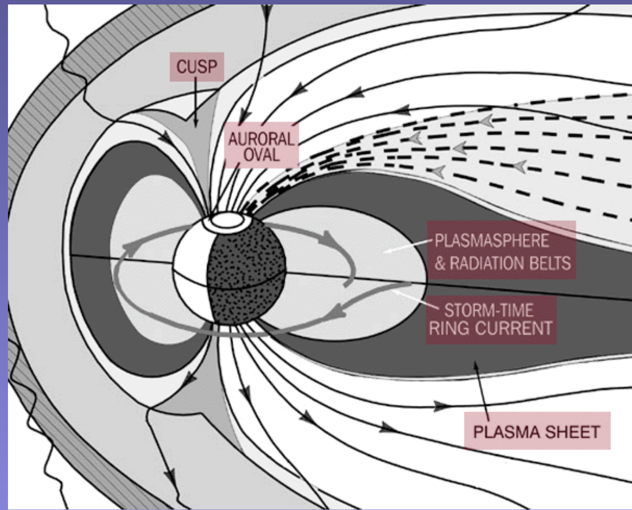
Quantifying energy transfer

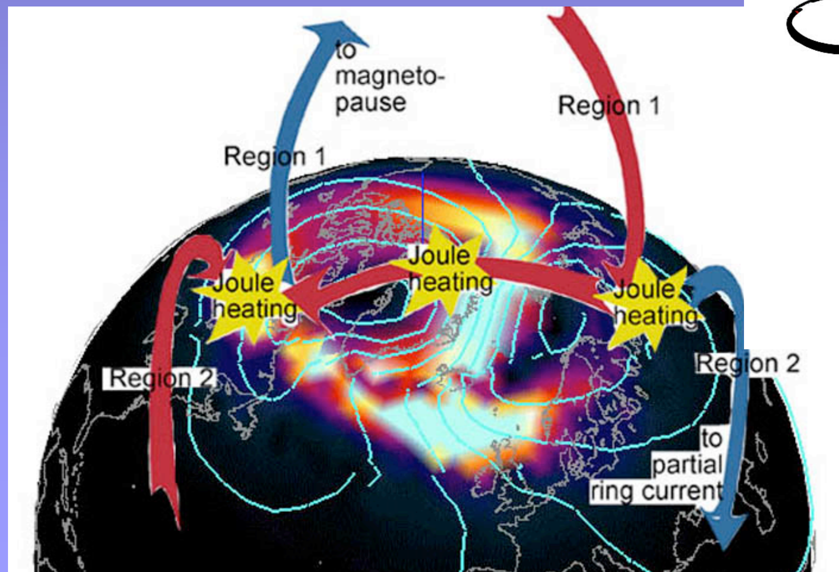
- Vast magnetosphere - cannot measure energy transfer globally using satellites!
- => comparative studies: correlate estimates of consumption to solar wind parameters
  - What comes out must come in
  - Equations, estimates
    - ε-parameter



Deriving epsilon (Akasofu, 1981)

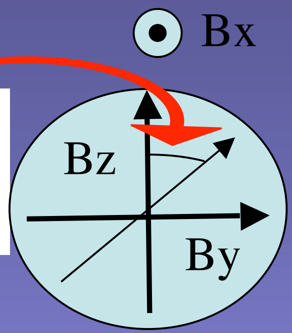
- Correlate input (solar wind) to output (magnetospheric and ionospheric energy consumption)
- Three output channels: P_{RC} (ring current; use Dst index), P_{JH} and P_{PR} (ionospheric Joule heating and auroral precipitation; use AE index)
- Find function of solar wind parameters that correlates with $P_{RC}+P_{JH}+P_{PR}$





Epsilon (Akasofu, 1981)

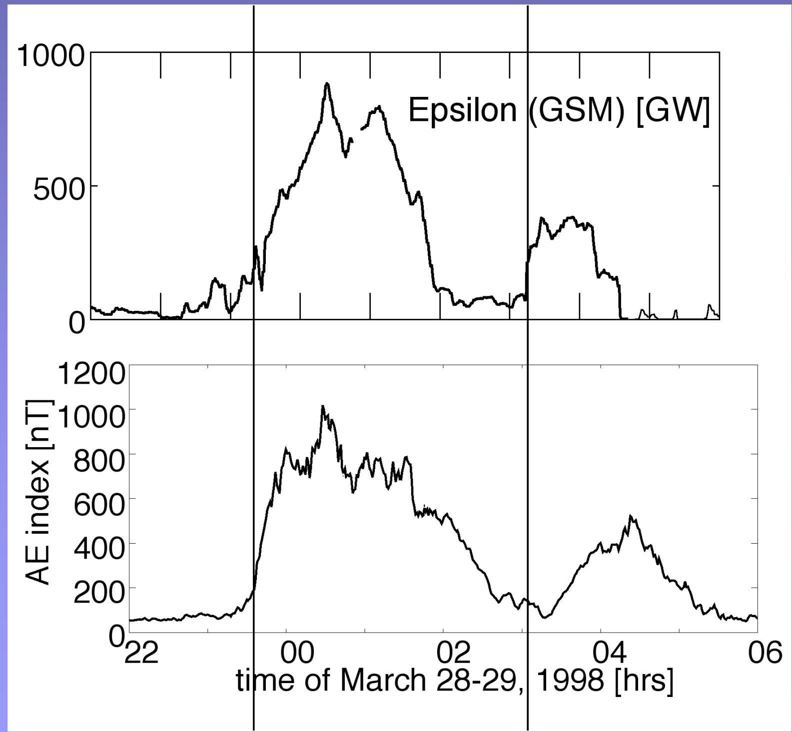
$$\epsilon = l^2 \frac{4\pi}{\mu_0} v B^2 \sin^4(\theta/2)$$



- Justification:
  - Solar wind electromagnetic energy over a sphere

$$4\pi l^2 \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \approx 4\pi l^2 \frac{1}{\mu_0} (\mathbf{B} \times \mathbf{v}) \times \mathbf{B} \quad [\frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}] = \frac{W}{m^2}$$

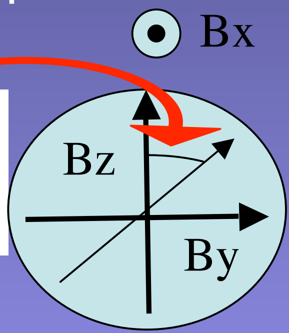
  - Restrict to southward IMF by sinus function (“half-wave rectified”)



