Planetary Magnetospheres

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Heliophysics Summer School: Year 4
July 28 – August 4, 2010
Boulder, Colorado

July 23, 2010

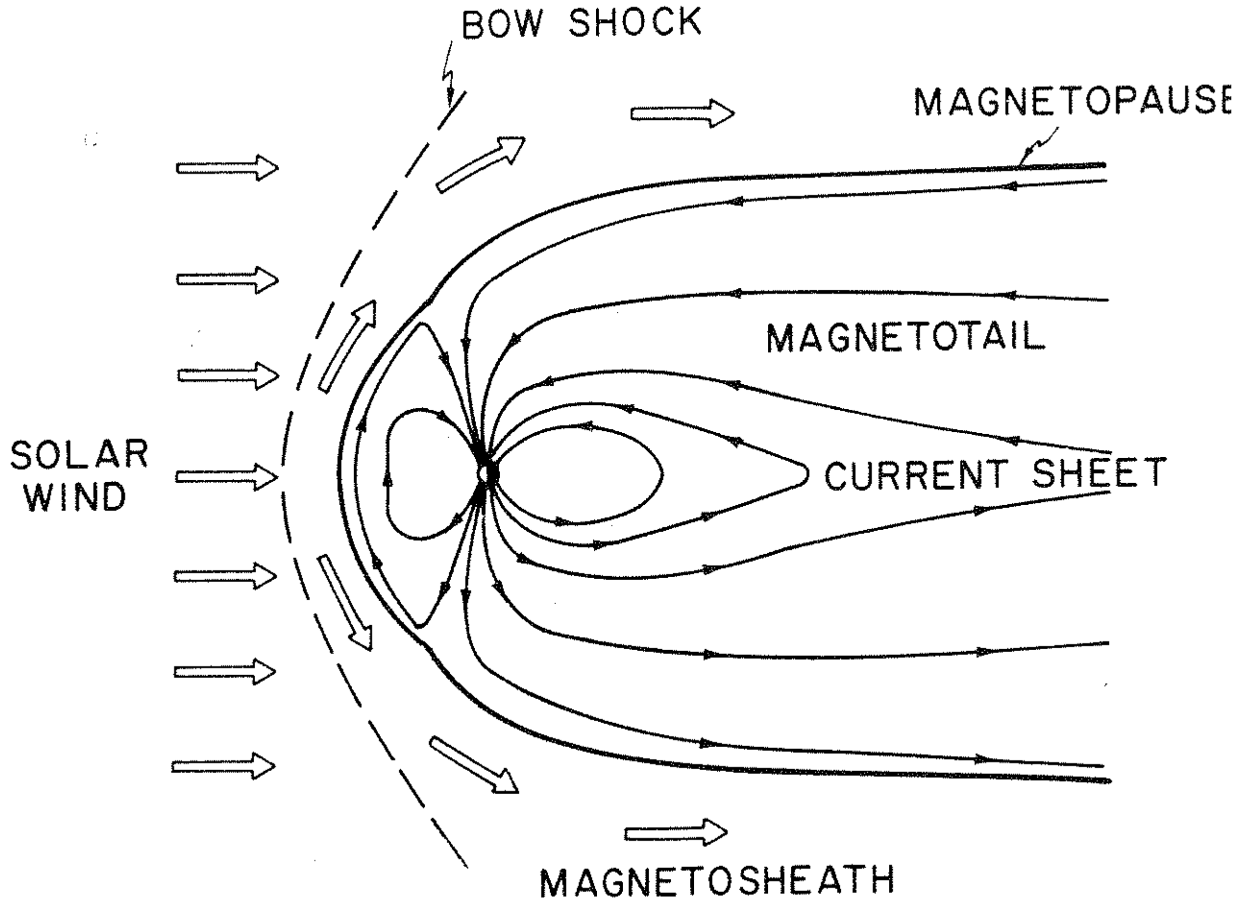


Figure 1: **Schematic view of a (magnetically closed) magnetosphere, cut in the noon-midnight meridian plane. Open arrows: solar wind bulk flow. Solid lines within magnetosphere: magnetic field lines (direction appropriate for Earth).**

