Space Weather Energetics

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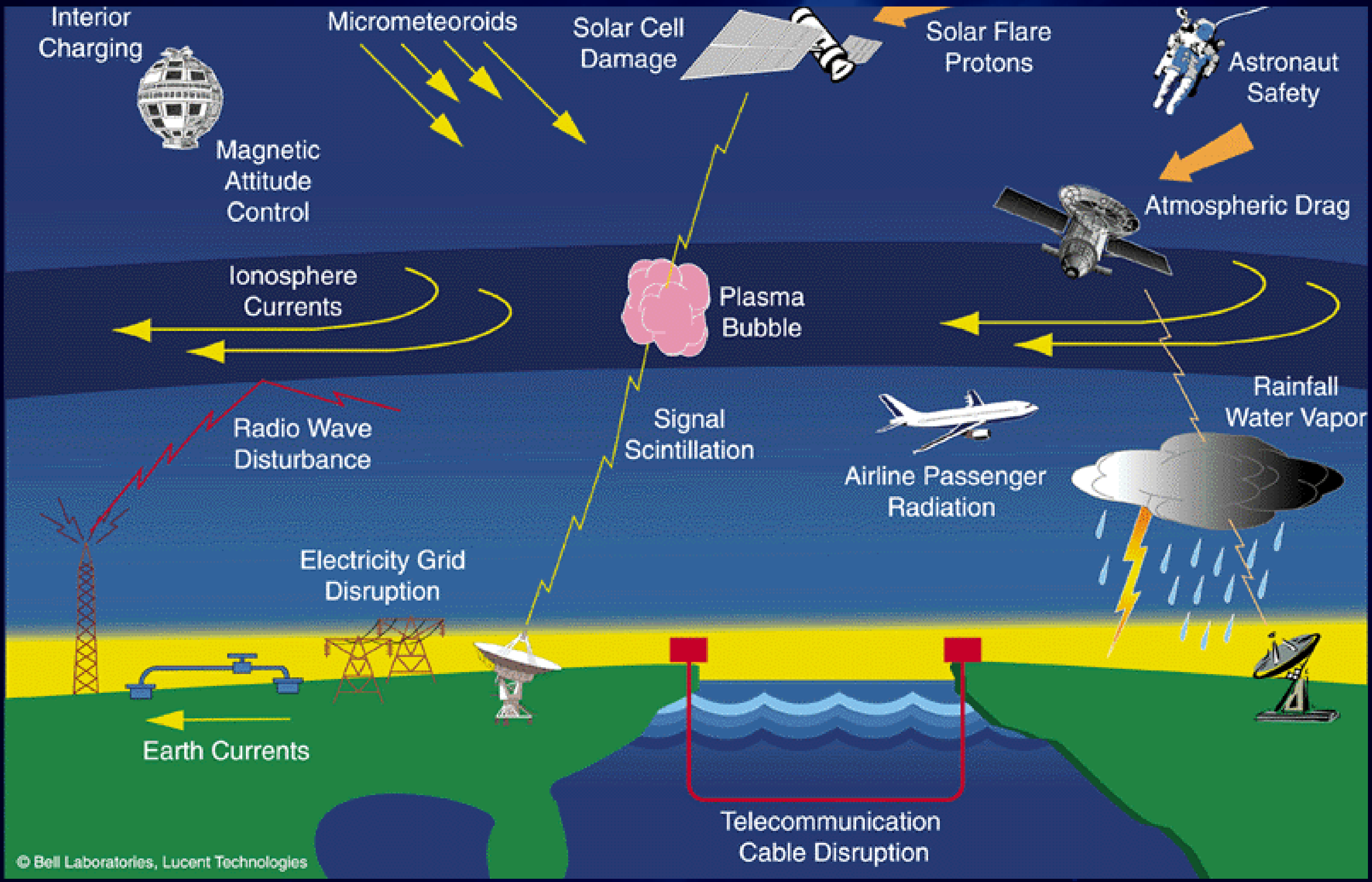
This is NOT a talk on space weather effects



What is energetics

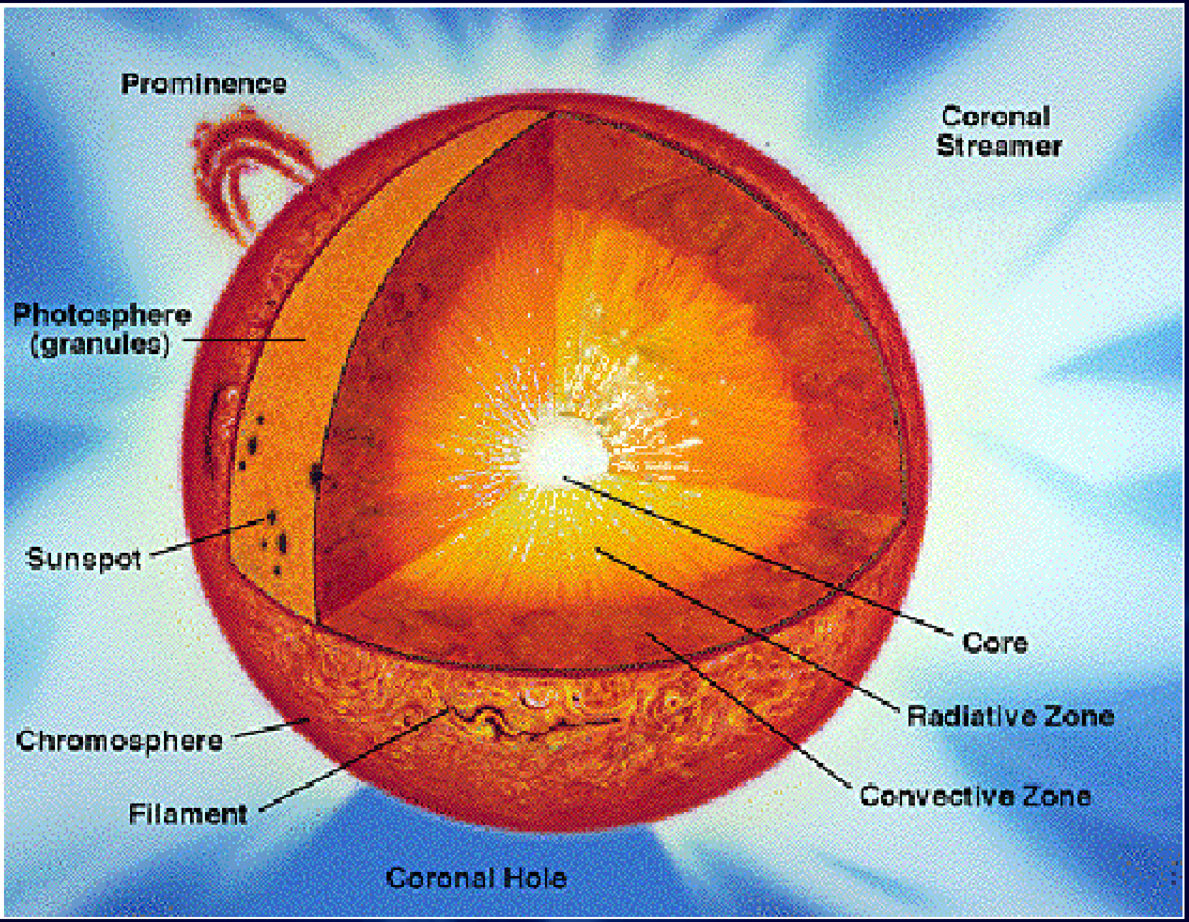
- **en•er•get•ics** \-iks\ *n pl but sing in constr* **1** : a branch of mechanics that deals primarily with energy and its transformations **2** : the total energy relations and transformations of a system (as a chemical reaction or an ecological community) ⟨~ of muscular contraction⟩ (*Webster's New Collegiate Dictionary*, 1981)

- energy sources and sinks
  - need for quantitative understanding
    - difficult as the numbers vary so much
- energy conversion
  - EM to kinetic; kinetic to EM
  - heating and acceleration

Part 1: Global energy budget

- sources of space weather energy
- storms
- energy input to the magnetosphere
- energy dissipation

The ultimate energy source

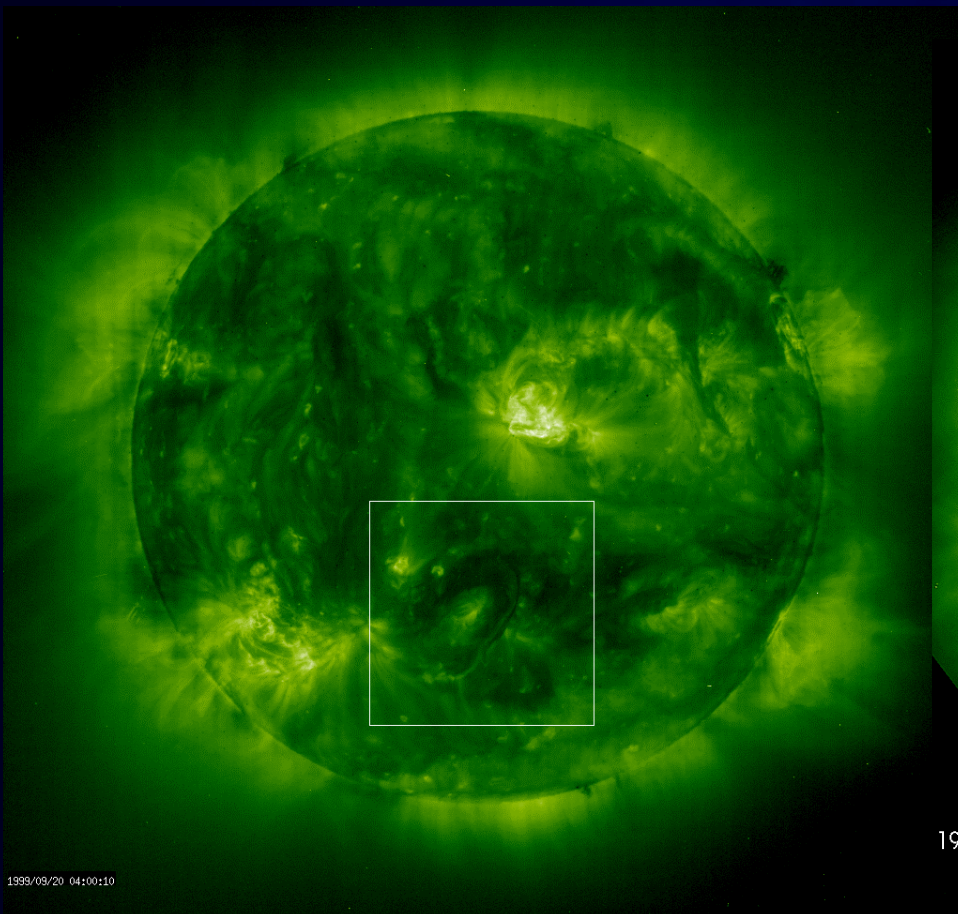


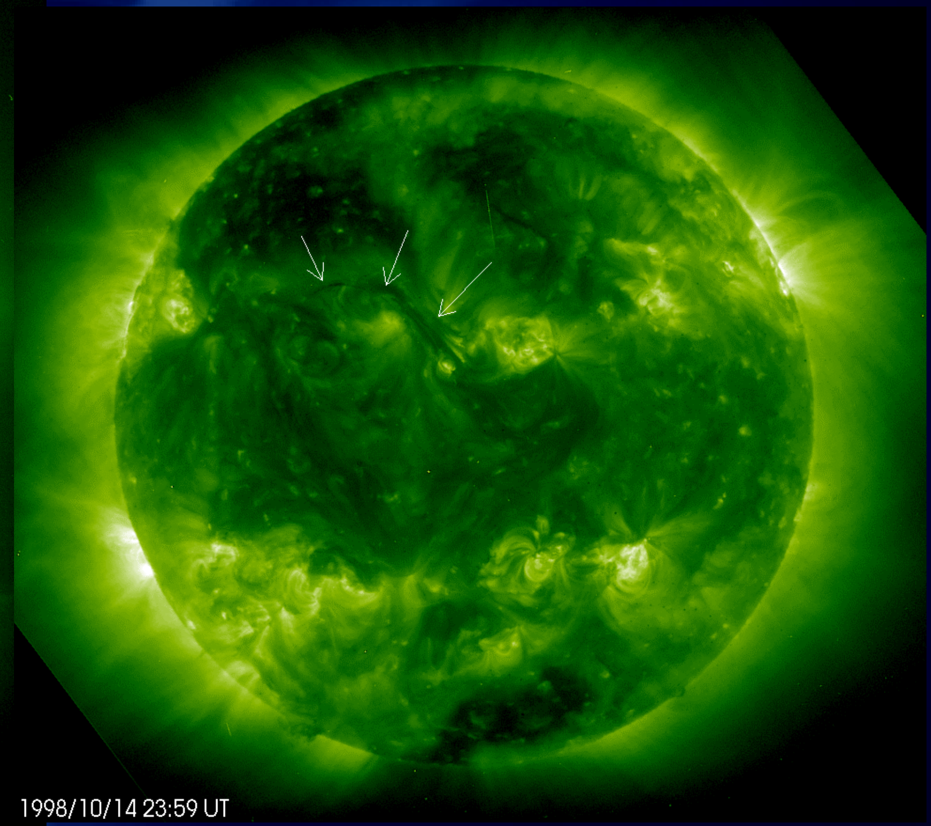
- total solar power: 3.86 x 10^{26} W
  - 60 million 1-GW nuclear power units for everyone on Earth

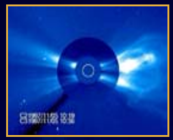
Solar power at 1 AU

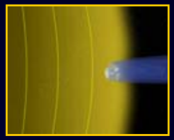
- total solar irradiation
  - solar "constant": 1366 ± 2 W m^{-2}
  - total irradiation on Earth: 1.7 x 10^{17} W
- solar EUV
  - about 50% in Ly-α (121.6 nm): 6 mW m^{-2}
  - total irradiation on Earth ~ 10^{12} W
    - this makes the ionosphere
  - large variations (factor of 2 over the solar cycle)
    - space weather in ionosphere and thermosphere
- solar wind
  - KE flux 0.01 – 10 mW m^{-2}
  - Poynting flux ~ 0 – 1 mW m^{-2}