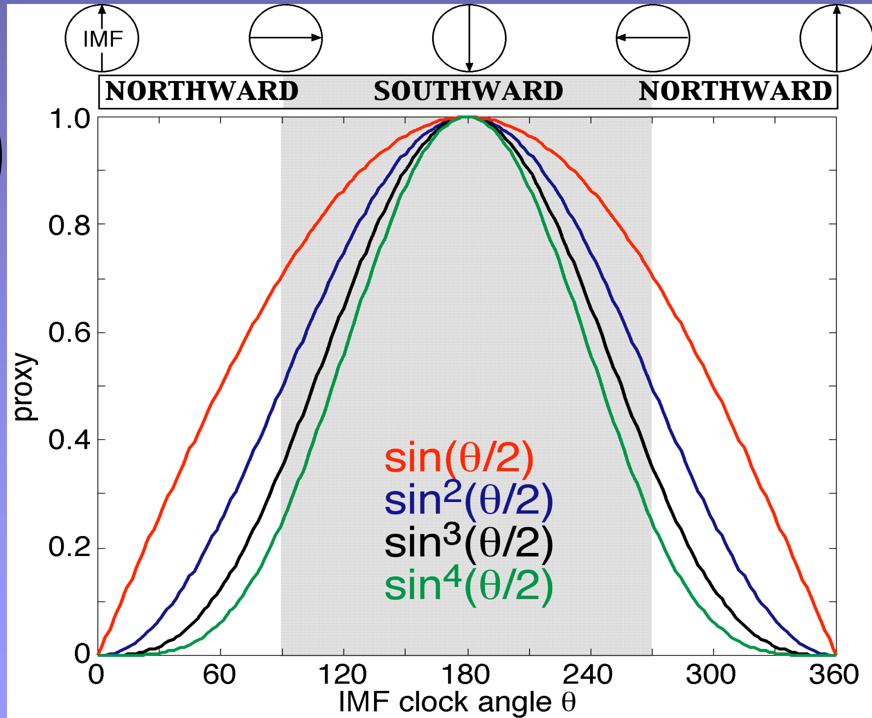
Angular dependency of proxies related to energy transfer

- Akasofu (1981)
  - Correlate AE and Dst with solar wind parameters

$$\epsilon = l^2 \frac{4\pi}{\mu_0} v B^2 \sin^4(\theta/2)$$



- Boyle et al. (1997)
  - Polar cap potential (often used to estimate reconnection efficiency) $\propto \sin^3(\theta/2)$
- Kan&Lee (1979)
  - Reconnection electric field $\propto \sin^2(\theta/2)$
- Gonzalez&Mozer (1974)
  - Potential $\propto \sin(\theta/2)$



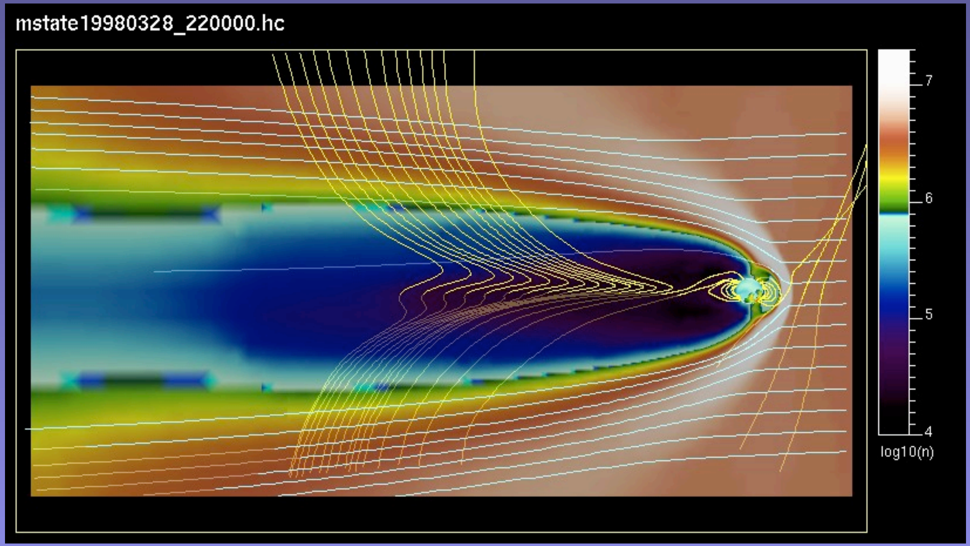
Typical problems to be solved with simulations

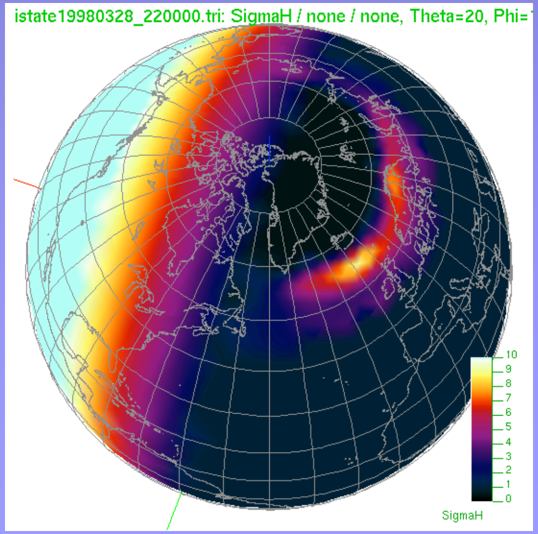
- Object of study far away, in-situ measurements not possible
  - Astrophysical objects
- In-situ measurements unrealistically expensive, simulations cheaper
- Phenomenon itself complicated (or global in nature), in-situ measurements provide only a glimpse of the situation
  - Global energy transfer in the magnetosphere!
- => Need to verify simulation performance

Utilizing global simulations in quantifying energy transfer

GUMICS-4, FMI's global MHD simulation

- Ideal conservative MHD
  - Solar wind, magnetosphere
- Boundary and initial conditions
  - Solar wind parameters
  - Dipole field
  - Ionosphere
- M-I coupling
  - To ionosphere: precipitation, field-aligned currents
  - From ionosphere: electric potential





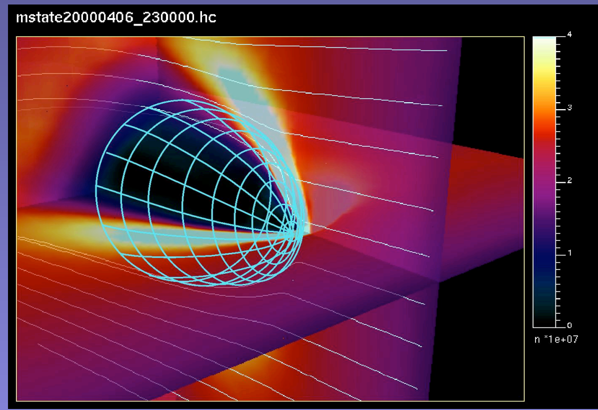
Energy transfer at magnetopause: Method

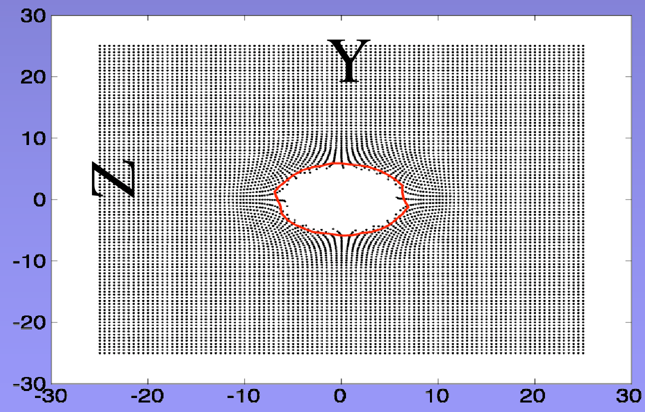
- Required steps using GUMICS-4:
  1. Find magnetopause surface from simulation (map streamlines)
  2. Determine surface element normal **n** and area dA
  3. Find GUMICS-4 total energy **K** at the surface location
  4. Determine the portion that is going inward