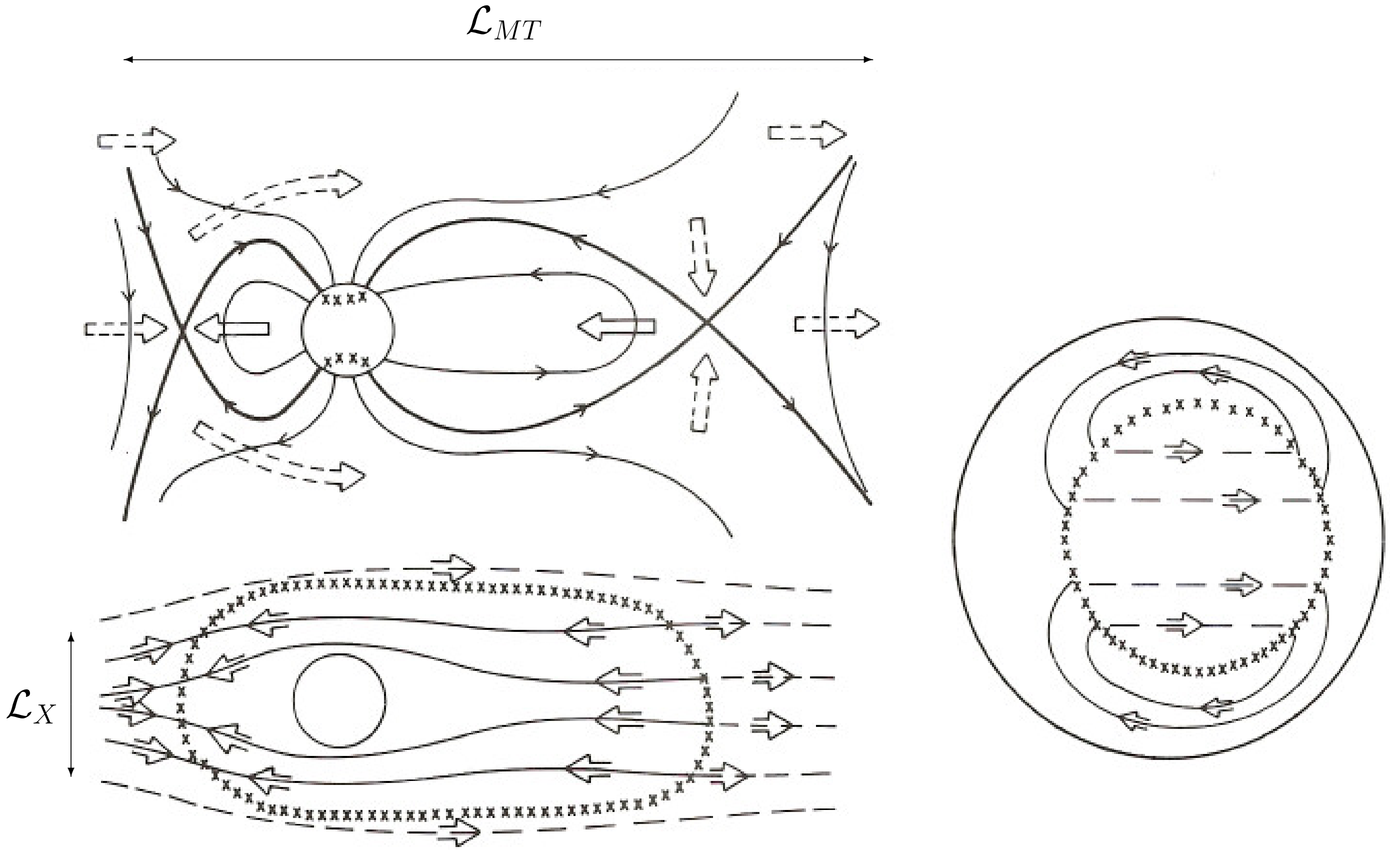


Figure 2: **Schematic topological view of a magnetically open magnetosphere. (a) [upper left]: noon-midnight meridian plane (solid lines: magnetic field lines, open arrows: plasma bulk flow directions). (b) [lower left]: equatorial plane (lines: plasma flow streamlines, line of x's: magnetic X-line = closed/interplanetary field line boundary). (c) [right]: projection on ionosphere (lines: plasma flow streamlines, line of x's: open/closed field line boundary = projection of magnetic X-line = polar cap boundary). The sunward direction is always to the left.**

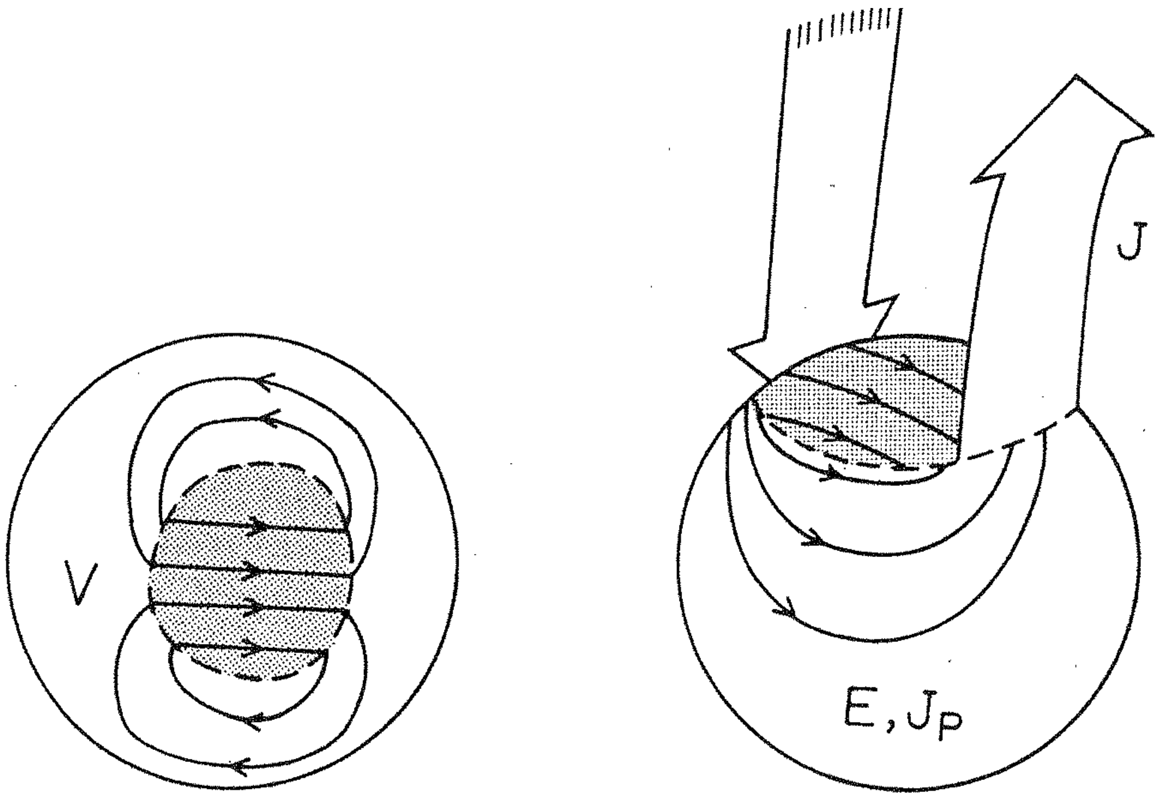


Figure 3: **Schematic diagram of magnetospheric convection. (Left) Streamlines of the plasma bulk flow; the Sun is on the left. (Right) Electric field lines and associated Pedersen currents, and the Birkeland (magnetic-field-aligned) currents (large arrows).**