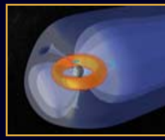
Sources of space weather on the Sun





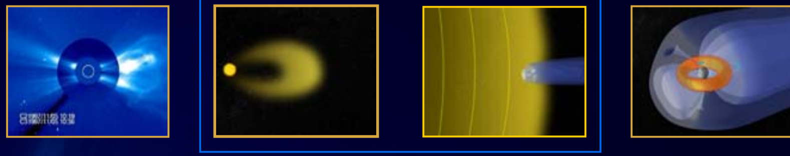




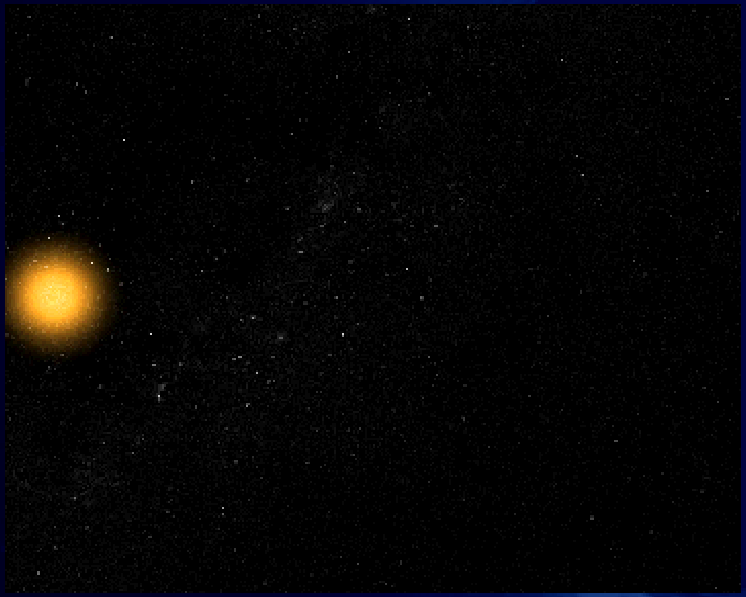


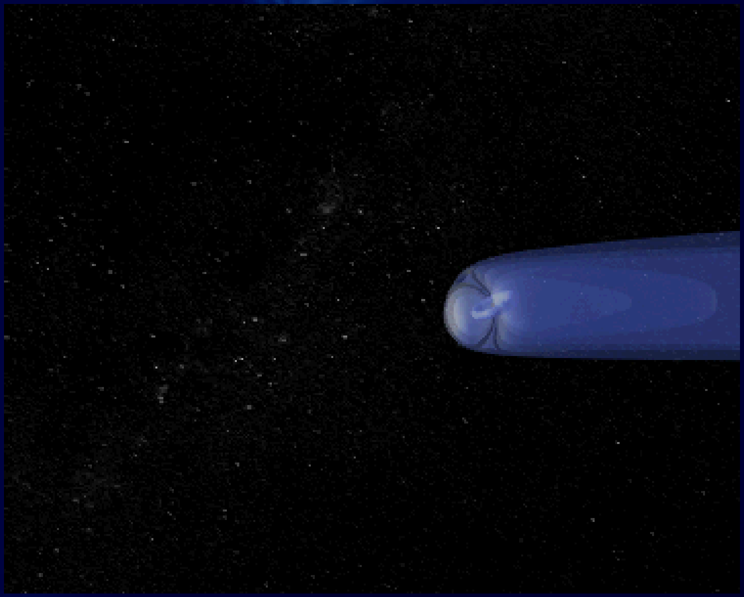
Coronal mass ejections (CME)

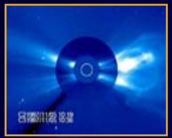
Main drivers of large space storms

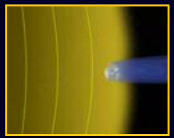
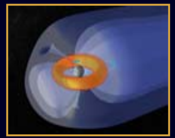


A cloud is released from the Sun and reaches the Earth in 2–4 days



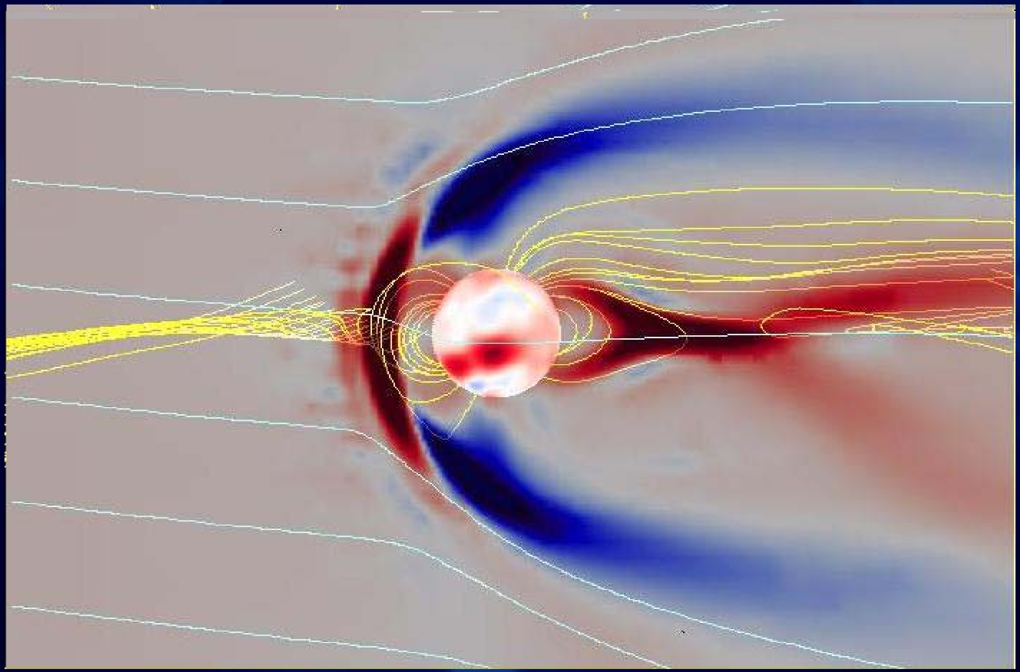




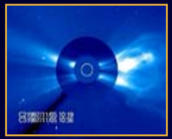
Solar wind – magnetosphere interaction

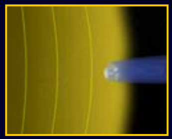
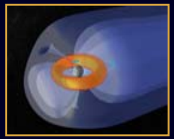
(MHD simulation by P. Janhunen)



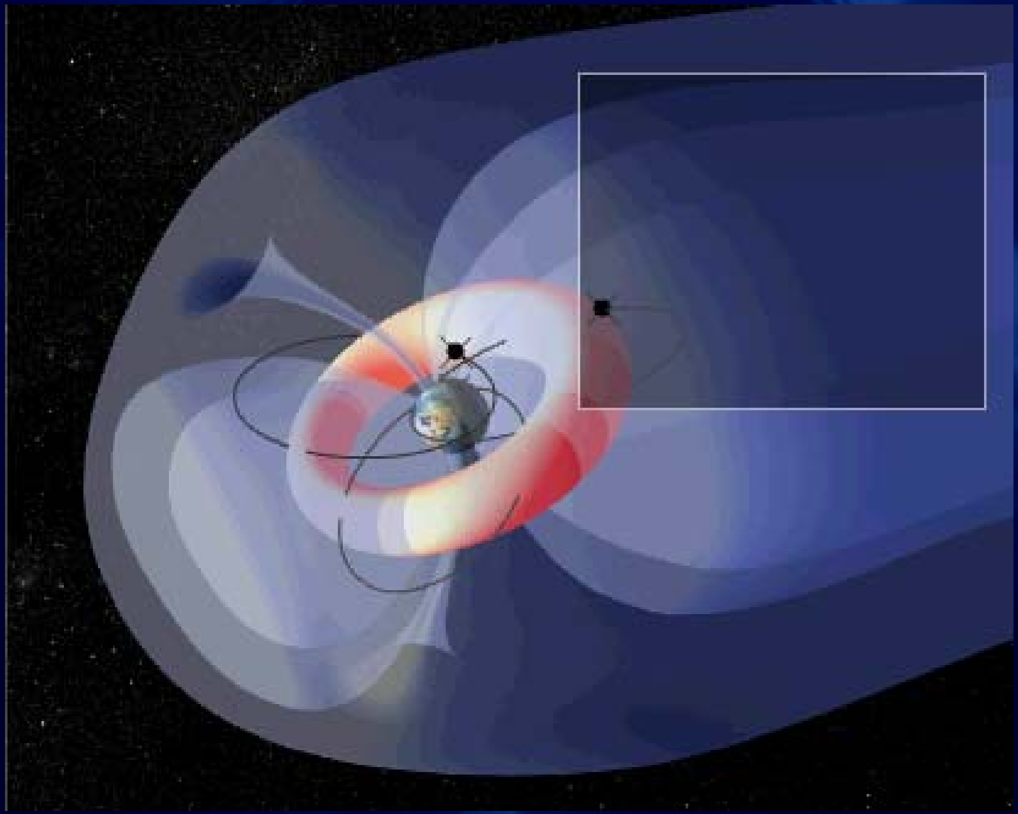
red: current out of the plane

blue: current into the plane

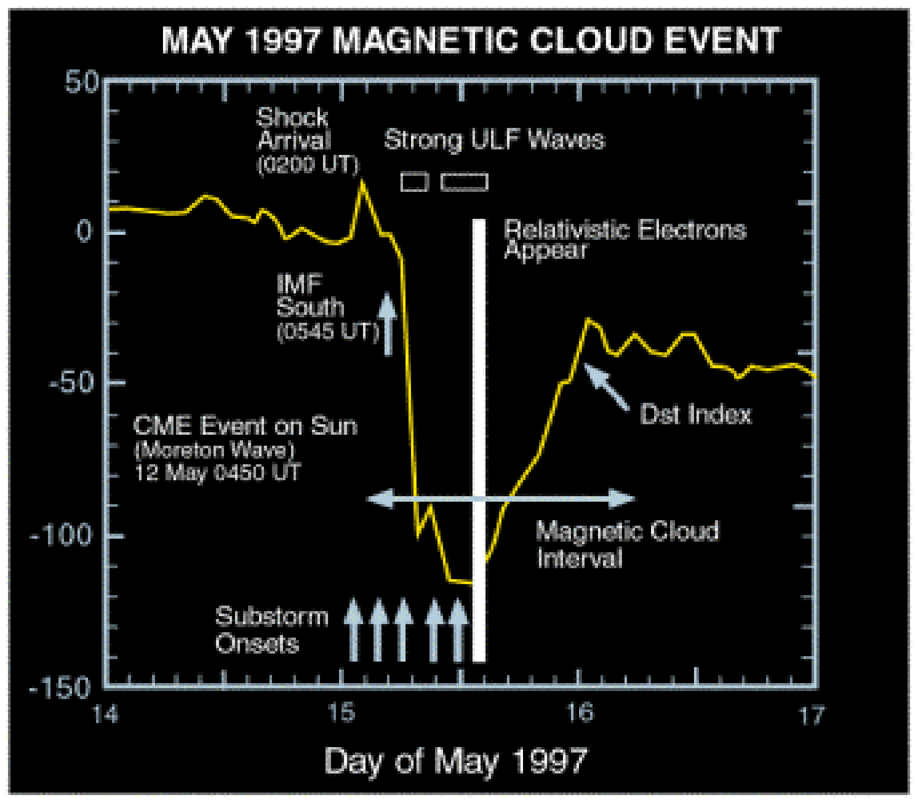


Strong electric currents are created in the Earth's environment



Magnetic storm energy



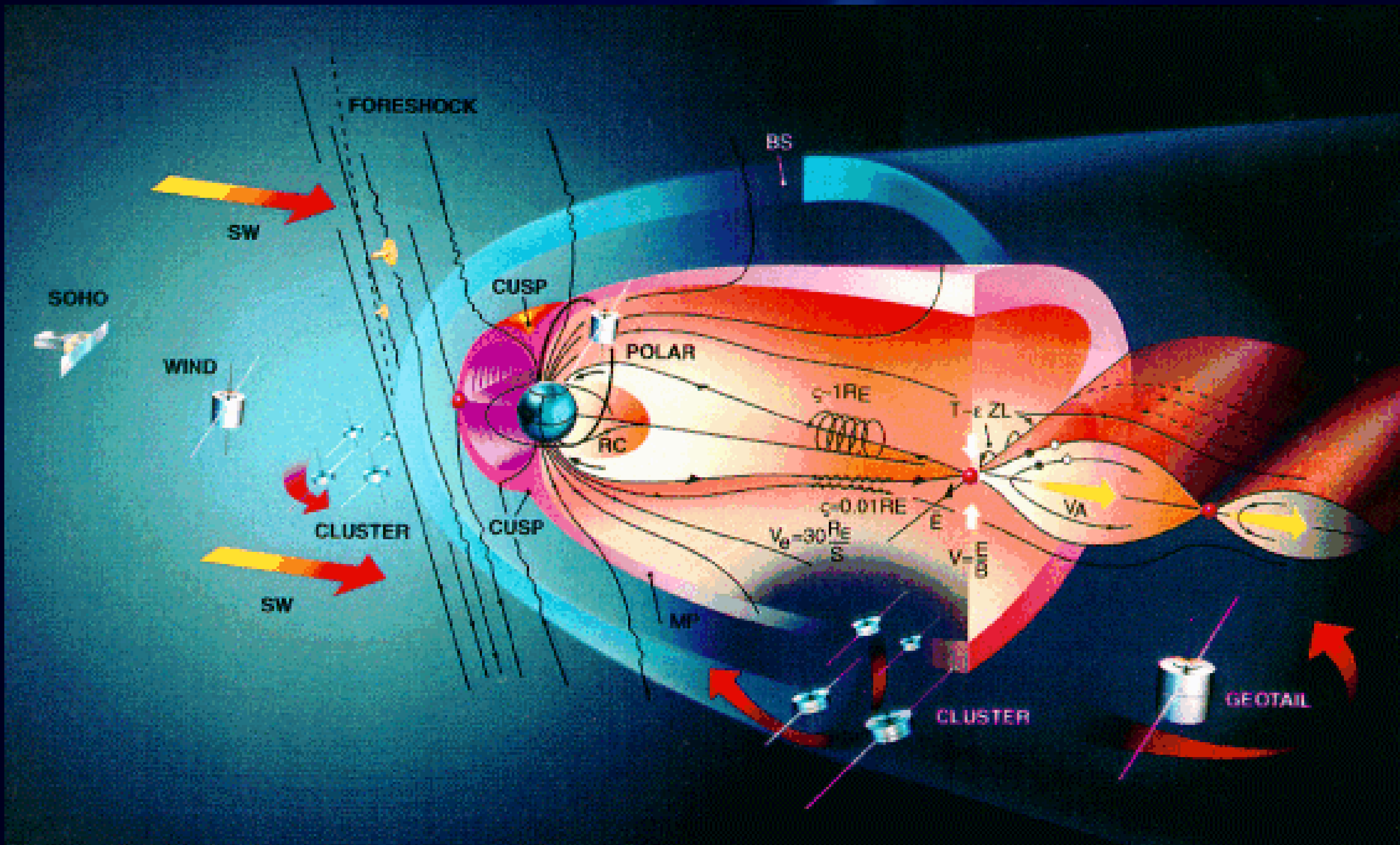
Source:

- the Sun

Sinks:

- polar ionospheres
- inner magnetosphere
- magnetotail

Solar wind – magnetosphere interaction



Input/output energy balance

- Energy comes from the solar wind
  - assuming: $n = 5\ \mathrm{cm}^{-3}$, $V = 400\ \mathrm{km/s}$, $B = 10\ \mathrm{nT}$, $r = 15\ R_E$
  - SW KE flux ~ $5 \times 10^{-4}\ \mathrm{W/m^2}$; power: 14000 GW
  - SW Poynting flux ~ $3 \times 10^{-5}\ \mathrm{W/m^2}$; power: 800 GW

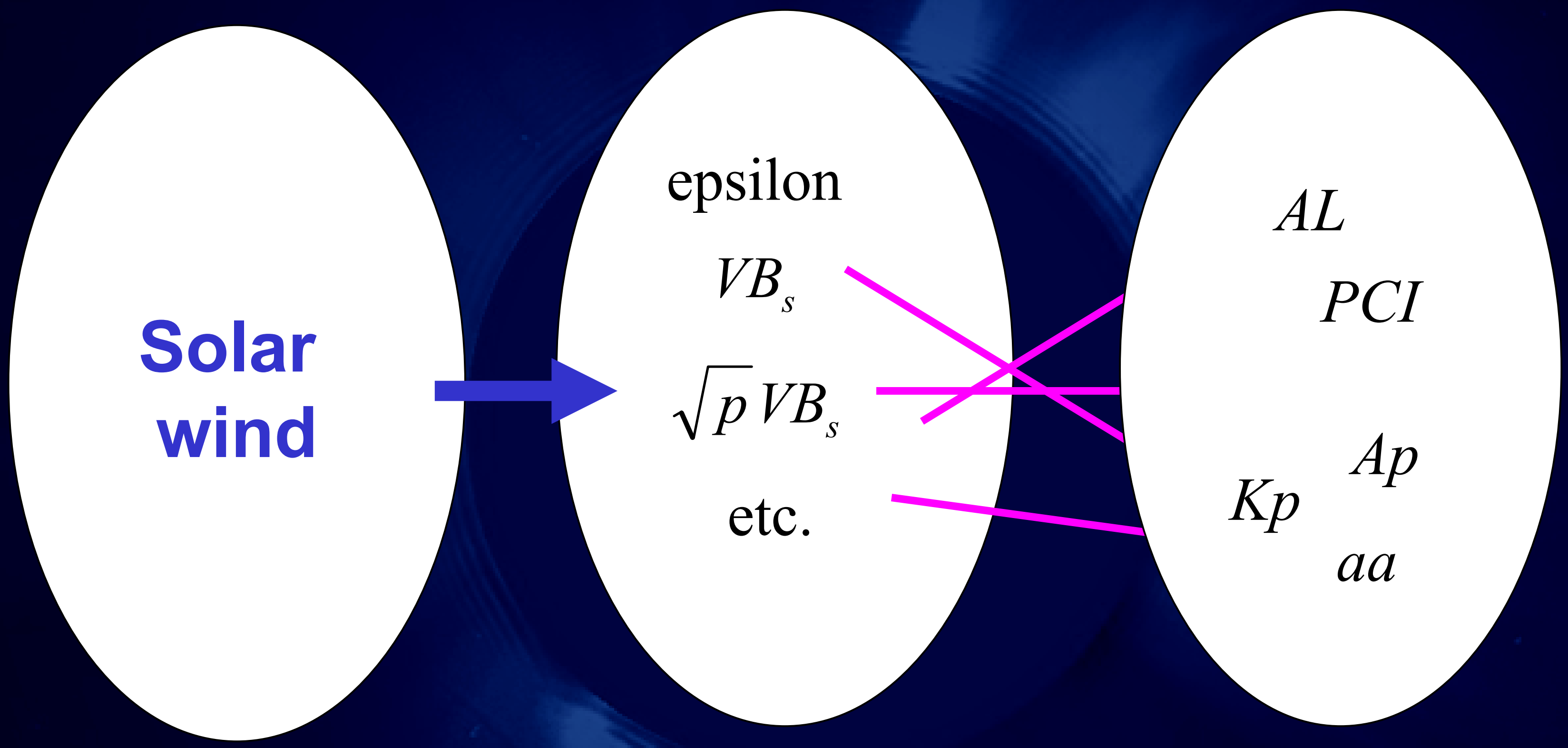
$$\frac{\text{KE flux}}{\text{Poynting flux}} = \frac{V \cdot \rho V^2}{VB^2/\mu_0} = \frac{V^2}{V_A^2} = M_A^2$$

- But the actual input power cannot be measured directly
- Output is difficult but possible to estimate
  - the efficiency of dissipation channels varies
  - numbers in the literature are very confusing
    - e.g., Weiss et al.,1992, and references therein (ICS-1 proceedings)

Energy dissipation

- keeping up the magnetotail
  - major factor (a few 100's of GW)
  - always there, but often "forgotten"
- dissipation in the ionosphere
  - some 75% of total input
  - Joule heating in the ionosphere (~50%)
  - electron precipitation (~25%)
- the ring current
  - role overestimated in old studies
    - 1980's: 90% of total
    - recent: less than 20%
- release of plasmoids
- minor effects (in terms of energy)
  - relativistic electrons, AKR, ionospheric outflow

Energy coupling functions



- different coupling functions $\leftrightarrow$ different time scales
  - AL (minutes)
  - <aa> (year)

The epsilon parameter of Akasofu

$$\varepsilon = 10^7 V B^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2$$

(SI units)

- widely used energy input estimate
- based on estimates of dissipation through ring current, Joule heating and auroral precipitation
  - state of the art around 1980
- merits
  - \+ units of power (W)
  - \+ strong IMF Z-dependence
  - \+ good correlation
  - – scaling factor l_0 ($\approx 7\, R_E$) is murky
  - – physical interpretation unclear

- often interpreted in terms of upstream Poynting flux

$$S = EH = VB^2/\mu_o = 10^7 V B^2 / 4\pi$$

- But does the energy really come from upstream Poynting flux?

Upstream Poynting flux

- Note that only $\mathbf{B}_T$ contributes to $\mathbf{S}$ toward the Earth!

$$S_X = (\mathbf{E}\times\mathbf{B})_x = ((\mathbf{V}\times\mathbf{B})\times\mathbf{B})_X / \mu_o$$
$$= V_X\left(B_Y^2 + B_Z^2\right)/ \mu_0$$

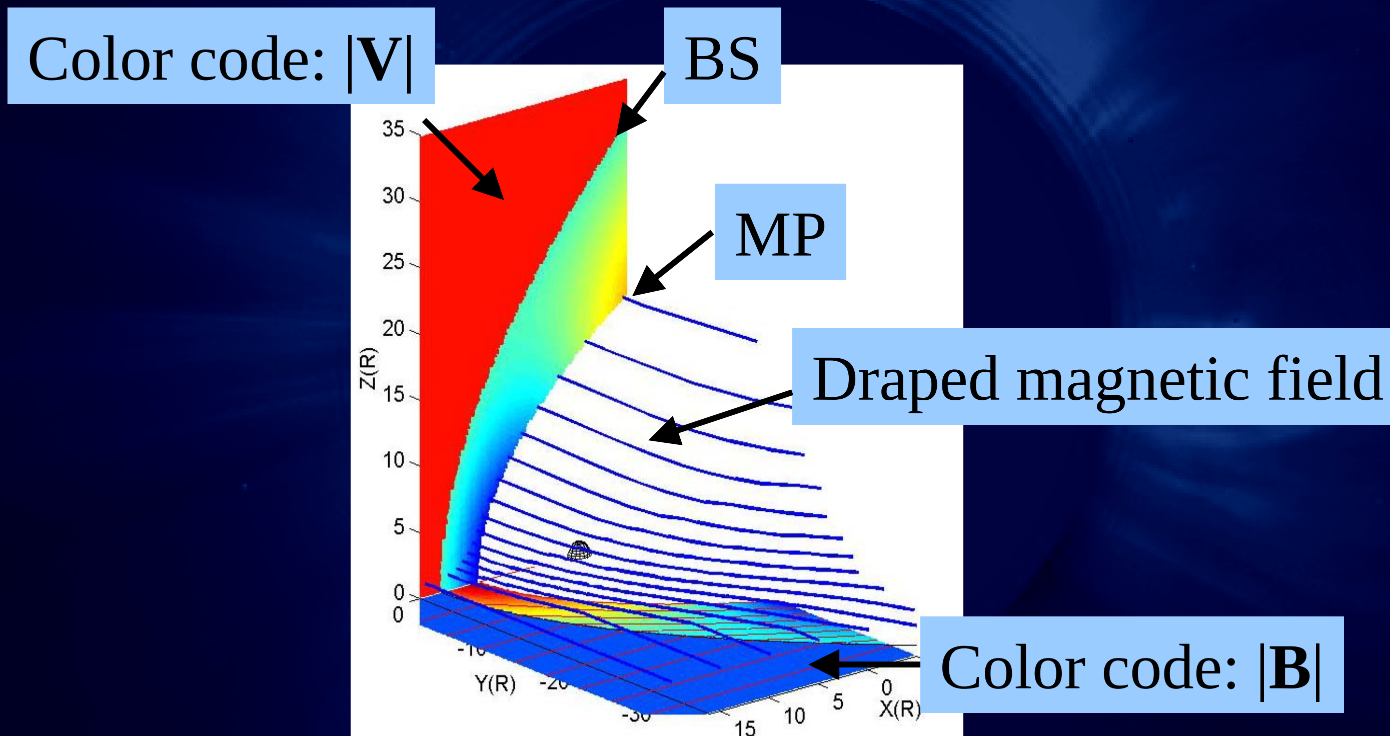
- example:
  - large B_X, small $B_Z < 0$, and $B_Y = 0$

    $\Rightarrow$ small Poynting flux toward Earth, weak IMF south,

    BUT large epsilon parameter

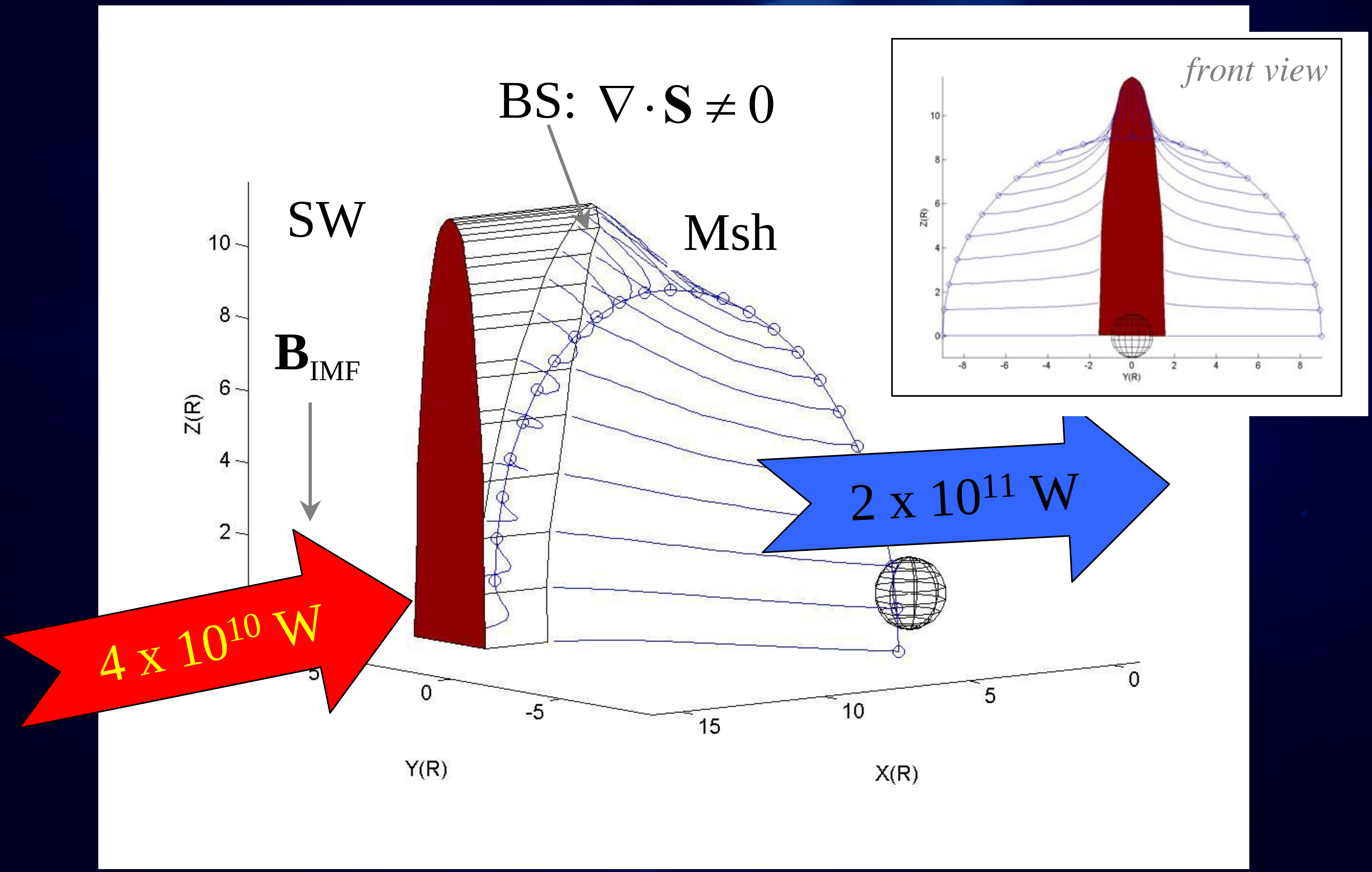
    - large B^2 and optimum clok angle
- Poynting flux is tricky
  - where is EM energy located ?
  - see, e.g., *Feynman Lectures in Physics, Vol 2*, Section 27