$$dE_q = dA\mathbf{K} \cdot \hat{\mathbf{n}}$$

  5. Surface total power: Sum over surface

$$P_s = \int dE_q$$



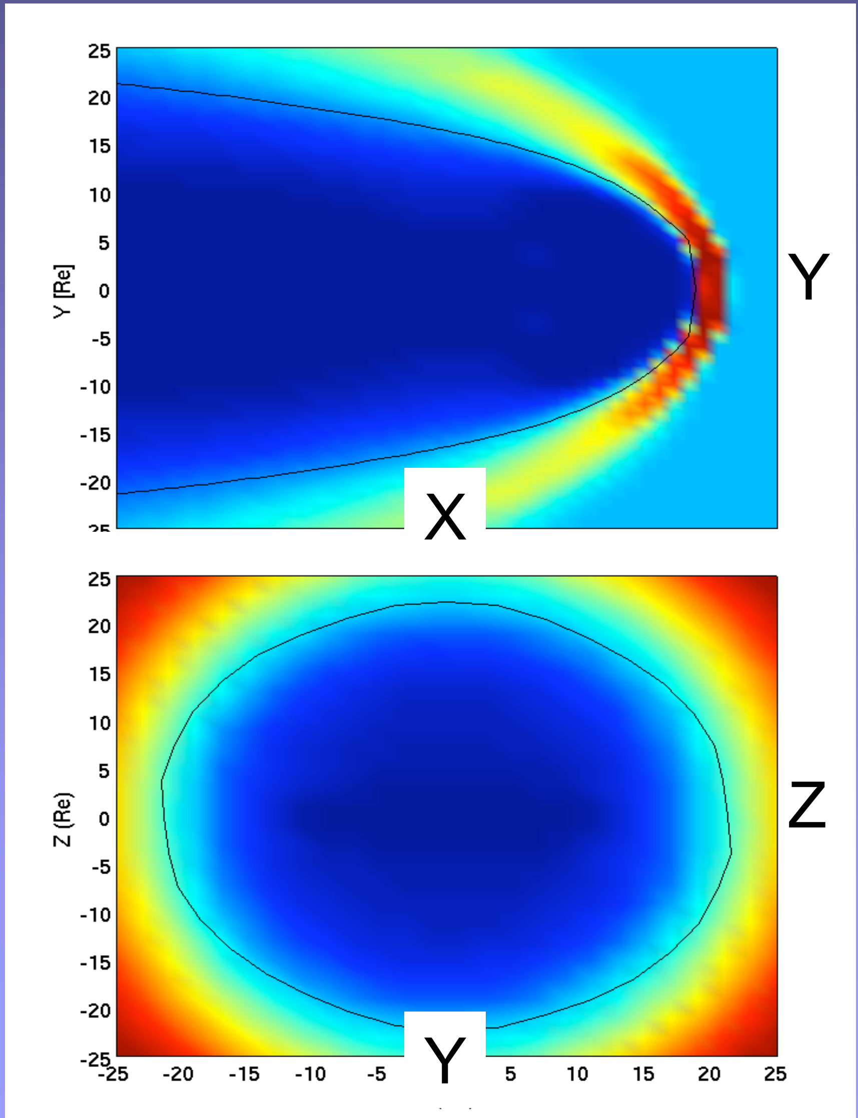


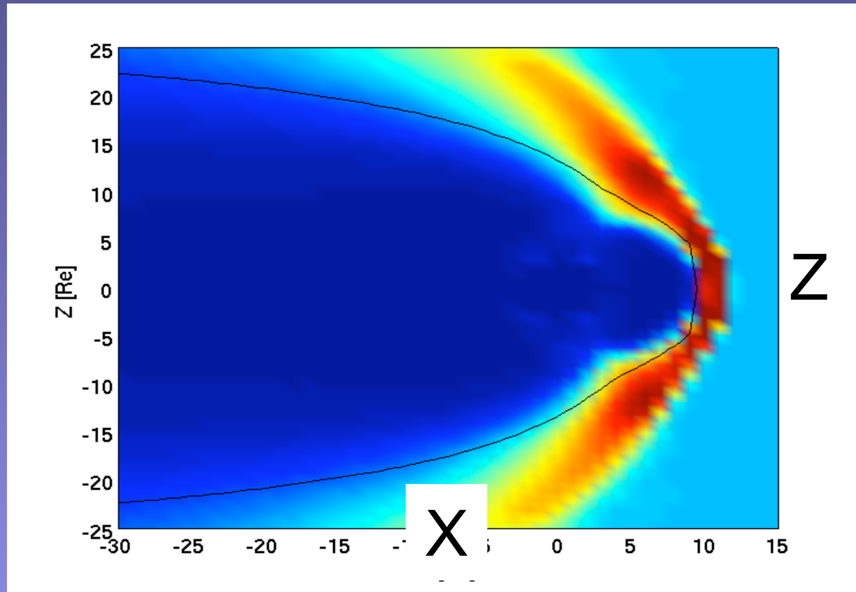
Palmroth et al., 2003

$$\mathbf{K} = \left(U + P - \frac{B^2}{2\mu_0}\right)\mathbf{v} + \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}$$

$$U = \frac{P}{\gamma - 1} + \frac{1}{2}\rho\mathbf{v}^2 + \frac{\mathbf{B}^2}{2\mu_0}$$