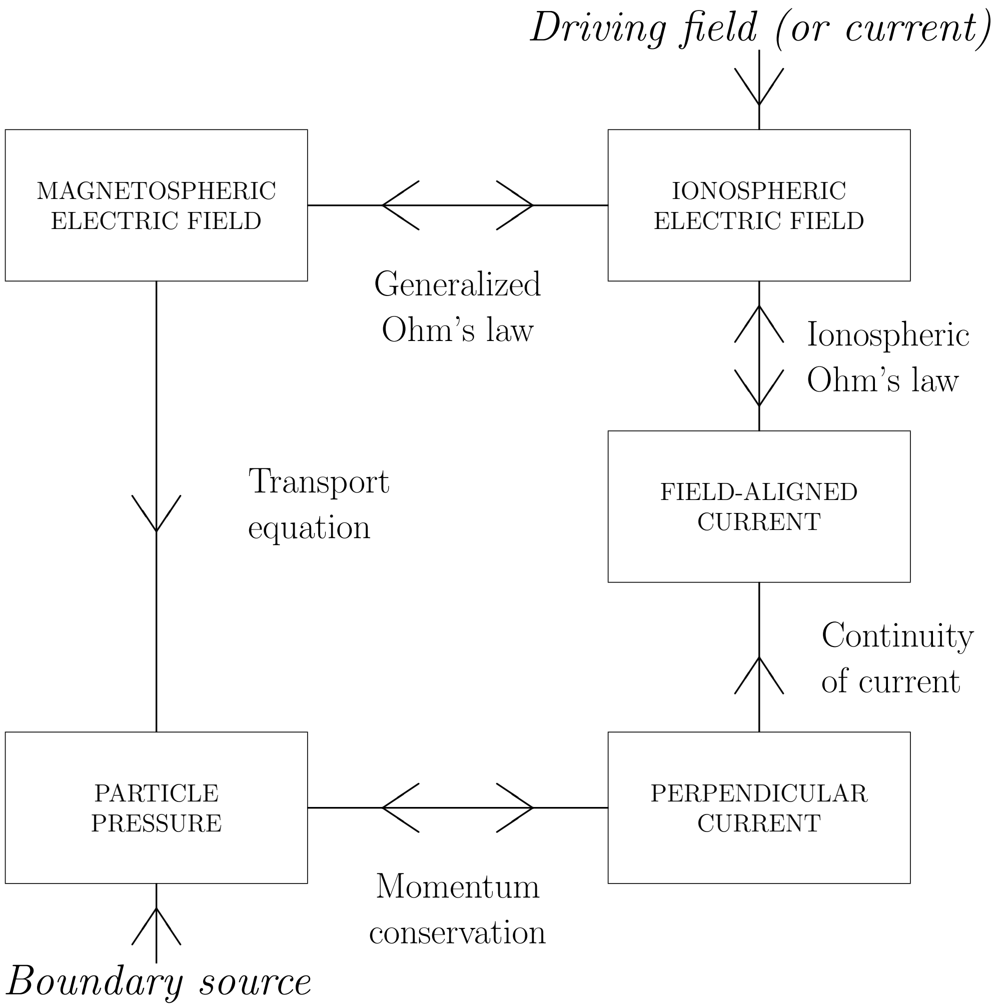


Figure 4: **Schematic diagram of self-consistent magnetosphere/ionosphere coupling calculations**

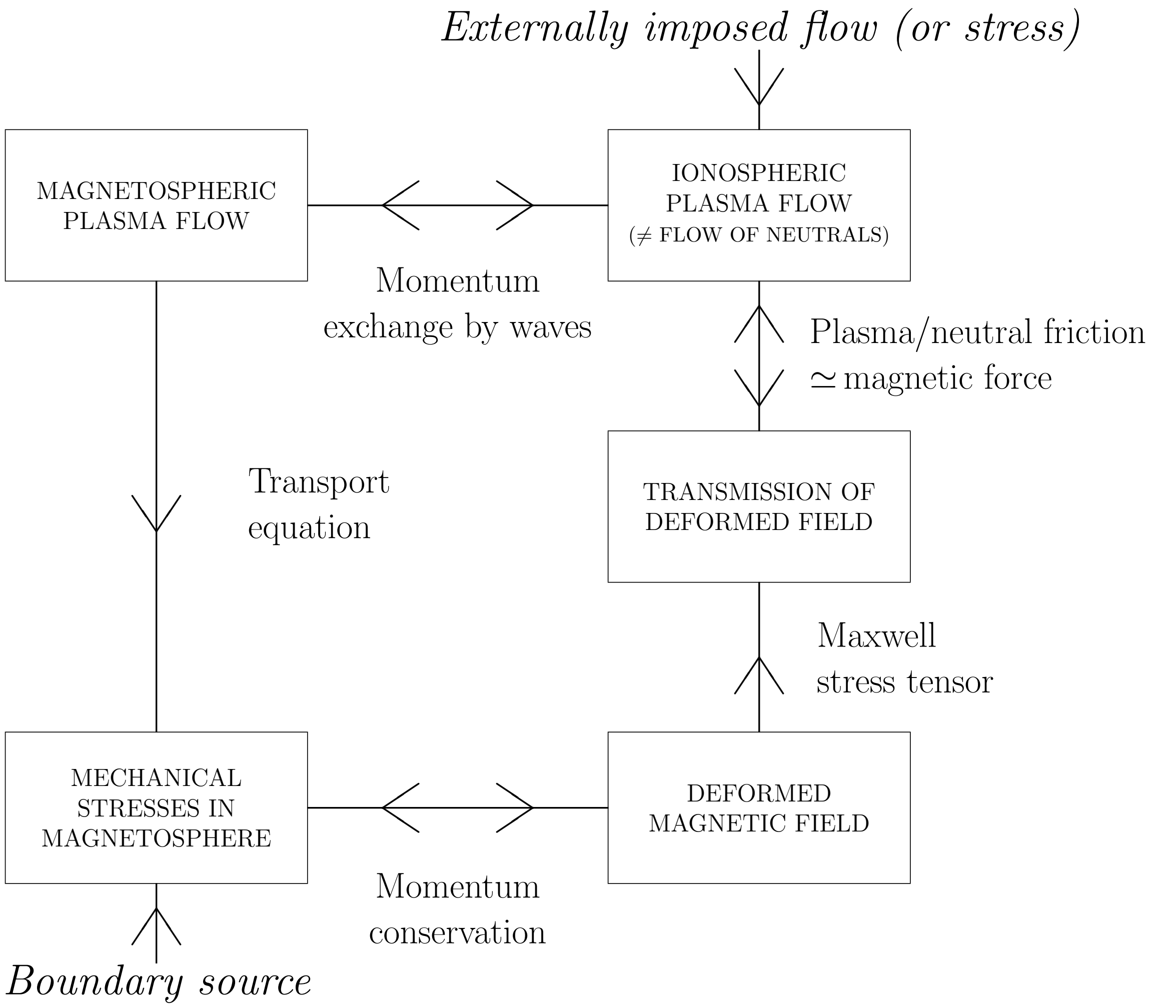


Figure 5: **Revised schematic diagram of magnetosphere/ionosphere coupling calculations.**