Bow shock, magnetosheath and Poynting flux

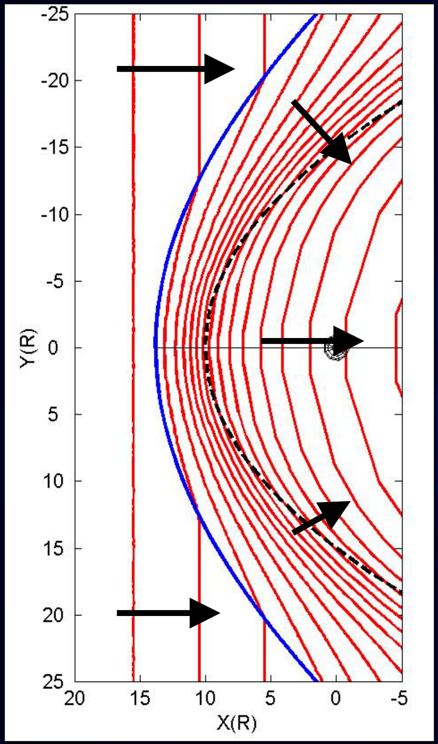


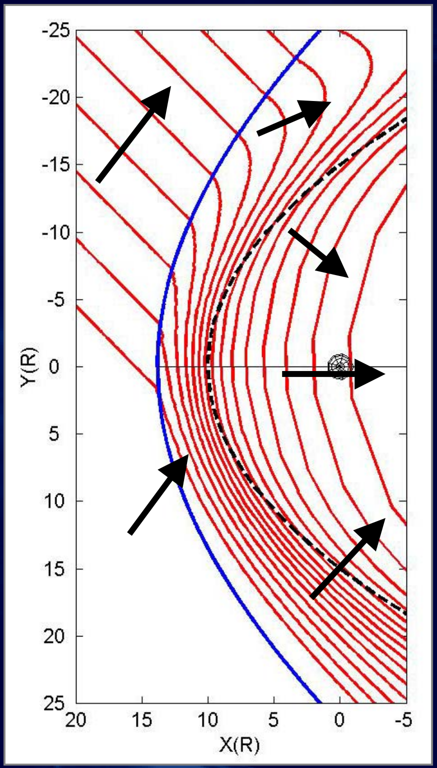
Magnetosheath flow model (Kallio and Koskinen, 2000)

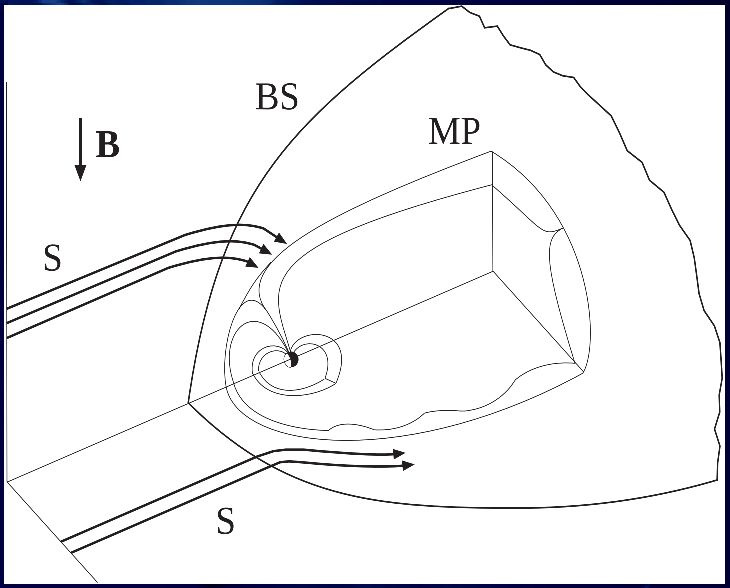
Bow shock transforms kinetic energy flux to Poynting flux (and heat)



Poynting flux stream lines

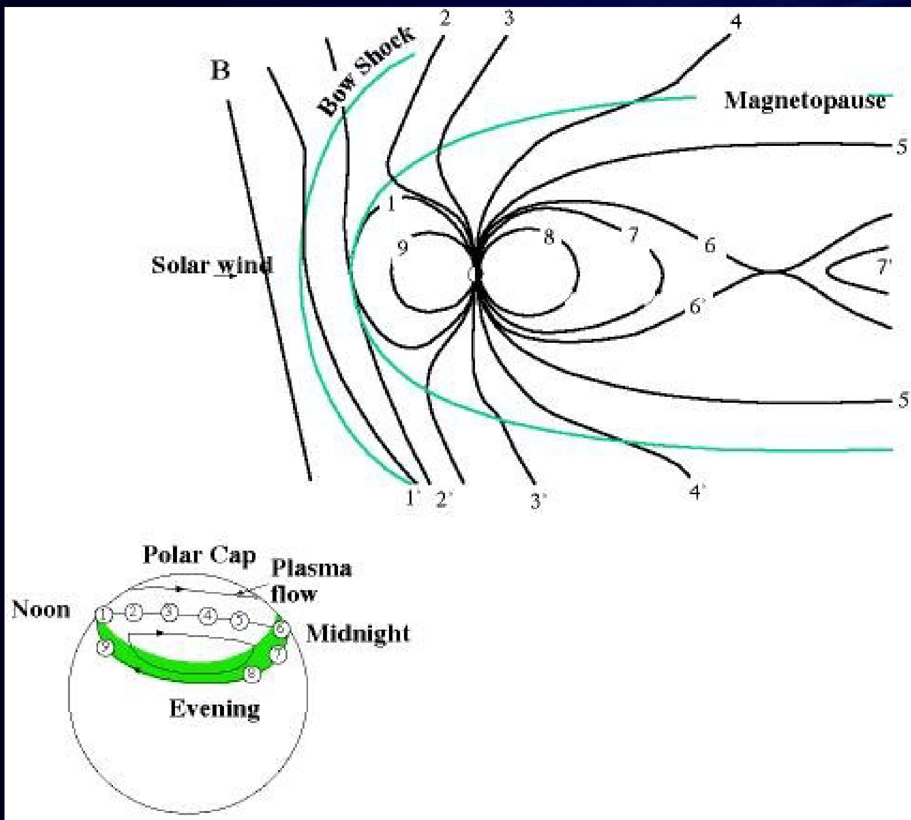






Next question: What is the area through which the Poynting flux "penetrates" through the magnetopause?

Reconnecting magnetosphere



- Reconnection makes efficient energy transfer possible
- Energy is not transferred at X-line only

- cartoon level presentation
- qualitative (zero-order) picture of magnetospheric convection

Quantitative energy transfer description is still missing

Basic physics

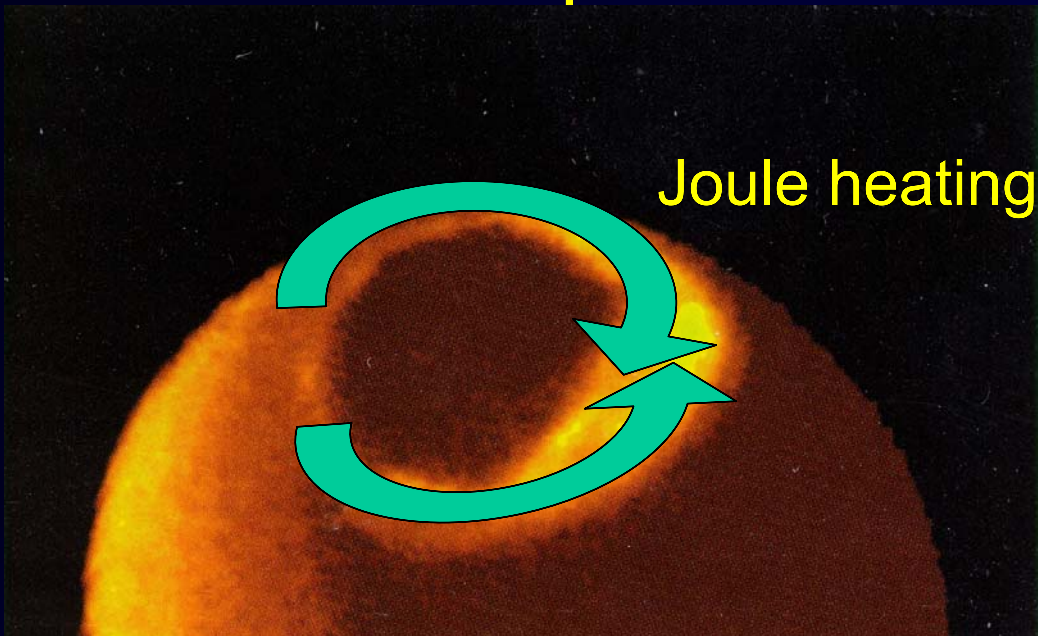
- reconnection
  - opening of the magnetopause
  - strong preference for southward IMF
  - conversion of magnetic energy to kinetic (flow and heat)
- dynamo (or generator)
  - conversion of kinetic energy to EM energy
  - maintenance of currents in a dissipative system

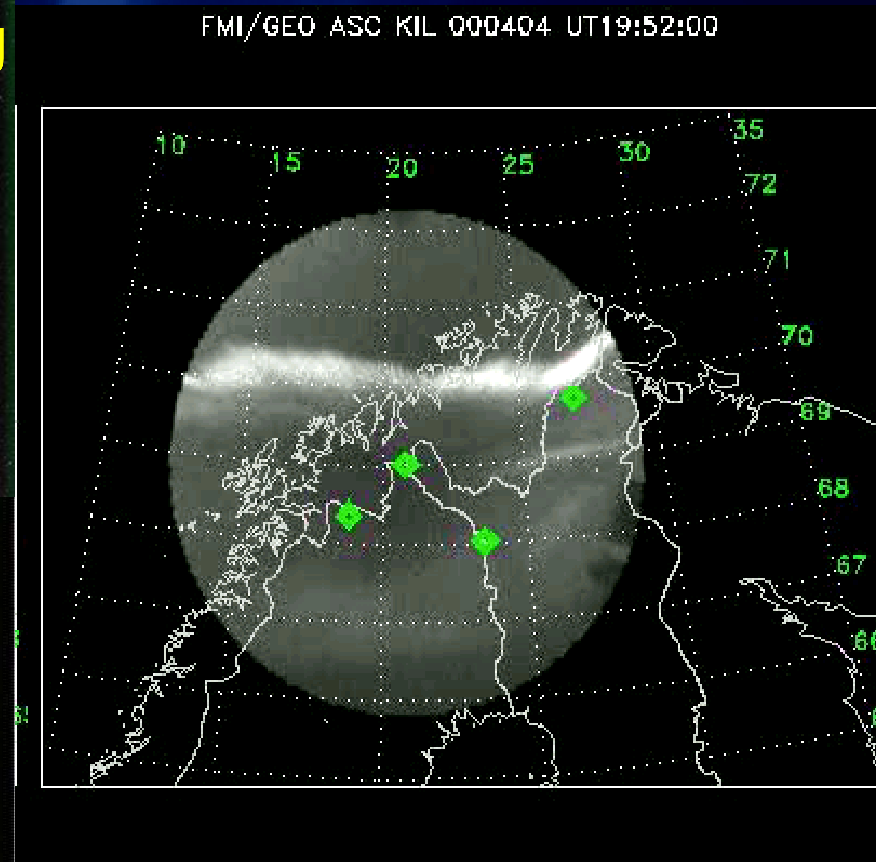
$$\frac{\partial B}{\partial t} = \left(\nabla \times \left(V \times B\right)\right) + \eta \nabla^2 B$$

?

There is no quantitative reconnection-dynamo theory for the solar wind – magnetosphere interaction!