Accuracy of method



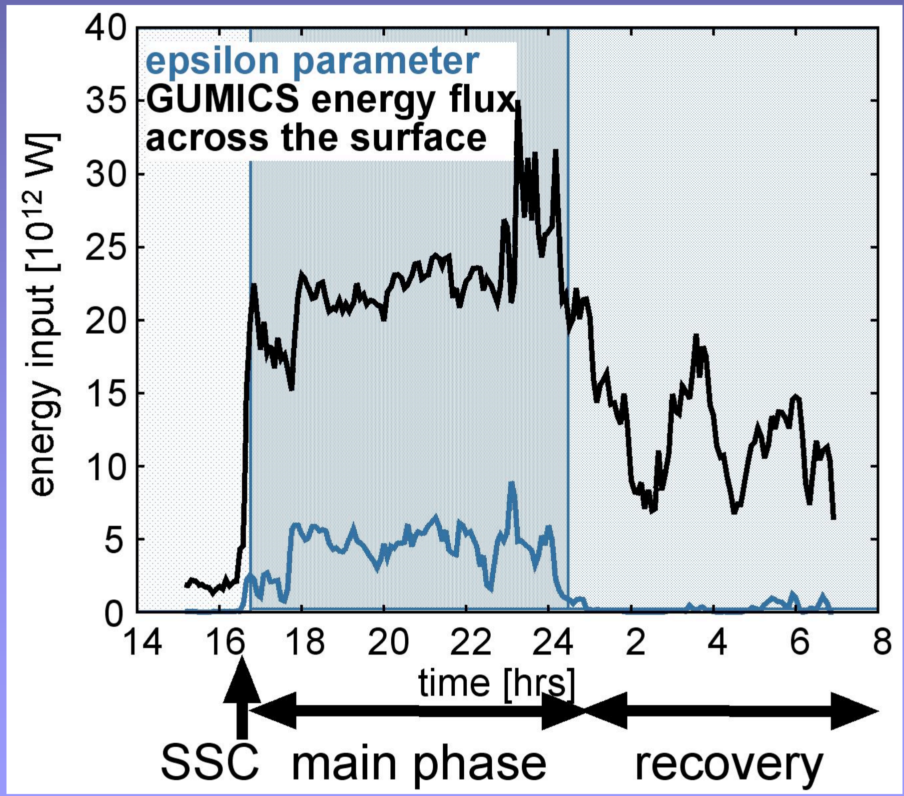


- Streamline-defined surface coincides with density gradient
- Surfaces smooth
  - -normal vector well-defined
- Total (summed) power vary by constant if surface location change by 1-2 grid cells
  - temporal evolution not affected

Total energy flux through magnetopause in GUMICS-4

- Temporal variation
  - Similarities to ε
  - Differences to ε
    - SSC, recovery
- Larger than epsilon
    - ε scaled to output
- Similar results in other events

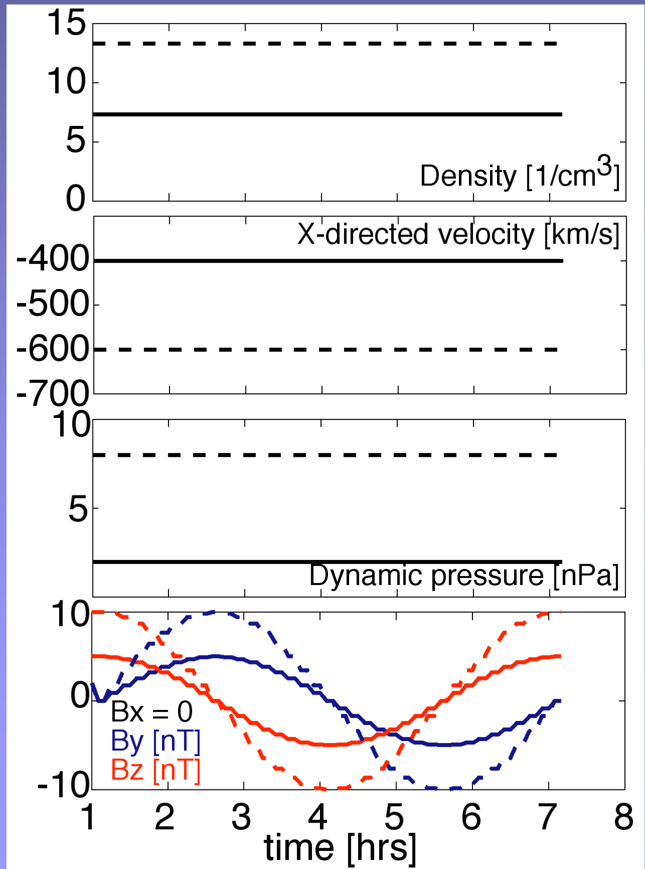
April 6-7, 2000, major storm



Angular dependency of energy transfer at magnetopause

- Which of the powers of sinus characterize the energy transfer in simulation?
- 4 synthetic runs with controlled solar wind
  - IMF clock angle rotates 360° with 10°/10min rate

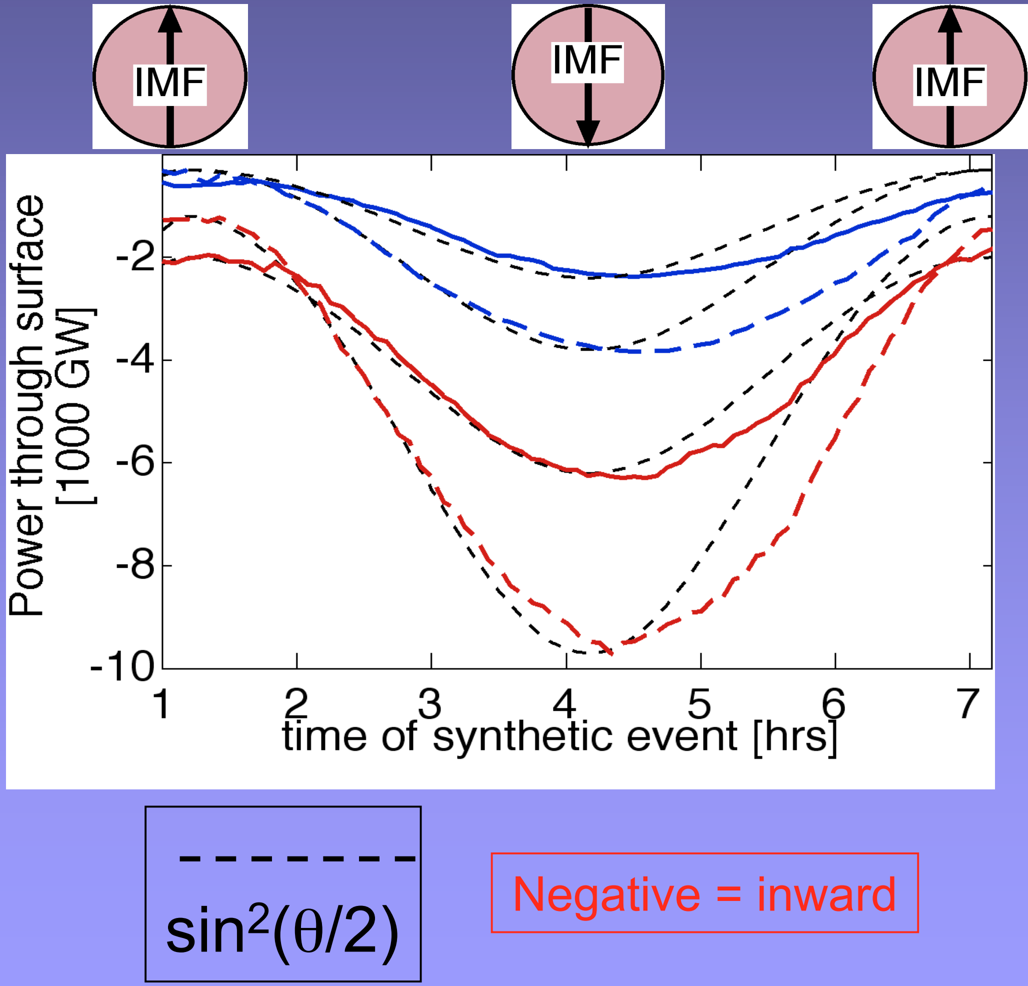
	Small p	High p
Small IMF	|IMF| = 5 nT Pdyn = 2 nPa	|IMF| = 5 nT Pdyn = 8 nPa
High IMF	|IMF| = 10 nT Pdyn = 2 nPa	|IMF| = 10 nT Pdyn = 8 nPa