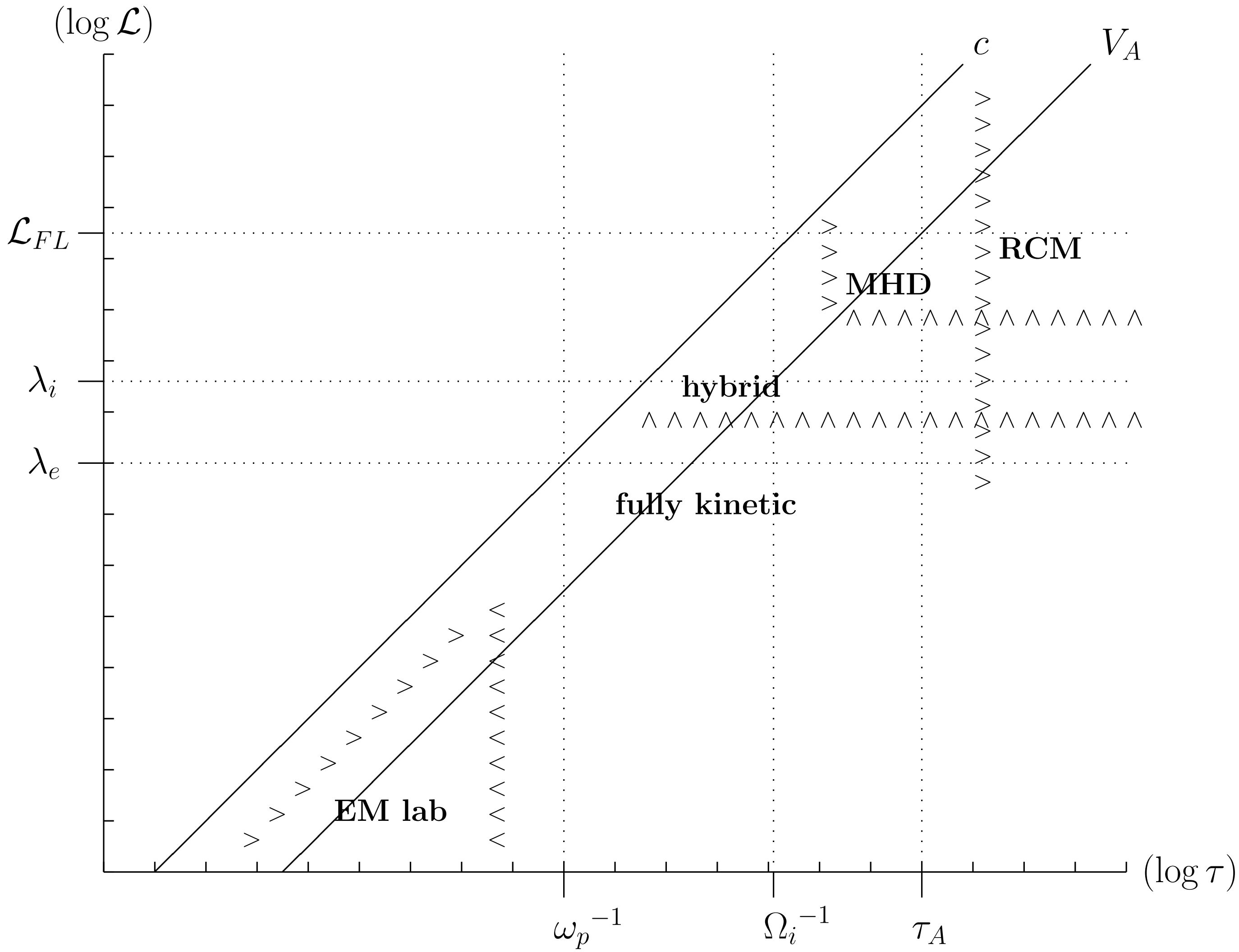


Figure 6: **Validity regions of various approximations. Tick marks are at factors of 10.**