Dissipation in the auroral zone





Auroral precipitation

Dissipation through Joule heating

- IMAGE magnetometer chain
  - *IL* ”index”
    - good proxy for *AL* in time sector 20–02 UT (local magnetic midnight at 2130 UT)
- proxy for the global heating

$$P(\mathrm{W}) = C \cdot 10^{8}\, IL(\mathrm{nT})$$

C ≈ 2–5 (see, Lu et al., 1998)
we use *C* = 3

- total JH dissipation

$$W_{IL}(\mathrm{J}) = \int P\, dt$$

- Note: Dissipation through precipitation is of the same order (~ 50% of JH)

Example: June 23, 1997

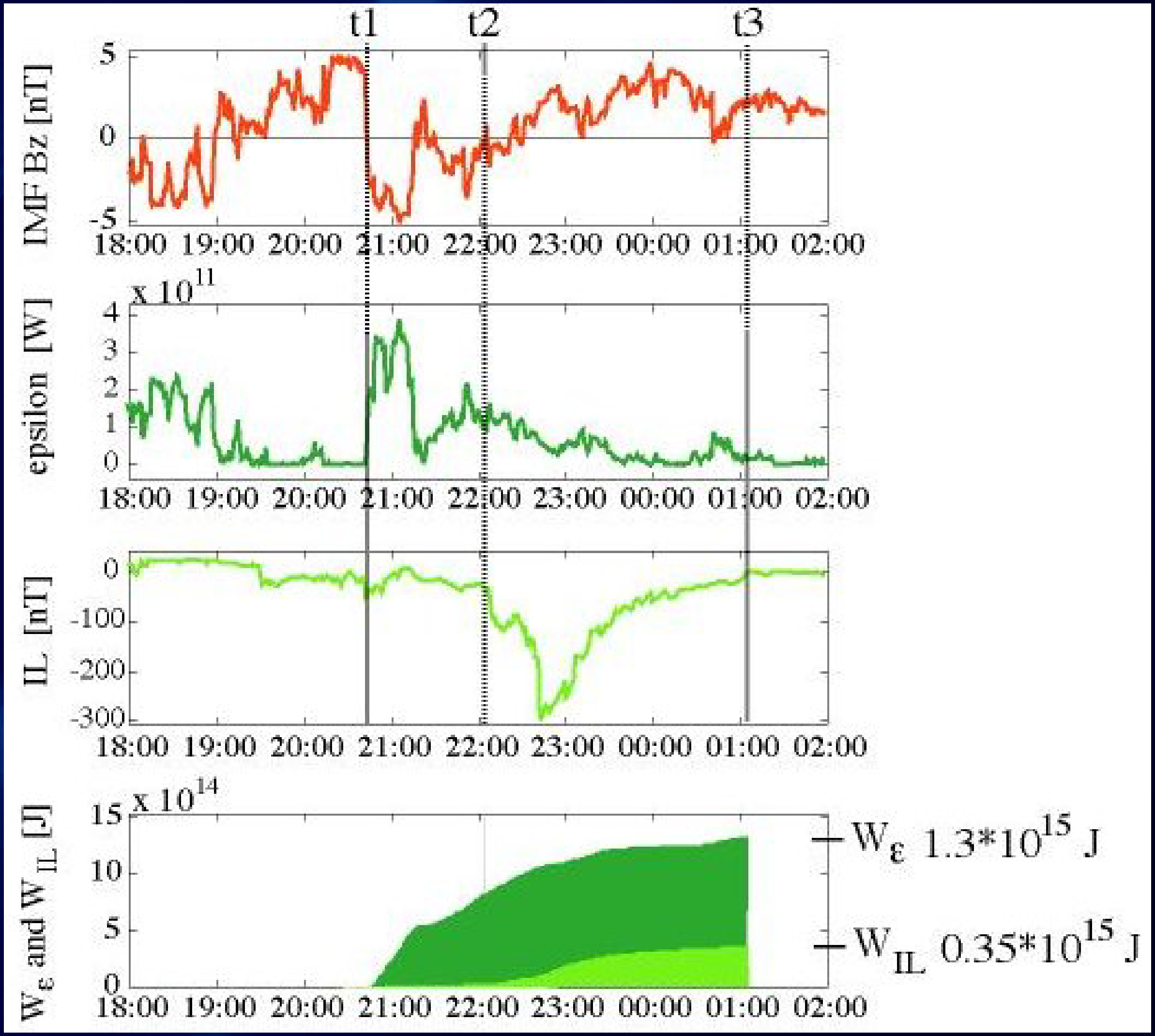
- typical isolated substorm
  - max *IL* ~300 nT
- input energy

$$W_\varepsilon(\mathrm{J}) = \int \varepsilon \, dt$$

- hemispheric Joule heating output:

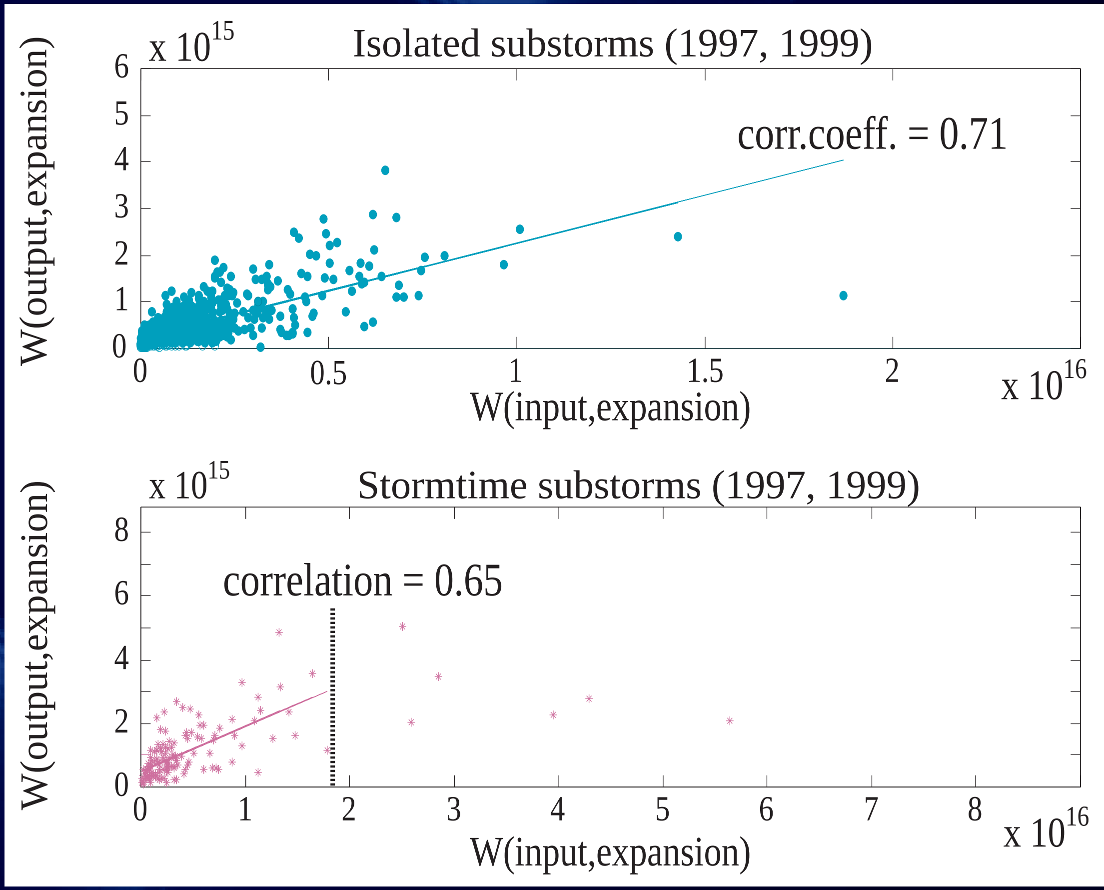
  W_{IL} ~ 25% of W_ε
- total dissipation in ionosphere:

  ~ 75% of W_ε
  - JH: 50%
  - precip: 25%



Input (epsilon) vs. output (Joule heating) energy correlations

- Eija Tanskanen et al., (submitted to JGR, 2001)
  - time sector 20–02 UT
  - quiet year (1997)
  - active year (1999)
- isolated substorms
  - best I/O correlation ≈ 0.7 when both calculated for the expansion phase
- storm-time substorms
  - for lage input the JH output does not follow the trend

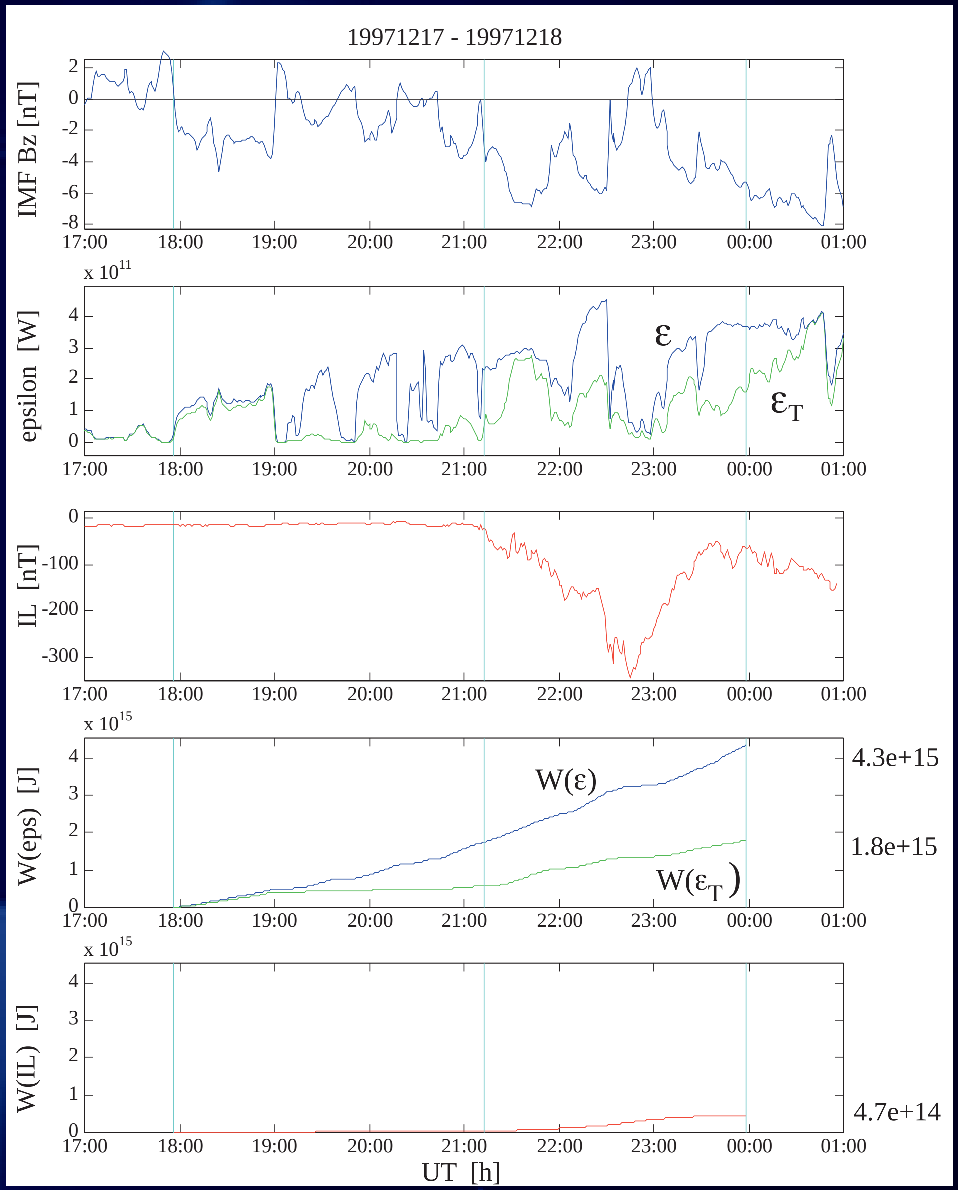


Results on ionospheric Joule heating
(hemispheric values multiplied by 2)

- fraction of epsilon input to Joule heating
  - isolated substorms
    - 1997: 70%
    - 1999: 50%
  - storm-time (*Dst* < –40 nT) substorms
    - 1997: 46%
    - 1999: 48%
- typical (median) total Joule heating
  - isolated substorms: 10^{15} J
  - storm-time substorms: 2 x 10^{15} J

Sometimes epsilon seems "too large"

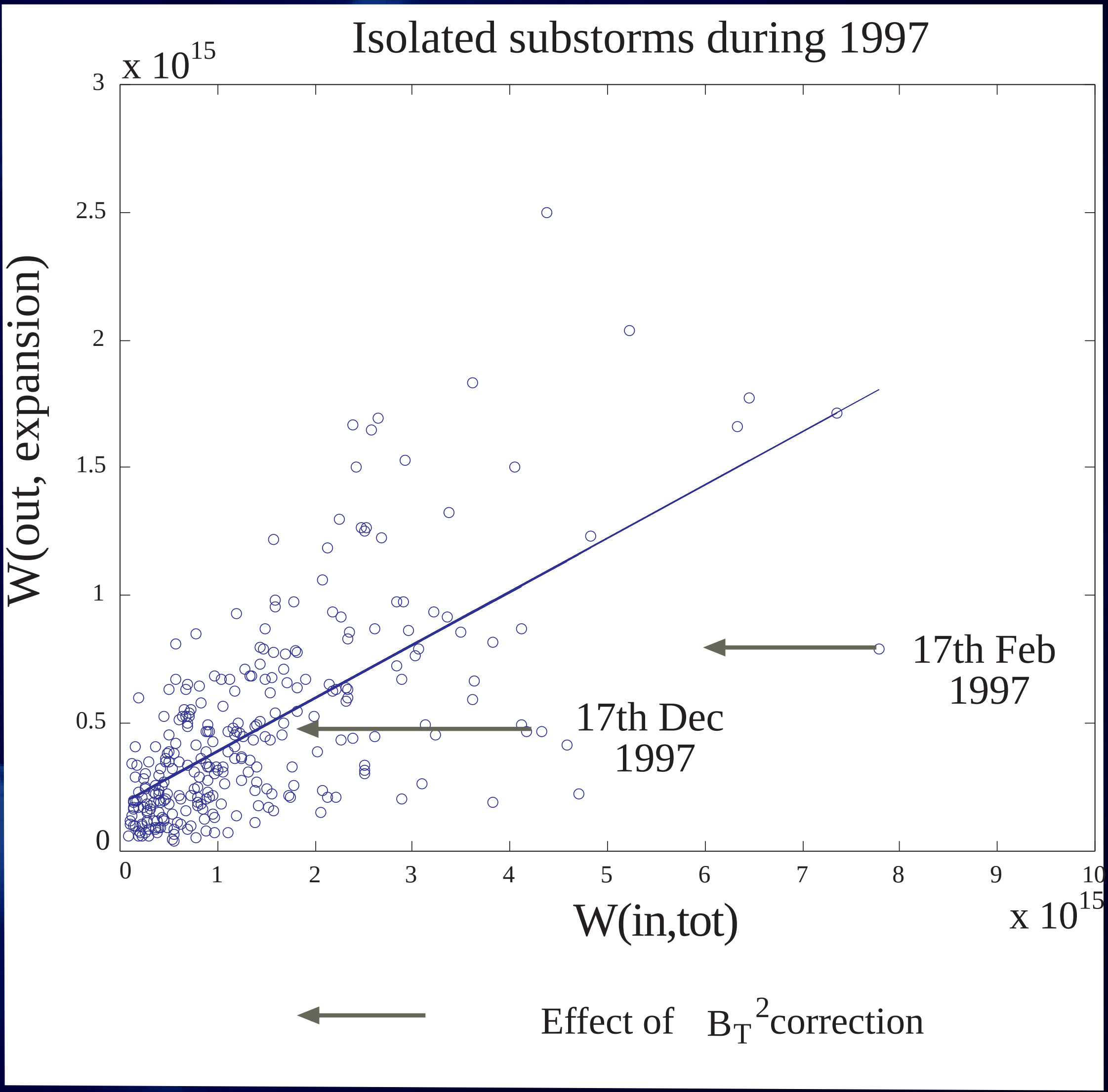
- December 17, 1997
  - large IMF *X*-component
    - large epsilon input
  - weak ionospheric dissipation
    - hemispheric JH 11% of ε
  - exclusion of IMF *X*-component reduces the input estimate to 42% of the "typical" epsilon
- Is this in favor of the Poynting flux interpretation of epsilon?



epsilon without IMF *X*-component

- epsilon with B_T
  - moves some “outliers” closer to the regression line
  - does not improve the input–output correlation

- Conclusion
  - epsilon is a transfer function estimating how much of solar wind total energy (kinetic and EM) is transferred into the magnetosphere
  - The upstream Poynting flux is not so important but B_Z is !



