Space Weather Energetics

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This is NOT a talk on space weather effects.
What is energetics

- energetics \-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) \(\sim\) 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

PHYSICS OF SPACE WEATHER
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: $3.86 \times 10^{26}$ 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 10¹⁷ W

- **solar EUV**
  - about 50% in Ly-α (121.6 nm): 6 mW m⁻²
  - total irradiation on Earth ~ 10¹² 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: \( n = 5 \text{ cm}^{-3} \), \( V = 400 \text{ km/s} \), \( B = 10 \text{ nT} \), \( r = 15 \text{ } R_E \)
  - SW KE flux \( \sim 5 \times 10^{-4} \text{ W/m}^2 \); power: 14000 GW
  - SW Poynting flux \( \sim 3 \times 10^{-5} \text{ W/m}^2 \); power: 800 GW

\[
\frac{\text{KE flux}}{\text{Poynting flux}} = \frac{V \cdot \rho V^2}{V B^2 / \mu_0} = \frac{V^2}{V_A^2} = M_A^2
\]

- 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 ↔ different time scales
  - AL (minutes)
  - \(<\text{aa}\)> (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
  \[ S = E H = V B^2 / \mu_0 = 10^7 V B^2 / 4\pi \]

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

- Note that only $B_T$ contributes to $S$ toward the Earth!

$$S_x = (E \times B)_x = \left((V \times B) \times B\right)_x / \mu_0$$

$$= V_x (B_Y^2 + B_Z^2) / \mu_0$$

- 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

Color code: $|V|$  
BS

Draped magnetic field

Color code: $|B|$  
MP

Magnetosheath flow model (Kallio and Koskinen, 2000)
Bow shock transforms kinetic energy flux to Poynting flux (and heat)
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

\[ \frac{\partial B}{\partial t} = (\nabla \times (\nabla \times B)) + \eta \nabla^2 B \]

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

Joule heating

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
  \[ P(W) = C \cdot 10^8 IL(\text{nT}) \]
  \[ C \approx 2–5 \text{ (see, Lu et al., 1998) we use } C = 3 \]
- total JH dissipation
  \[ W_{IL}(J) = \int P \, dt \]
- Note: Dissipation through precipitation is of the same order (~ 50% of JH)
Example: June 23, 1997

- typical isolated substorm
  - max $IL \sim 300$ nT

- input energy
  \[ W_\varepsilon (J) = \int \varepsilon \, dt \]

- hemispheric Joule heating output:
  $W_{IL} \sim 25\%$ of $W_\varepsilon$

- total dissipation in ionosphere:
  $\sim 75\%$ of $W_\varepsilon$
  - 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 $\approx 0.7$
  - when both calculated for the expansion phase
- storm-time substorms
  - for large 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 ($D_{st} < -40$ nT) substorms
    - 1997: 46%
    - 1999: 48%

- typical (median) total Joule heating
  - isolated substorms: $10^{15}$ J
  - storm-time substorms: $2 \times 10^{15}$ J
Sometimes epsilon seems ”too large”

- December 17, 1997
  - large IMF X-component
    - large epsilon input
  - weak ionospheric dissipation
    - hemispheric JH 11% of $\varepsilon$
  - 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?

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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

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

- zeroth approximation

$$\Delta B \leftrightarrow Dst$$

- SW pressure correction

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

- major contributions to $Dst^*$
  - tail currents $\sim 25\%$
  - ground induction $\sim 25\%$
  - consistent with Polar/CAMMICE data (Turner et al., 2001a)
Dissipation through the ring current

- injection rate + decay (with time constant $\tau_R$)
  - 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 (integrated 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 dissipates 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.
Energy conversion:
- magnetic energy
  → electron kinetic energy
  → X-rays (EM radiation)

Flare X-rays

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
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
  - $\frac{\partial \mathbf{B}}{\partial t} = - \nabla \times \mathbf{E}$
  - 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!