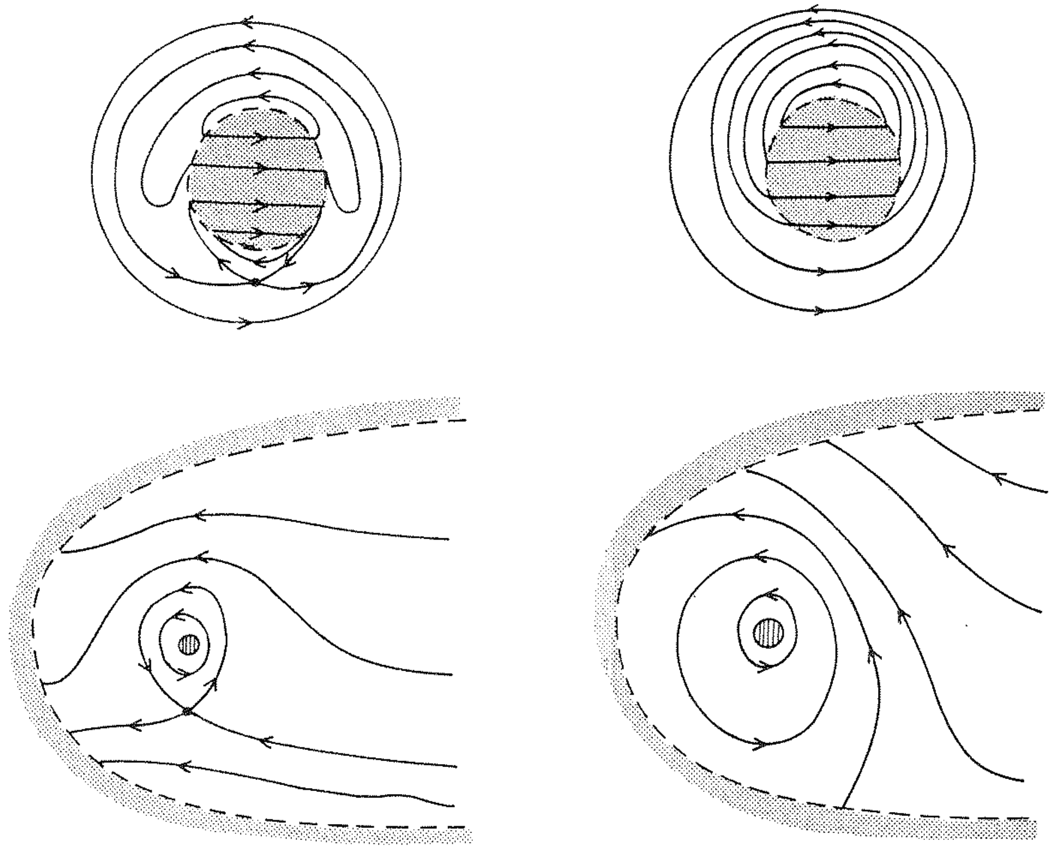


Figure 7: **Streamlines of plasma flow: (top) looking down on the topside ionosphere, (bottom) projected along magnetic field lines to the equatorial plane of the magnetosphere; (left) magnetospheric convection dominant, (right) corotation dominant**

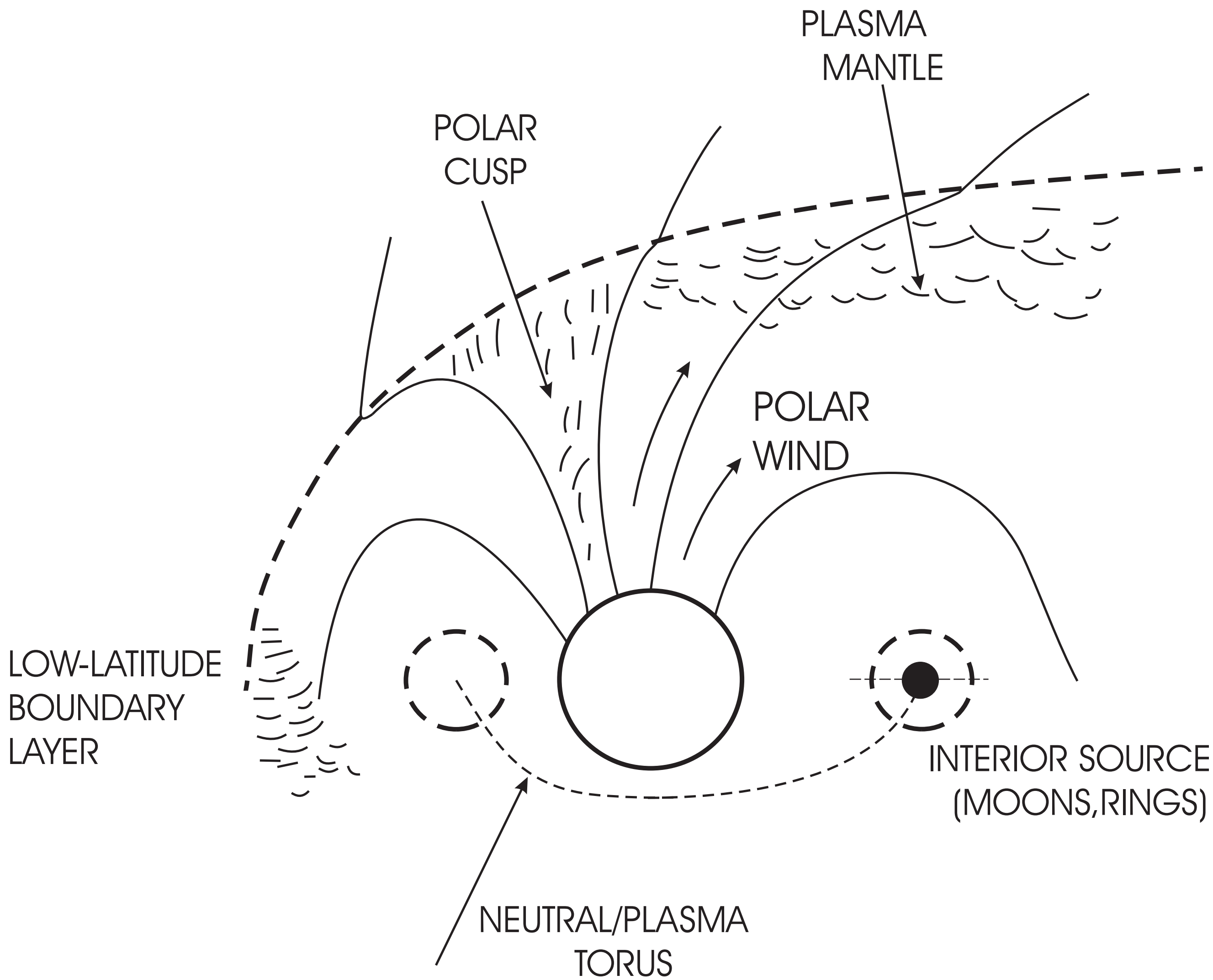


Figure 8: **Sketch of plasma source locations (not to scale, schematic, only northern hemisphere shown).**

Energy storage, transfer, and conversion

Mechanical energy (kinetic energy of motion):

$$\frac{\partial}{\partial t} U_{mech} + \nabla \cdot \left[\mathbf{V} U_{mech} + \mathsf{P} \cdot \mathbf{V} + \mathbf{q} \right] = \mathbf{E} \cdot \mathbf{J} + \rho \mathbf{V} \cdot \mathbf{g}$$

$$U_{mech} \equiv \tfrac{1}{2} \rho V^2 + \epsilon \qquad \epsilon = \textbf{Trace } (\mathsf{P})$$

Electromagnetic energy (Poynting's theorem):

$$\frac{\partial}{\partial t} \frac{1}{8\pi} \left[B^2 + E^2 \right] + \nabla \cdot \left[\frac{c}{4\pi} \mathbf{E} \times \mathbf{B} \right] = -\mathbf{E} \cdot \mathbf{J}$$

Gravitational energy (approximate):

$$\frac{\partial}{\partial t} \left[\rho \Phi_G \right] + \nabla \cdot \left[\rho \mathbf{V} \Phi_G \right] = -\rho \mathbf{V} \cdot \mathbf{g}$$