Ring current and the *Dst* index

- Dessler-Parker-Sckopke (DPS) relation

$$\Delta B = -\frac{\mu_0}{2\pi}\frac{W_{RC}}{B_0 R_E^3}$$

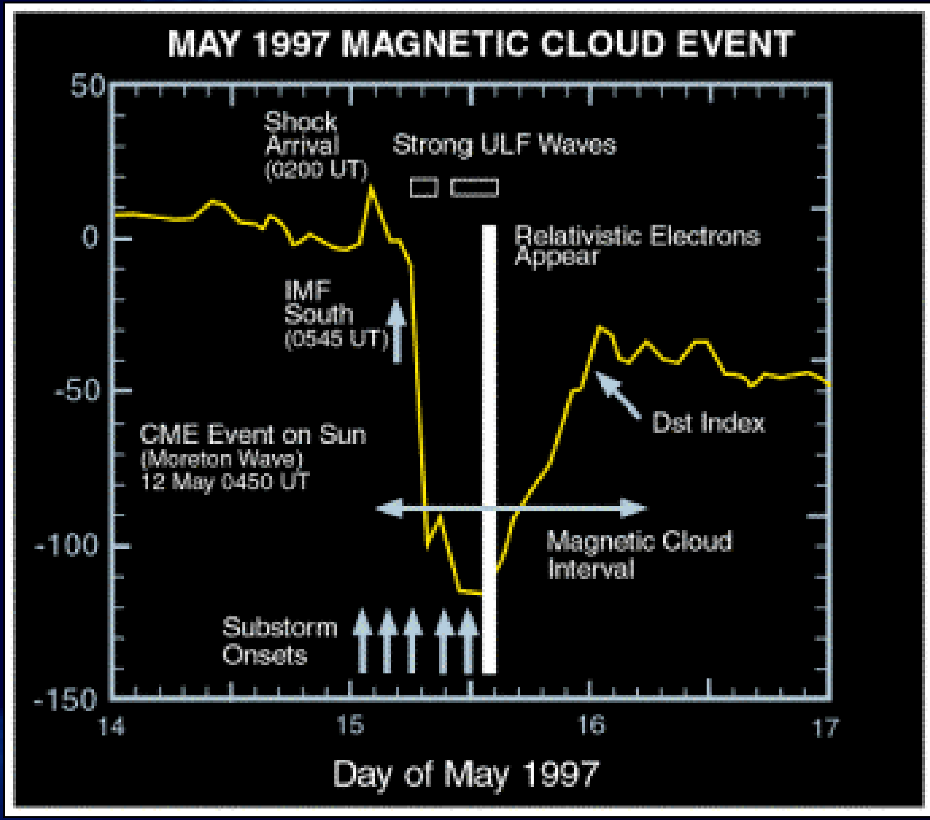
- zeroth approximation

$$\Delta B \leftrightarrow Dst$$

- SW pressure correction

$$Dst^* = Dst - b\sqrt{p} + c$$

- major contributions to *Dst**
  - tail currents ~ 25%
  - ground induction ~ 25%
  - consistent with Polar/CAMMICE data (Turner et al., 2001a)



Disspation through the ring current

- injection rate + decay (with time constant τ_R)
  - from the DPS formula (pressure corrected)

$$P = -4 \times 10^{13} \left(\frac{\partial Dst^*}{\partial t} + \frac{Dst^*}{\tau_R} \right)$$

  - considering the tail and ground induction effects

$$P = -2 \times 10^{13} \left(\frac{\partial Dst^*}{\partial t} + \frac{Dst^*}{\tau_R} \right)$$

  - a factor of two reduction in RC dissipation estimates

Study of 6 storm events
(Turner et al., 2001b)

- Joule heating and auroral precipitation using the AMIE technique
- ring current dissipation from *Dst** with 50% reduction
- relative energy output (intergrated power over the storms)
  - Joule heating: 44 – 69%
  - Auroral precipitation: 17 – 35%
    - ➢ ionospheric total: 78 – 87%
  - ring current: 9 – 16%
  - plasmoids: 4 – 13%
- integrated epsilon input and total output in rough balance
  - plasmoid energy not well estimated

Conclusions on global energy budget

- Ionosphere seems to be able to dissipate more than 75% of input energy (if calculated as epsilon).
- Ring current disspates some 10–20%.
- Most of the remaining energy is released downwind from the tail.

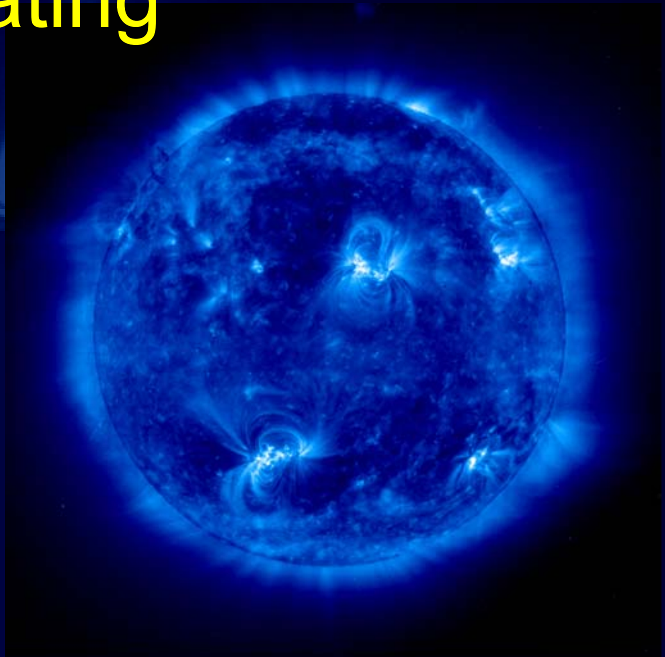
- Note:
  - epsilon is not necessarily scaled right $\Rightarrow$ there may be room for larger output through tail processes
  - be careful with power vs. energy!
    - different processes have different time scales

But is this kind of budgeting practice satisfactory ?

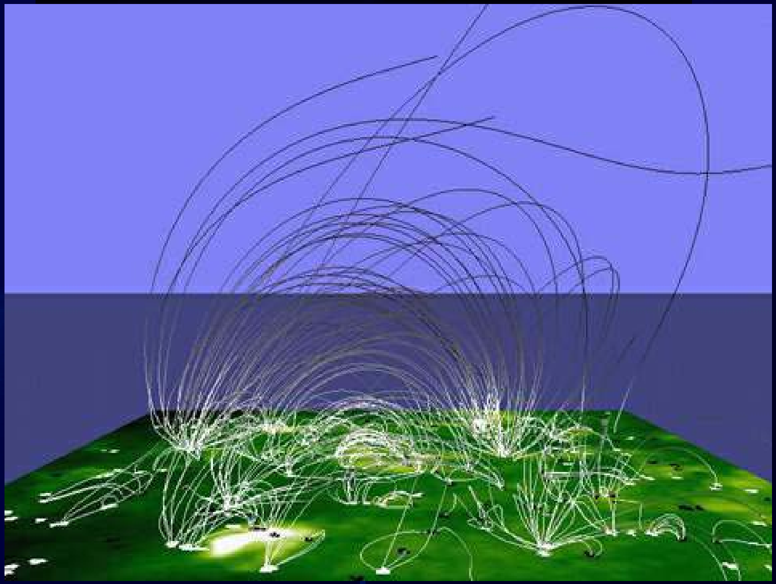
Part 2: Energy conversion

- coronal heating
- flares
- CME release
- SEP acceleration
- acceleration in the magnetosphere

Coronal heating

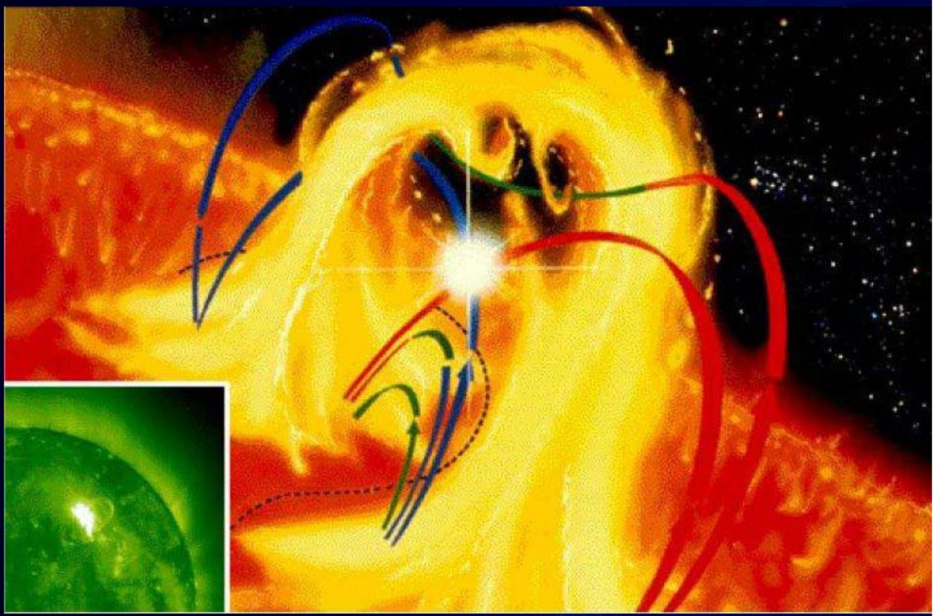


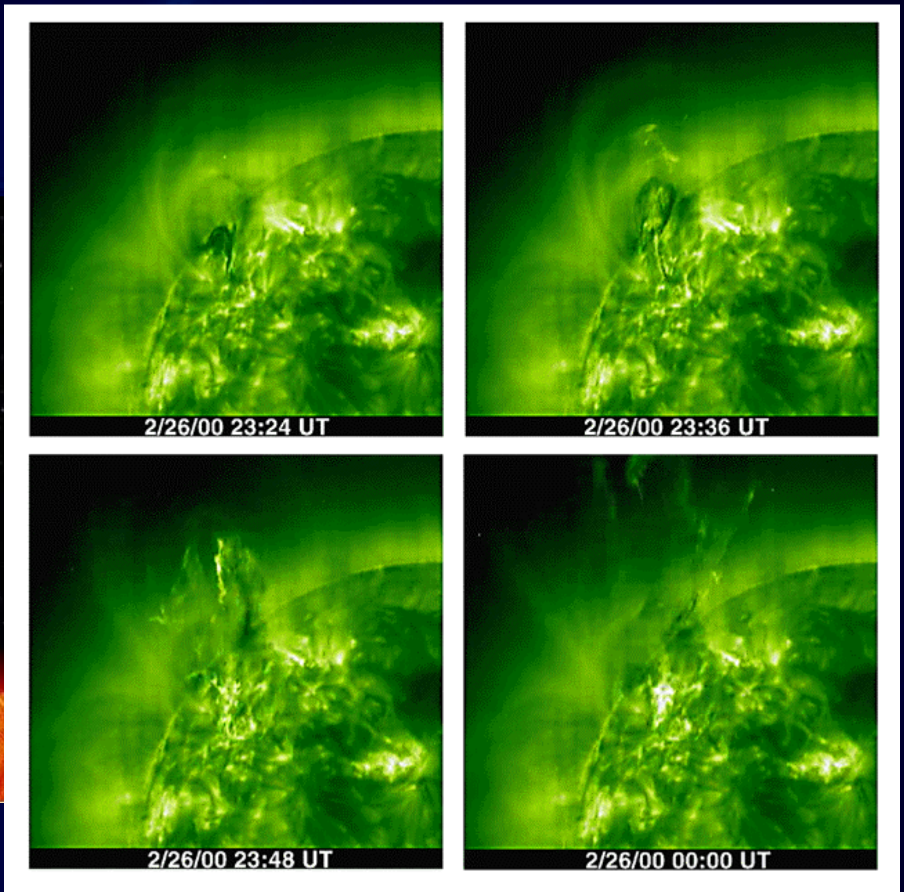
- Problem:
  - chromosphere: 10 000 K
  - corona 1 000 000 K
  - jump at a thin transition layer



- There is enough energy but how is it stopped exactly at the thin transition layer ?
  - role of microflaring ?
  - Alfvén waves ?