Angular dependency of energy transfer at magnetopause

- 4 synthetic runs with controlled solar wind
  - IMF clock angle rotates 360° with 10°/10min rate

	Small p	High p
Small IMF	|IMF| = 5 nT Pdyn = 2 nPa	|IMF| = 5 nT Pdyn = 8 nPa
High IMF	|IMF| = 10 nT Pdyn = 2 nPa	|IMF| = 10 nT Pdyn = 8 nPa

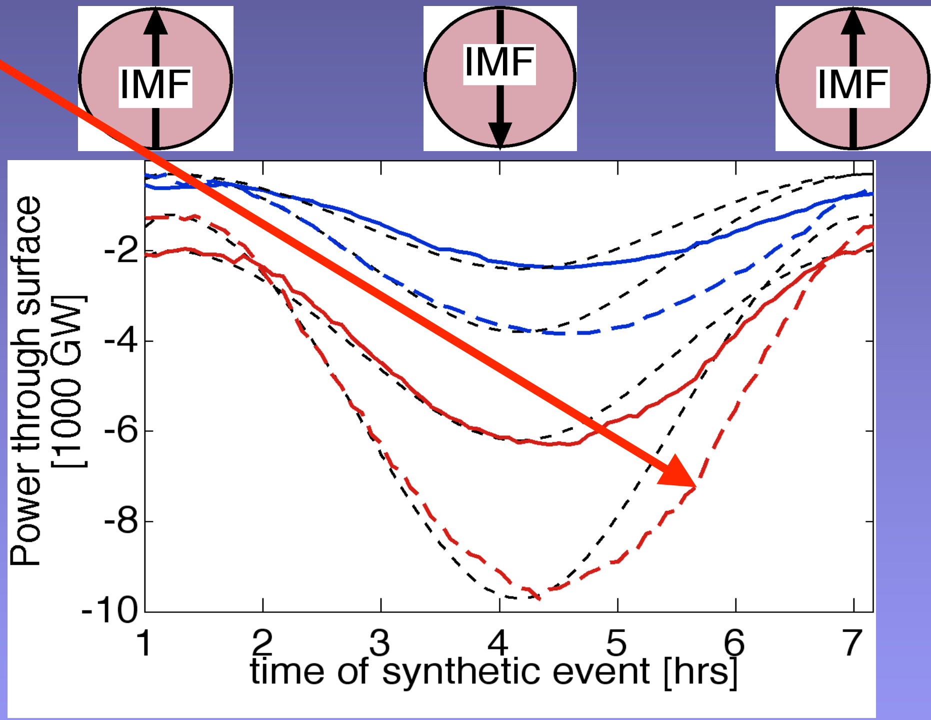


Negative = inward

Hysteresis in power input P_s?

- Caused by convection time delay? NO
  - Energy input continues as long as open field lines convect towards tail reconnection region
- Caused by method? NO
- Caused by simulation? Possibly NO
- Unknown phenomenon in nature? It seems so!
  - Poynting vector at magnetopause seems to be the cause (largest constituent of **K**)

Ask printouts of Palmroth et al., (2006) for further details



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

$$P_s = \int dA \mathbf{K} \cdot \hat{\mathbf{n}}$$

Total energy flux has memory?

- Poynting vector **S**: largest constituent in total power
  - Through surface

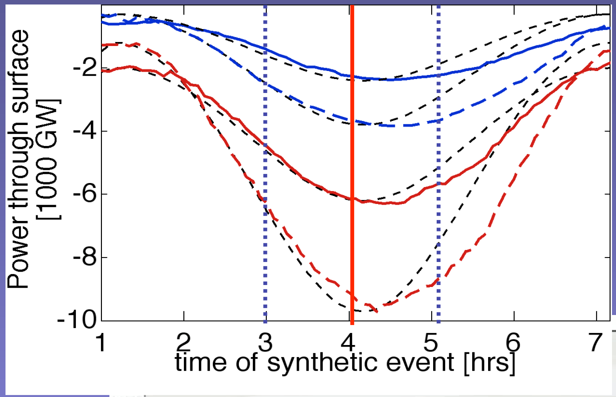
$$\mathbf{S}\cdot\hat{\mathbf{n}} = \left[\mu_0^{-1}(\mathbf{B}\times\mathbf{v})\times\mathbf{B}\right]\cdot\hat{\mathbf{n}}$$

$$= \mu_0^{-1}(B^2\mathbf{v} - (\mathbf{B}\cdot\mathbf{v})\mathbf{B})\cdot\hat{\mathbf{n}}$$

- Hysteresis could be in
  - Magnitude of B or v
  - Angle between v and surface
  - Angle between v and B
  - Angle between B and surface

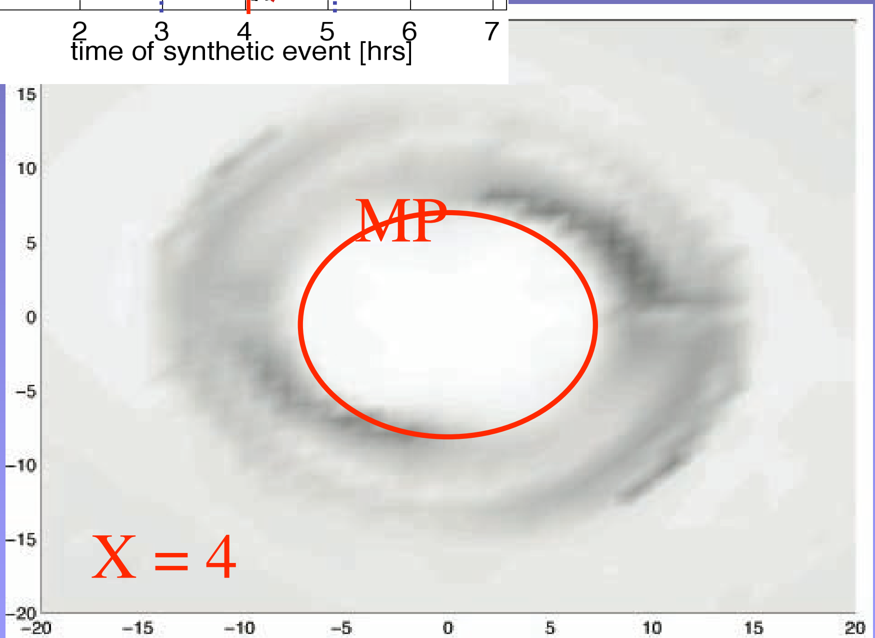
- Magnitude of v: No
- Magnitude of B: Yes
- Angle between v and surface: No
- Angle between v and B: No
- Angle between B and surface: Yes
- => hysteresis caused by direction and magnitude of magnetic field at the surface