Conversion rates between different forms of energy

$\mathbf{E} \cdot \mathbf{J} > 0$ **electromagnetic $\longrightarrow$ mechanical**

$\mathbf{E} \cdot \mathbf{J} < 0$ **mechanical $\longrightarrow$ electromagnetic**

$\rho \mathbf{V} \cdot \mathbf{g} > 0$ **gravitational $\longrightarrow$ mechanical**

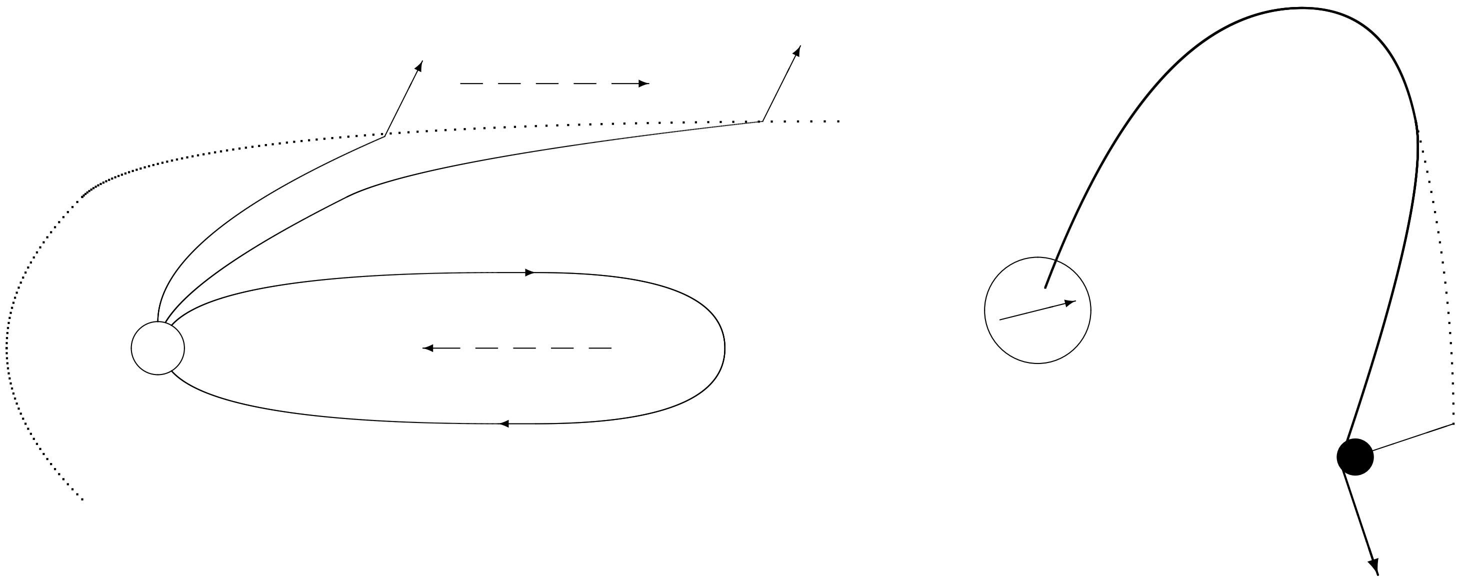
$\rho \mathbf{V} \cdot \mathbf{g} < 0$ **mechanical $\longrightarrow$ gravitational**

Primary source of energy for Earth's magnetosphere: kinetic energy of solar-wind bulk flow.

(Thermal and magnetic energies of the solar wind are small compared to the kinetic energy of the bulk flow, but not necessarily small compared to energies dissipated in the magnetosphere; the reason they are not important is that at the bow shock they are overwhelmed by additional thermal and magnetic energies extracted from the flow.)

For magnetospheres of rapidly rotating giant planets (Jupiter, Saturn), primary source of energy is kinetic energy of the rotating planet.

Conversion of bulk flow kinetic energy to magnetic energy



(*Left*): deformation of magnetotail field by external plasma flow. Solid lines: magnetic field lines. Dashed arrows: plasma flow direction. Dotted line: magnetopause. (*Right*): deformation of planetary magnetic field by torque from magnetospheric plasma element (black sphere). Solid line: actual magnetic field line. Dashed line: undistorted magnetic field line. Arrow on planet's surface: direction of rotational motion.

Relation between global energy input rate and force

Bulk flow of a medium carries not only kinetic energy but also linear momentum; extracting kinetic energy from the flow necessarily means also extracting linear momentum, which requires a force to be applied to the medium. By comparing solar wind energy and momentum flux across surfaces upstream and downstream of the entire magnetosphere, one can relate the net rate of energy extraction (power) $\mathcal{P}_{sw}$ from solar wind flow to the force F in the direction of solar wind flow:

$$\mathcal{P}_{sw} = \mathrm{F}\overline{V}$$

The linear momentum that is extracted together with the kinetic energy is a conserved quantity which cannot simply disappear; it is transferred to and exerts an added force on the massive Earth.

(Similar considerations relate energy extracted from a planet's rotation to torque.)

Conversion of magnetic to mechanical energy

- **collisional and Joule heating in the ionosphere**
- **auroral particle acceleration and precipitation: frequently attributed to Birkeland (magnetic-field-aligned) electric currents accompanied by electric fields parallel to the magnetic field (rate of energy supply =** $E_{\parallel} J_{\parallel}$**)**
- **formation and energization of plasma sheet (by magnetic reconnection and adiabatic compression)**
- **energization of ring current particles by inward transport: by adiabatic compression, drift in electric fields, conservation of adiabatic invariants — all equivalent (Hines, 1963)**