Energy release in flares



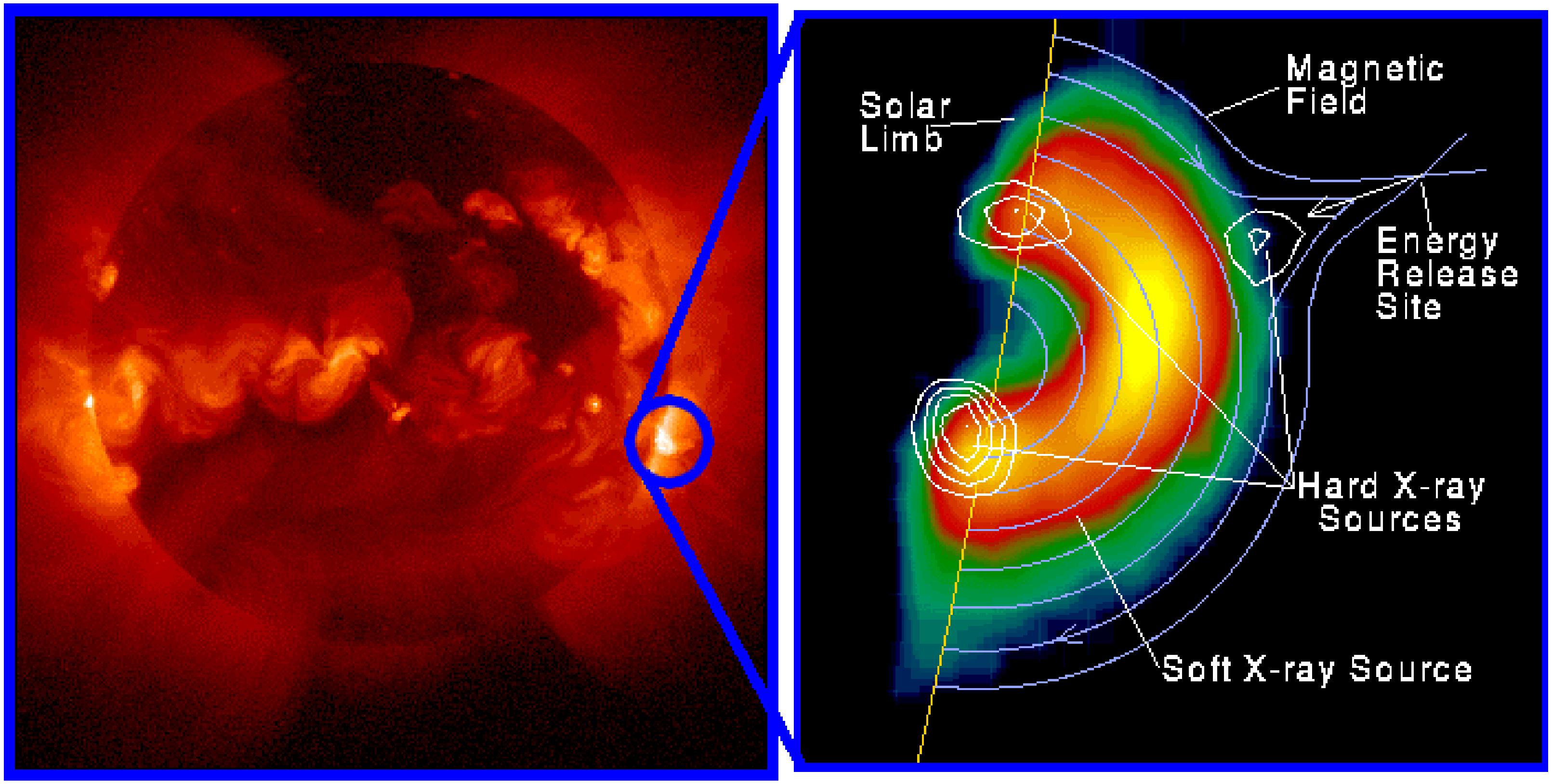


- power $10^{20} – 10^{21}$ W
- total energy release up to 10^{25} J
  - resemblance with substorms but 10^{10} times more energy involved
- temperatures within flares up to 100 MK.

Flare X-rays

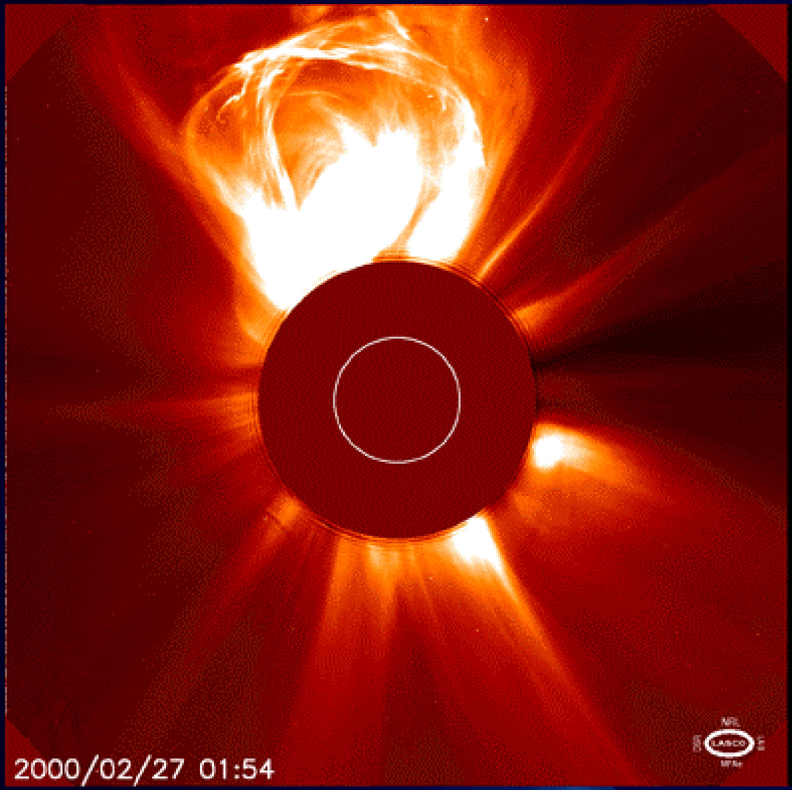
Energy conversion:

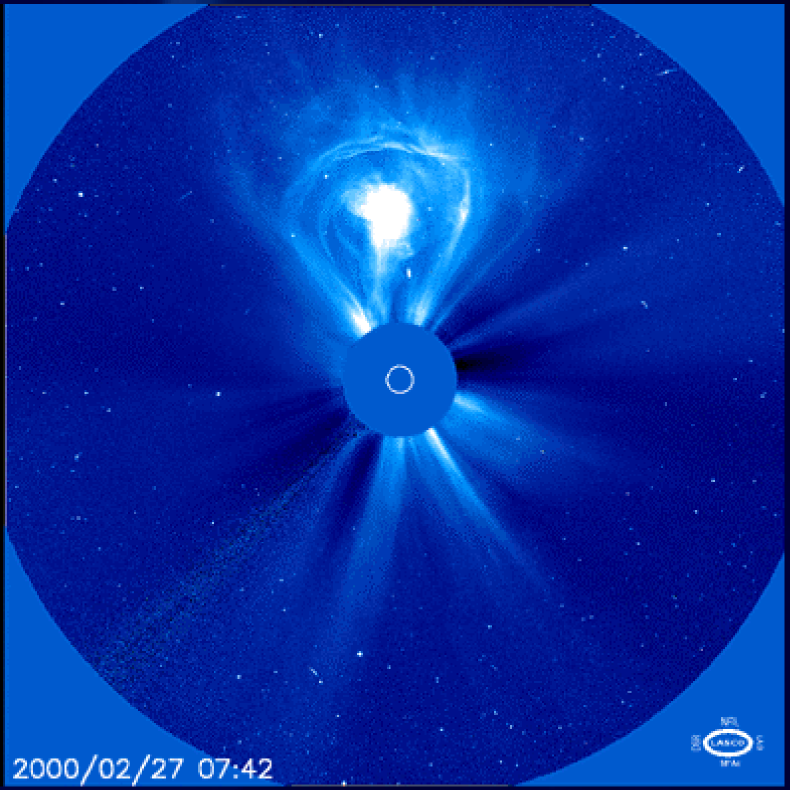
- magnetic energy
  - → electron kinetic energy
    - → X-rays (EM radiation)



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

CME release

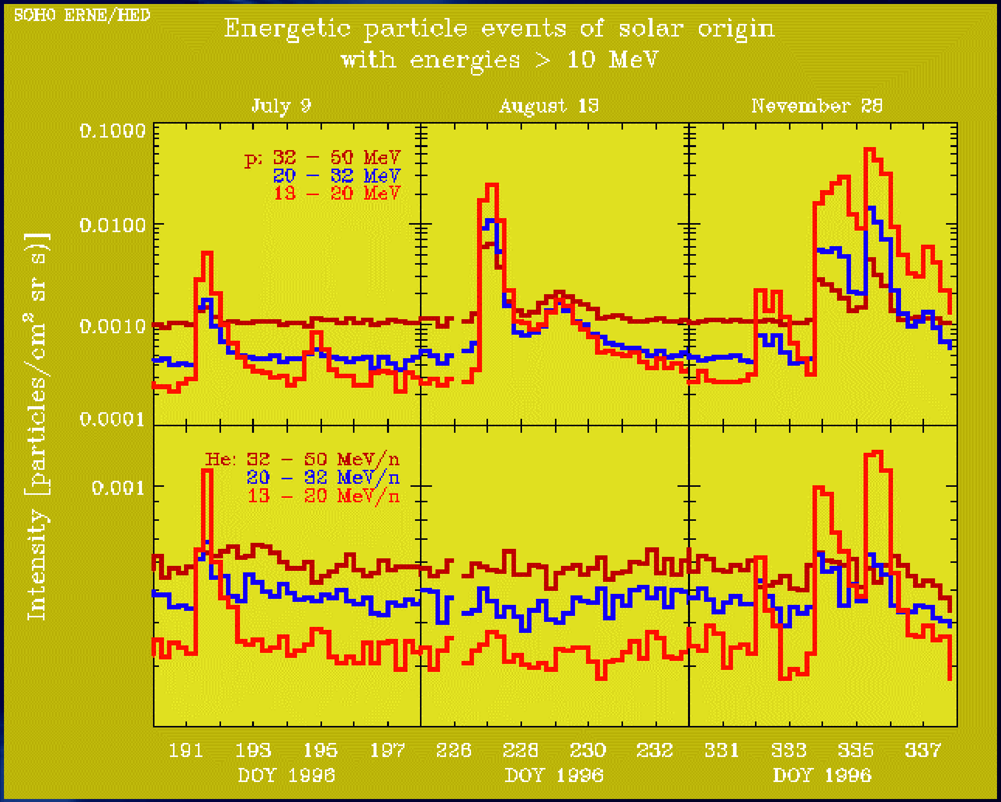




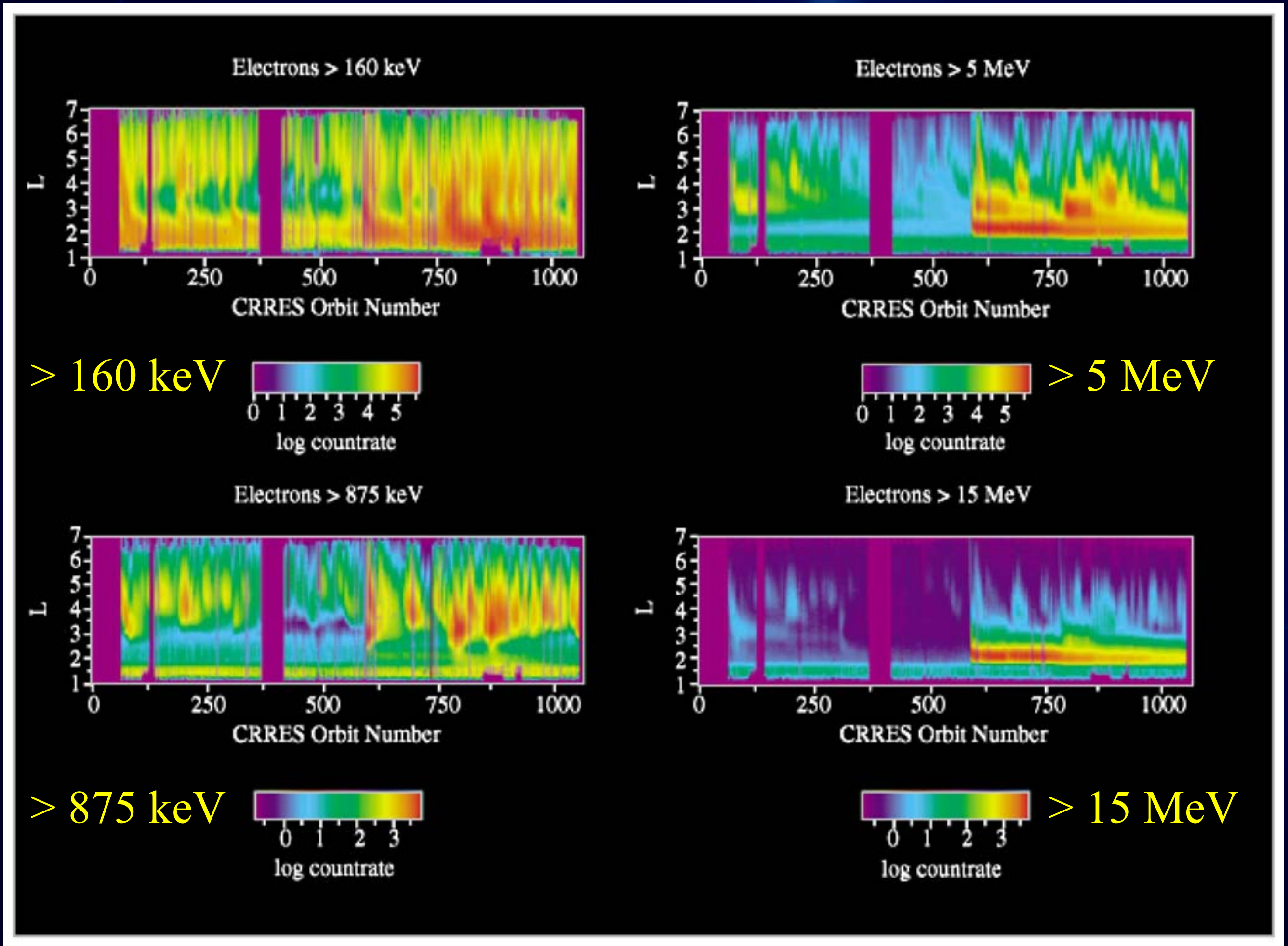
- total kinetic energy leaving the Sun: 10^{24}–10^{25} J
  - conversion of magnetic energy to kinetic energy
- relationship to flares to be understood