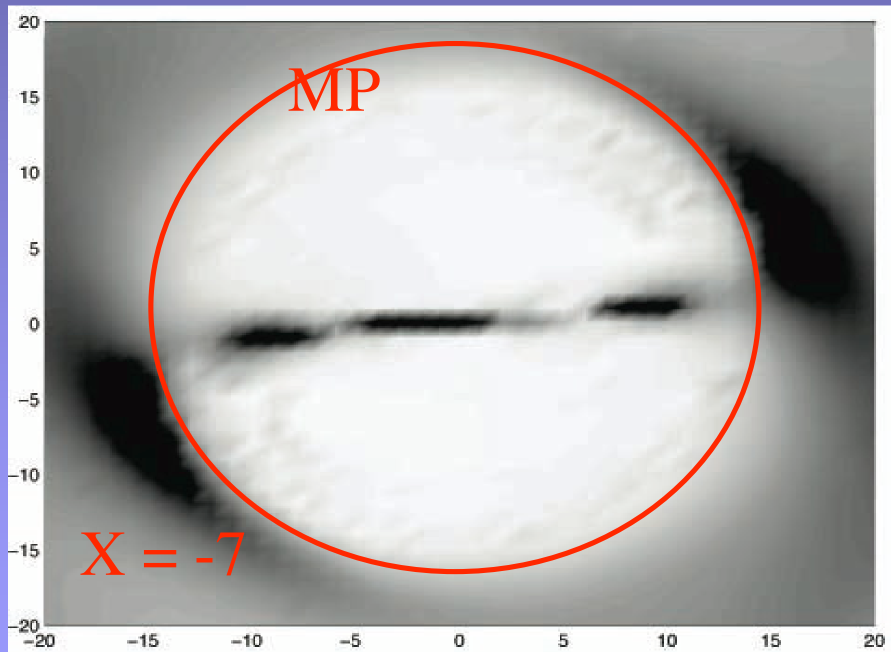
Difference of B at symmetric times of due south field



$$H = \frac{|\mathbf{B}_{T-\tau} - \mathbf{B}^*_{t+\tau}|}{|\mathbf{B}_{T-\tau}|}$$

T = symmetry time
τ = 60 min (in figs)
* Indicates mirroring with respect to XZ plane so that structural asymmetry is eliminated



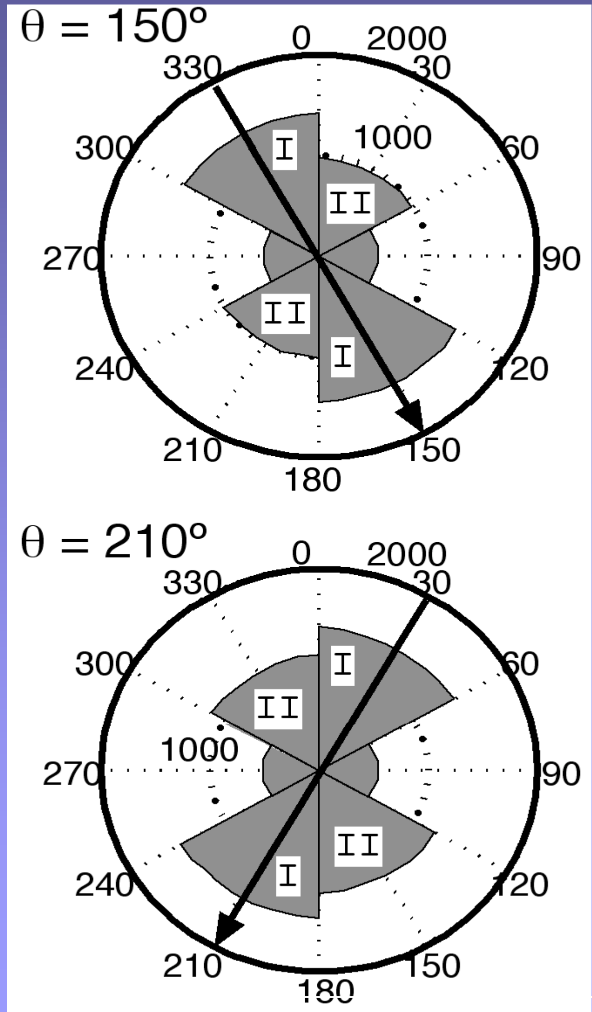


- Difference large in the magnetosheath

Run: small IMF, high p

Azimuthal power transfer distribution

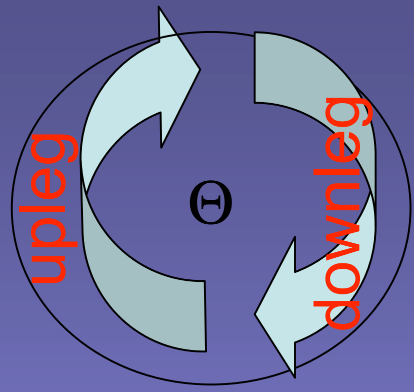
- Integrate power transfer over X, study as function of clock angle
- Largest power transfer from sectors aligned with the clock angle (consistent with Palmroth et al., 2003)
- Hysteresis is caused by residual power transfer from sectors where clock angle has recently visited
  - True for all runs
- No x-dependence found
  - Whole surface takes part in hysteresis

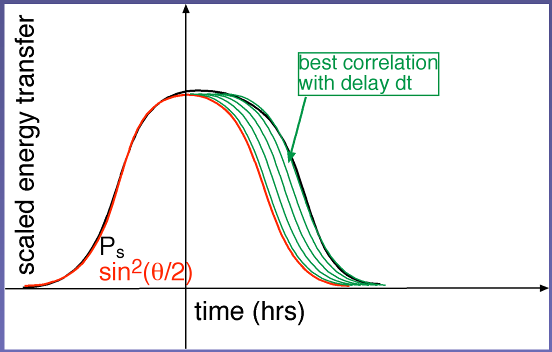


Run: small IMF, high p

Time delays

- Correlate upleg input power to upleg $\sin^2(\theta/2)$
  - Find delay with which highest correlation
- Increasing IMF increases delay
- Increasing dynamic pressure shortens delay