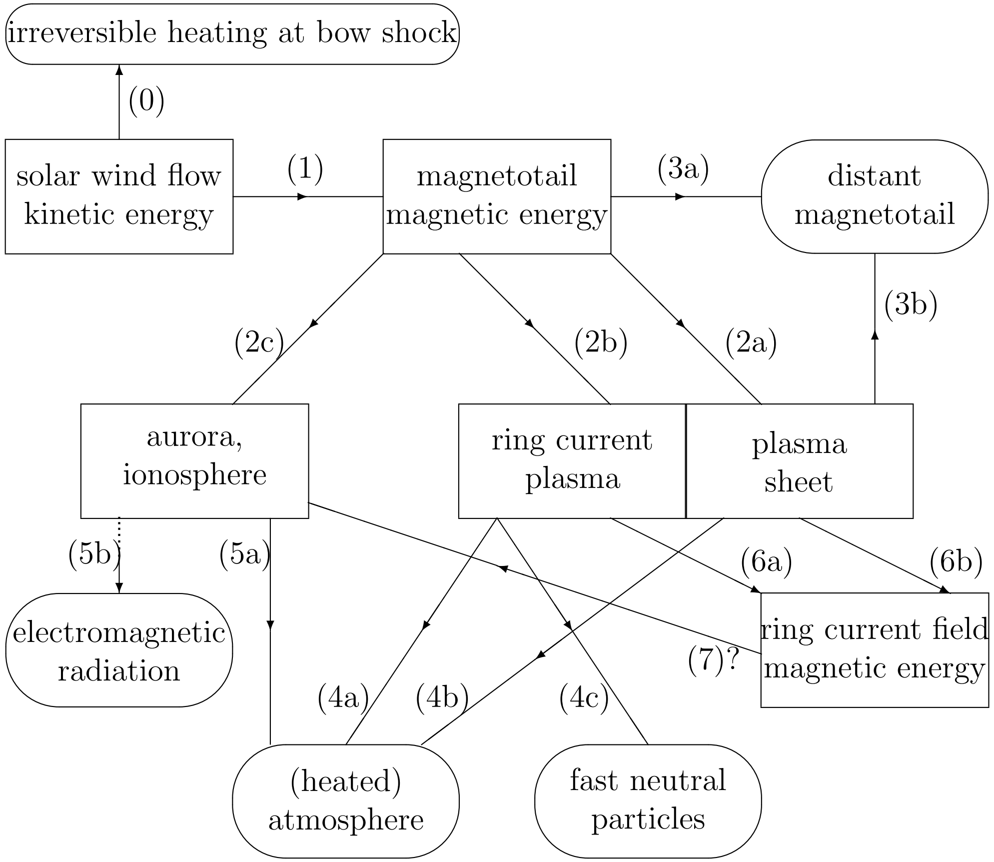


Figure 9: **Energy flow chart for solar-wind-dominated magnetosphere (example: Earth). Rectangular boxes: energy reservoirs. Rounded boxes: energy sinks. Lines: energy flow/conversion processes (dotted line: process of less importance); numbers keyed to description in text (question mark: process uncertain).**

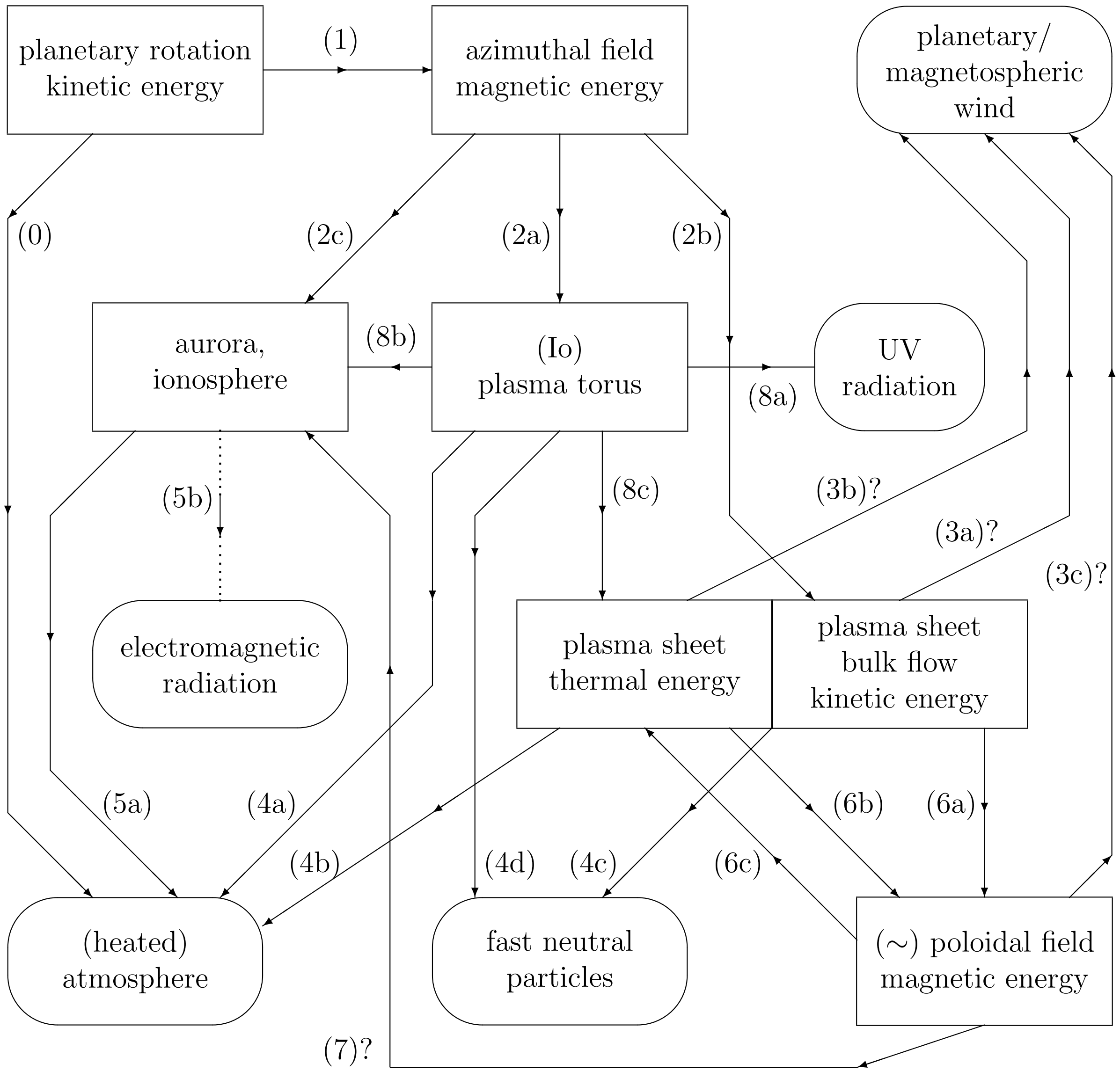


Figure 10: **Energy flow chart for rotation-dominated magnetosphere (example: Jupiter).**