Acceleration of solar energetic particles

- large differences between individual events
  - energies
  - temporal evolution
- reconnection
  - solar flares
  - CME release
- shock structures
  - near the Sun
  - interplanetary space

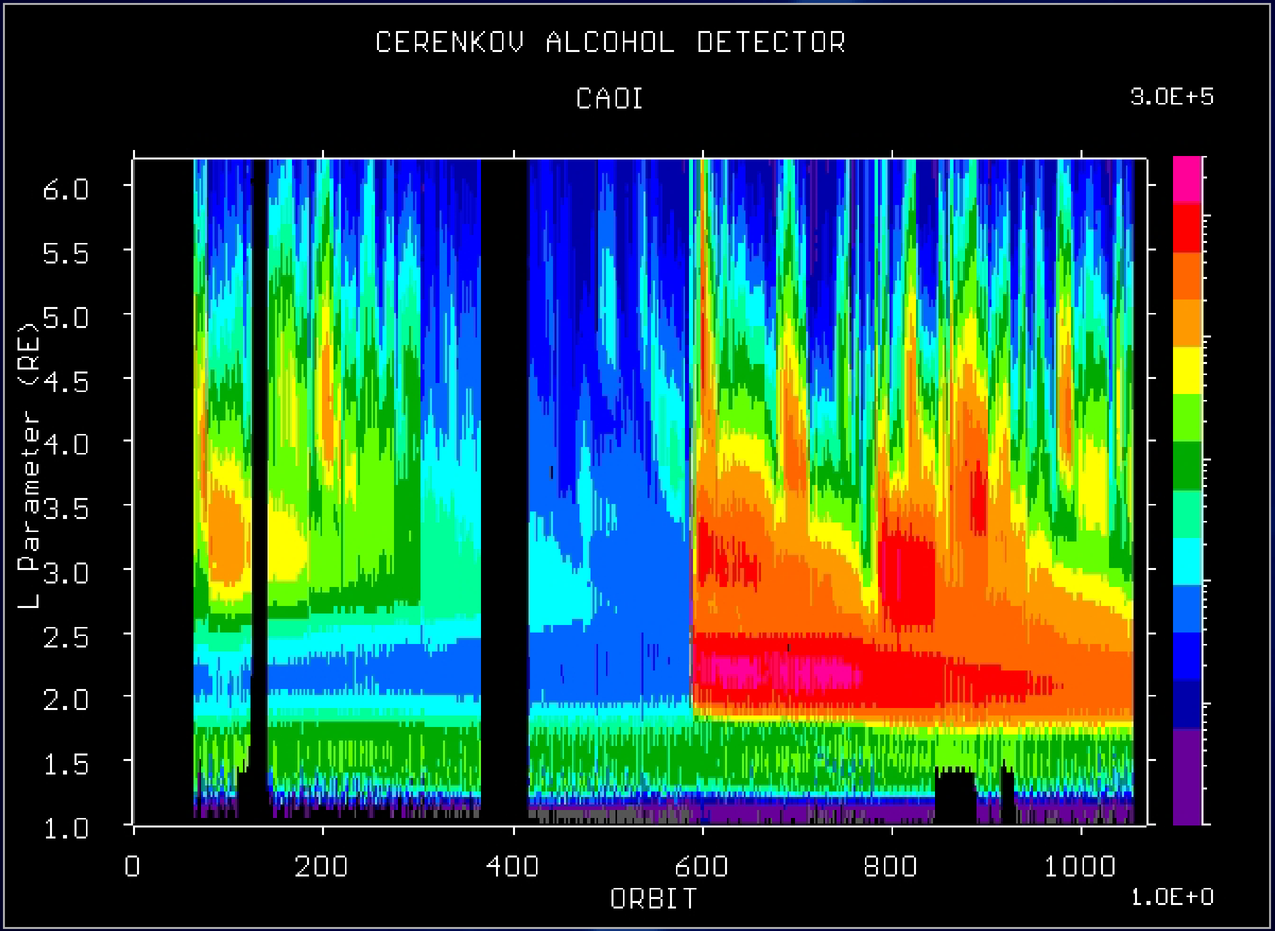


Storm-time injections to radiation belts



CRRES electron observations
August 1990 – October 1991.

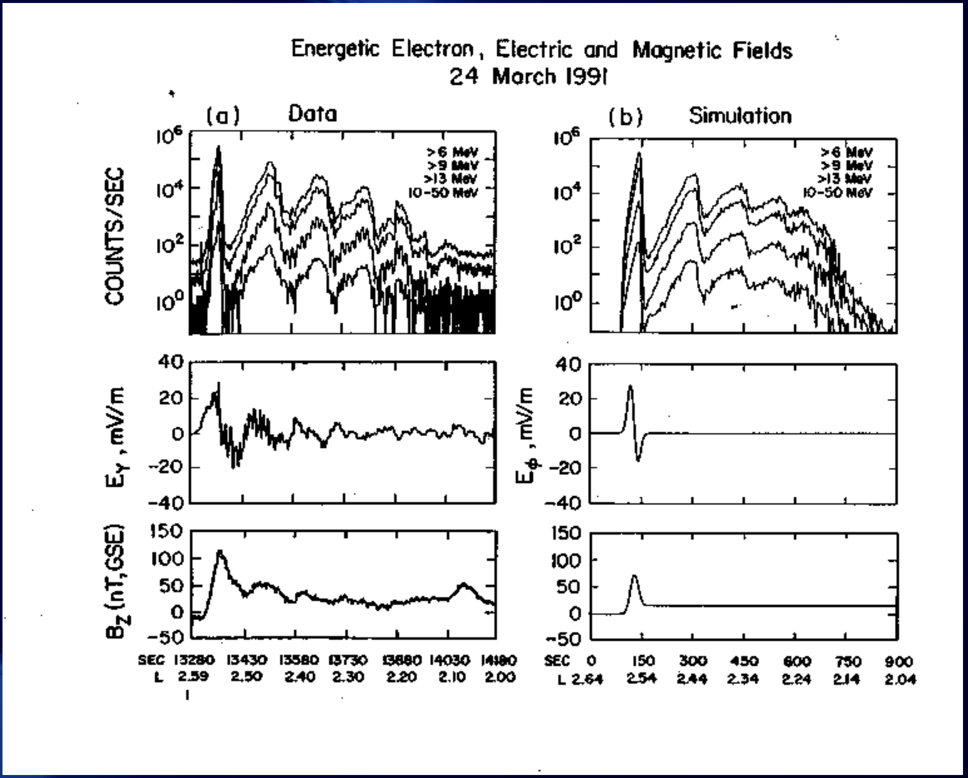
Appearance of killer electrons



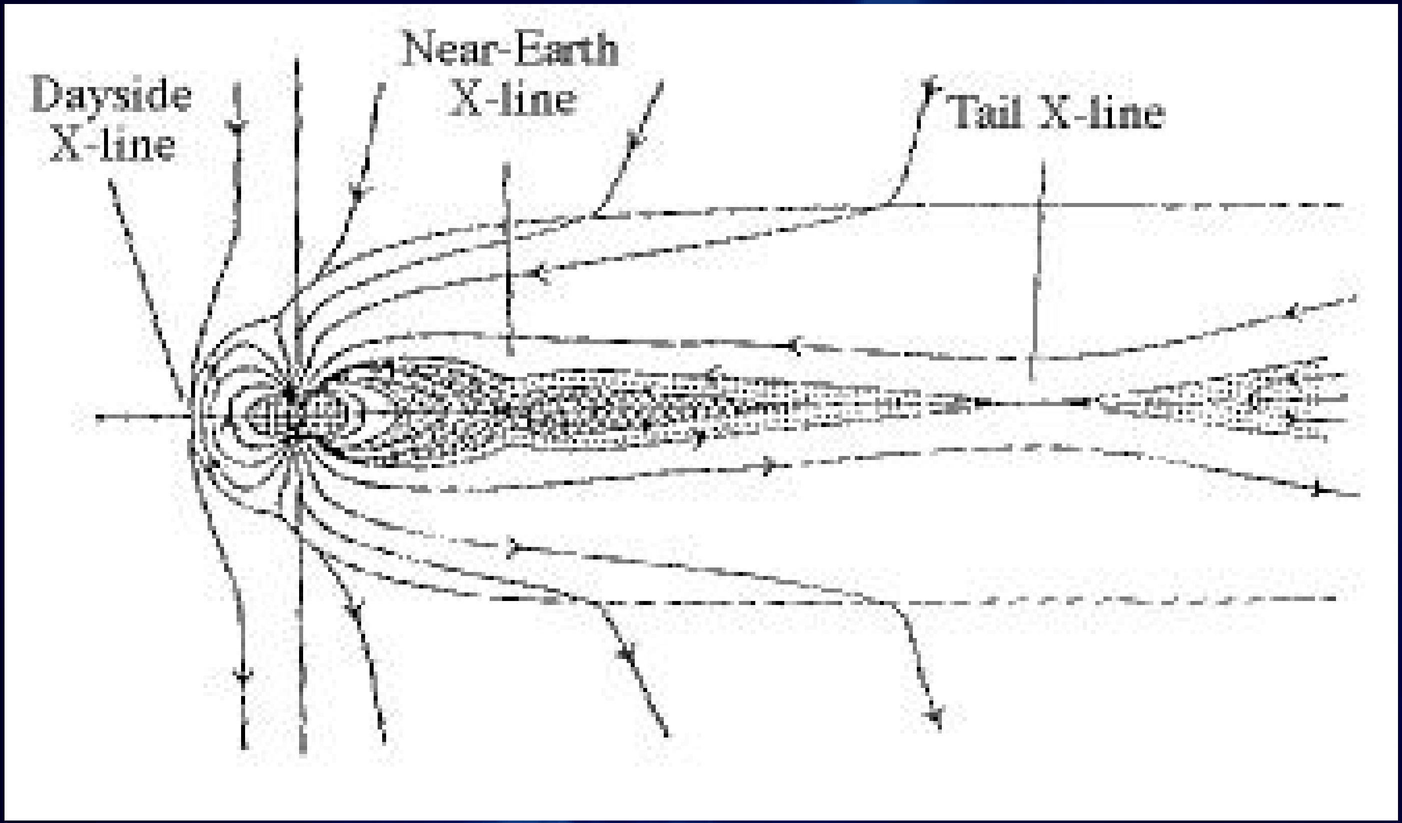
CRRES observations of electrons > 5 MeV;
August 1990 – October 1991.

Storm-time acceleration

- modeling of the March 1991 storm (Li et al., 1993)
- rapid compression of the magnetosphere
    - $\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E}$
    - acceleration in MeV–range
    - rapid (~1 min)
    - needs an energetic seed population



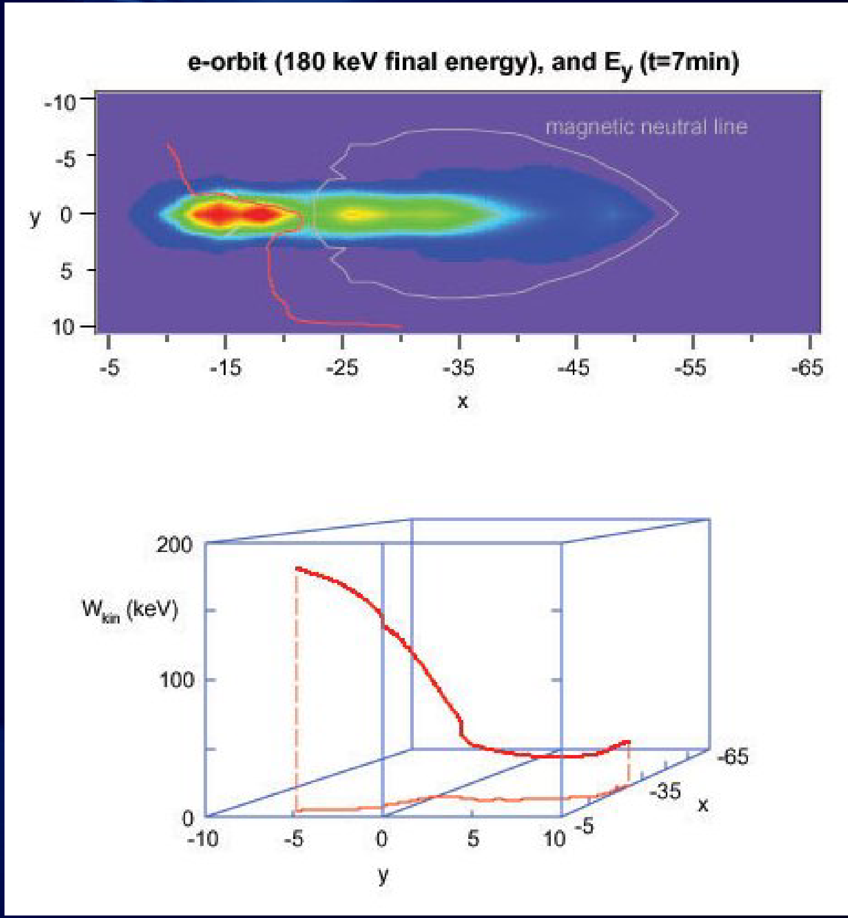
Role of substorms: X-line formation



- rapid near-Earth neutral-line formation / current disruption leads to strong inductive electric field

Electron acceleration near X-line, substorm expansion phase

- time-varying MHD-simulation (courtesy J. Birn)
- 35 keV $\rightarrow$ 180 keV in 7 min
- Is this efficient enough ?
- Does this provide sufficient seed population for storm-time acceleration ?



The future
(if there are any students present, wake up)

- Look for relevant questions
  - avoid to do ”just another isolated substorm study”
  - try to answer open questions instead of once more confirming accepted results
  - there are several in PHYSICS of space weather
- Move away from cartooning and hand-waving
  - be more quantitative
  - learn to estimate errors
  - do not make statistics for too few data points
- Read literature
  - wheel, gunpowder, and a few other things have already been invented

Thank you !