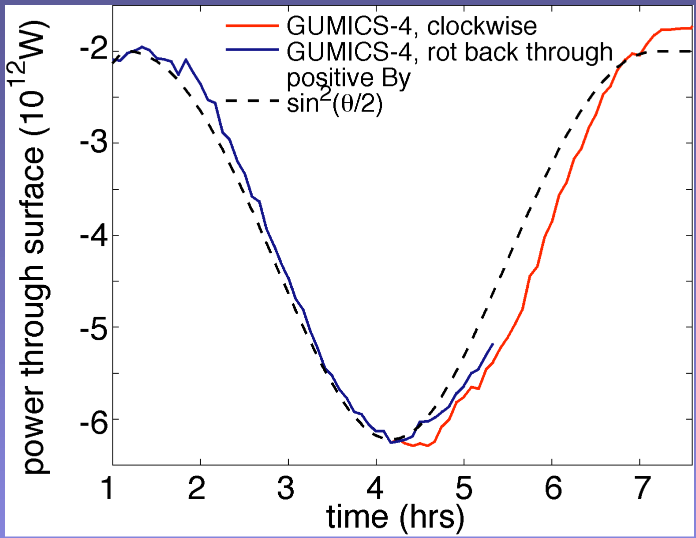




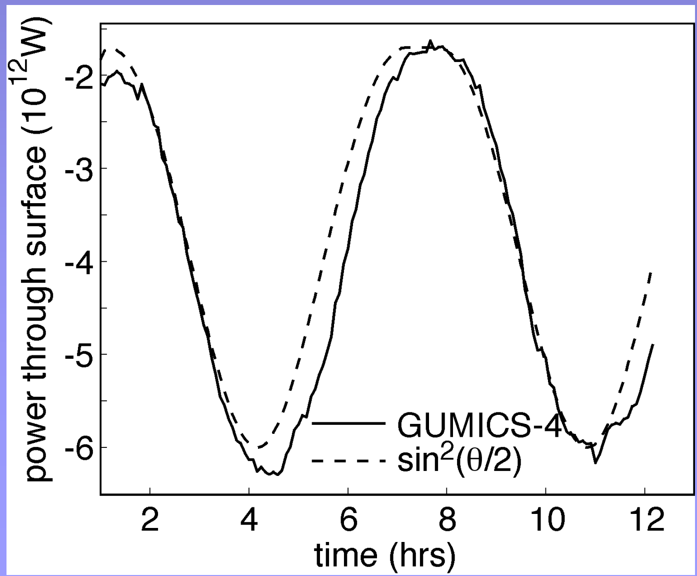
Run params./ Solar wind	Delay min
Large IMF Small pdyn	40
Small IMF Small pdyn	30
Large IMF Large pdyn	30
Small IMF Large pdyn	20

What about other drivers?

- IMF rotation counter-clockwise
  - (handedness in Hall conductivity in ionosphere, co-rotation electric field)
    - Hysteresis appears
- IMF rotation back through positive By
  - Hysteresis appears
    - Time delay shorter!
- Second IMF rotation
  - Hysteresis disappears during 2nd downleg, but appears during 2nd upleg!
    - Northward IMF “cleans” the situation

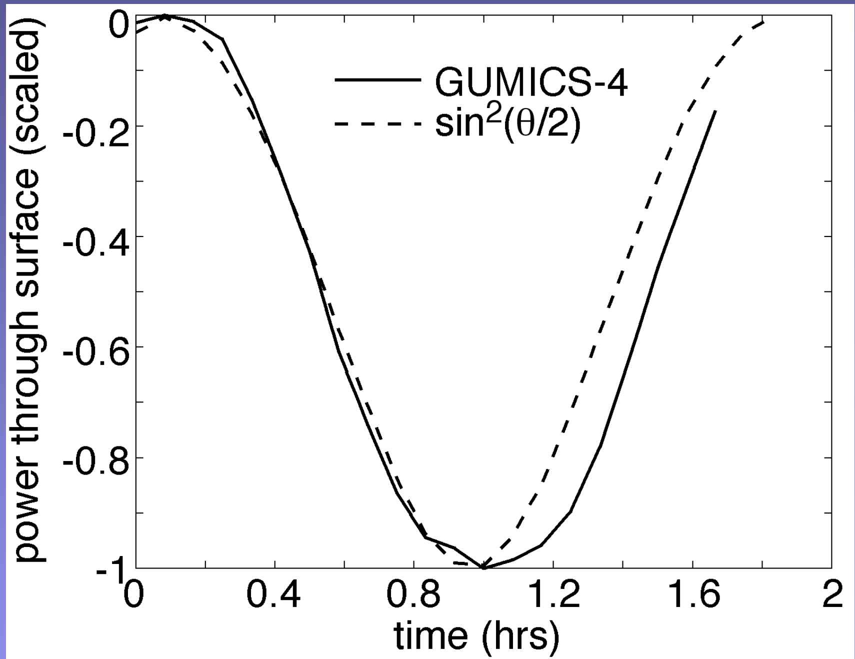


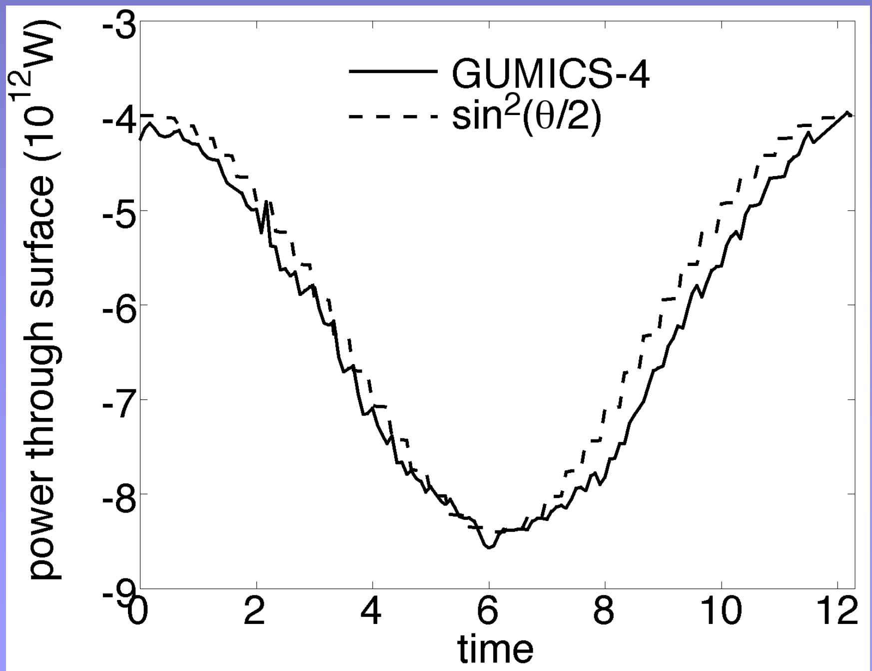
Run: small IMF, high p



What about other drivers?

- Twice as fast rotation
  - Hysteresis appears
- Twice as slow rotation
  - Hysteresis appears





Run: small IMF, high p

(runs with lower magnetospheric resolution, hence different surface location and total area - changes magnitude of transferred energy)

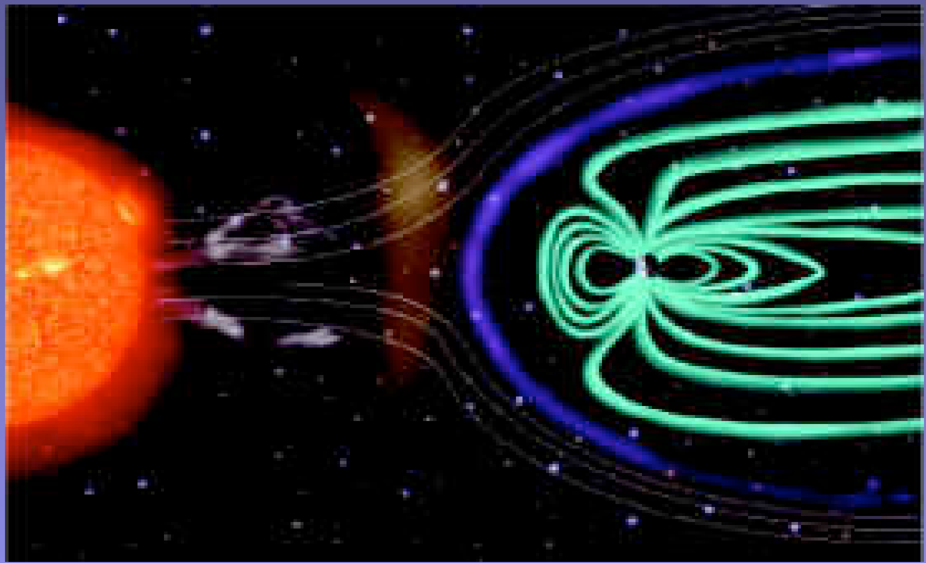
Facts and hints:

- Hysteresis caused by magnitude and direction of magnetic field at the surface
- Newly activated reconnection tends to eliminate hysteresis
  - Time delay shortened during rotation back through positive By
    - Points to reconnection processes
- Delay increases with increasing IMF
    - Points to reconnection processes
- Delay shortens with increasing pressure
  - Large p_{dyn} - smaller surface - shorter time scales
- Clock angle dependency
  - Residual transfer from sectors where clock angle recently visited
    - Points to reconnection processes
- Difference largest in the magnetosheath
- => Origin in magnetopause or magnetosheath? Both?

Hypotheses

- To alter magnetic field one needs to alter currents
  - Which current system has hysteresis?
    - Region 1 checked: no cause found
    - Plasma sheet system checked: no cause found
    - Hysteresis has no x-dependence (it has azimuthal dependence): current systems often appear within certain x-range => currents not the cause?
  - Inertial ionosphere would be good candidate: How?
- Does reconnection process itself alter magnetic field pattern at the magnetopause?
  - Clock angle dependency suggests this
  - Longmore et al. (2006): Reconnection alters magnetosheath flow pattern
  - Coleman (2005): Clock angle is not preserved in magnetosheath, changes due to reconnection (at least)

Magnetopause reconnection: Hole in a boat analogy



- Magnetosphere obstacle in solar wind
- Reconnection “makes holes” to magnetopause surface
- Sheath knows locally where holes are - adjusts its flow pattern

- But why don’t the holes close after large energy input?

Possible consequences:

- If energy transfer depends on prior large energy input
  - Correlating e.g., AE and solar wind parameters may lead to wrong conclusions
- Simulation power output (e.g. in ionosphere) directly proportional to P_s at magnetopause
  - Correlating simulation AE and ε would give a delay that could be thought of loading-unloading behavior
    - BUT: In simulation, energy is processed without delays, so loading-unloading would be wrong conclusion. On the contrary, simulation shows that delay comes already from magnetopause processes!
- Observational verification of hysteresis is difficult!

References:

Akasofu, S.-I. (1981), Energy coupling between the solar wind and the magnetosphere, Space Sci. Rev., *28*, 121-190, 1981

Axford, W.~I., and Hines, C.~O. (1961) A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys. *39*, 1433-1464, 1961.

Boyle, C. B., Reiff, P. H., and Hairston, M. R. (1997) Empirical polar cap potentials, J. Geophys. Res., *102*, 111-126, 1997.

Coleman, I. J. (2005), A multi-spacecraft survey of magnetic field line draping in the dayside magnetosheath, Ann. Geophys., *23*, 885–900, 2005.

Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., *6*, 47-48, 1961.

Gonzalez, W. D. and Mozer, F. S. (1974) A quantitative model for the potential resulting from reconnection with an arbitrary interplanetary magnetic field, J. Geophys. Res., *79*, 4186-4194, 1974.

Kamide, Y., and Baumjohann, W.,(1993) Magnetosphere - ionosphere coupling, Springer-Verlag, Berlin, Germany, 1993

Kan, J. R., and L. C. Lee (1979) Energy coupling function and solar wind-magnetosphere dynamo, Geophys. Res. Lett., *6*, 577-581, 1979.

Longmore, M., Schwartz, S.J., and Lucek, E.A. (2006), North-South IMF and a magnetosheath flow effect on the magnetic field line draping pattern in the dayside magnetosheath, in press, Ann. Geophys., 2006.

Matsumoto and Hoshino (web): http://center.stelab.nagoya-u.ac.jp/web1/cawses/2004/sm0008/kelvin/kelvin.html

Palmroth, M., Pulkkinen, T. I., Janhunen, P., and Wu, C.-C., (2003) Stormtime energy transfer in global MHD simulation, J. Geophys. Res., *108*, doi:10.1029/2002JA009446, 2003.

Palmroth et al., Hysteresis in solar wind power input to the magnetosphere, to appear in Geophys. Res. Lett., 2006

Shue, J.-H., Song, P., Russell, C. T., Steinberg, J. T., Chao, J. K., Zastenker, G., Vaisberg, O. L., Kokubun, S., Singer, H. J., Detman, T. R., Kawano, H., (1998) Magnetopause location under extreme solar wind conditions, J. Geophys. Res., *103*, 17,691-17,700, 1998.

Thomsen, M. F., J. E. Borovsky, R. M. Skoug, and C. W. Smith, Delivery of cold, dense plasma sheet material into the near-Earth region, J. Geophys. Res., 108(A4), 1151, doi:10.1029/2002JA009544, 2003.

Wing, S., and P. T. Newell, 2D plasma sheet ion density and temperature profiles for northward and southward IMF, *Geophys. Res. Lett.*, *29*(9), 1307, doi:10.1029/2001GL013950, 2002.