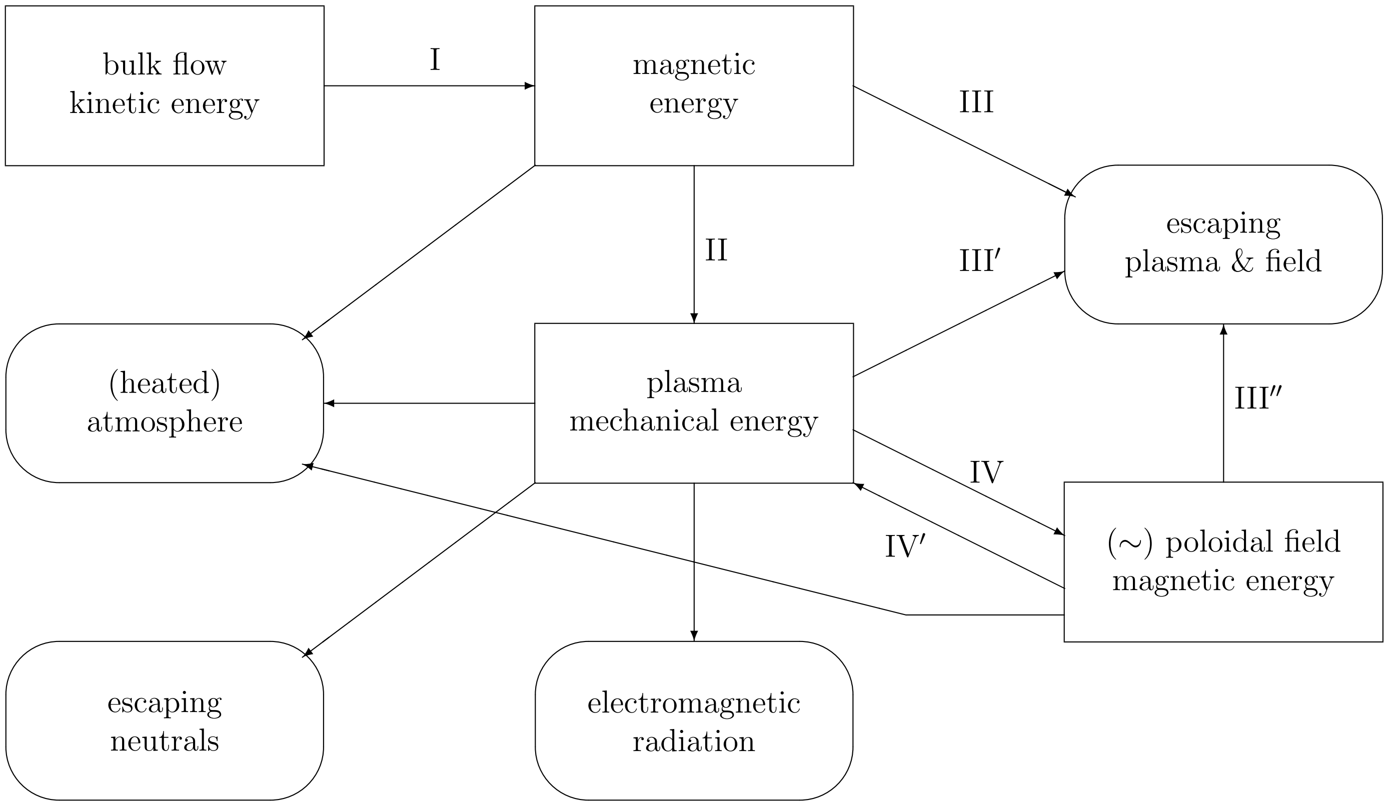


Figure 11: **(Simplified) general energy flow chart for planetary magnetospheres. Rectangular boxes: energy reservoirs. Rounded boxes: energy sinks. Lines: energy flow/conversion processes.**

Two prototypical examples of magnetospheric variability:

1. **magnetospheric substorm**
2. **magnetic storm**

Both are produced essentially by southward interplanetary magnetic field, so are they really different, except for time scale?

(question put to me by a solar physicist)

1. What is a substorm? What is a storm?

(a) **Defining phenomenon?** *(observed)*

(b) **Defining process?** *(conceptual)*

There does not seem to be a generally accepted clear definition of the magnetospheric substorm, either as phenomenon or as process — in contrast to the magnetic storm, for which there is a clear definition as phenomenon.

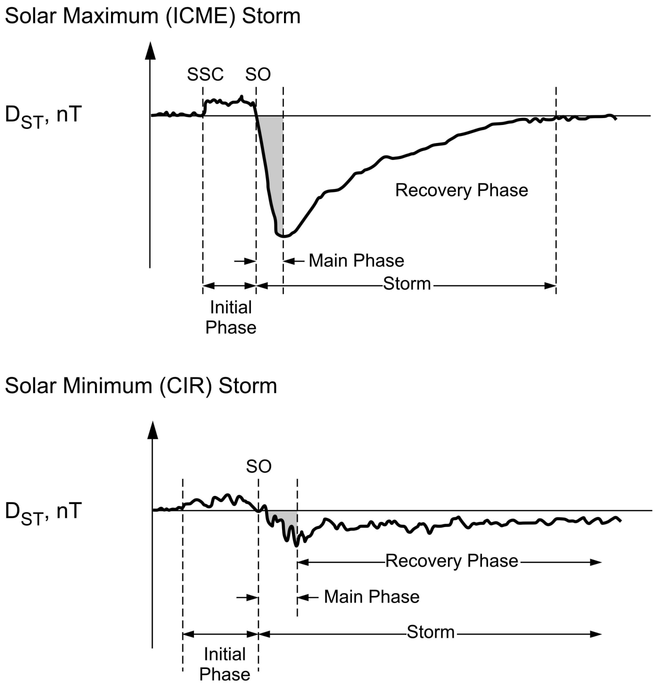


Figure 12: **Schematic time history of geomagnetic field variation for two typical magnetic storms. Time range: several days. Vertical variation range: $\sim 100-200$ nT. SSC: storm sudden commencement. SO: storm onset (adapted from Tsurutani *et al.*, 2006).**

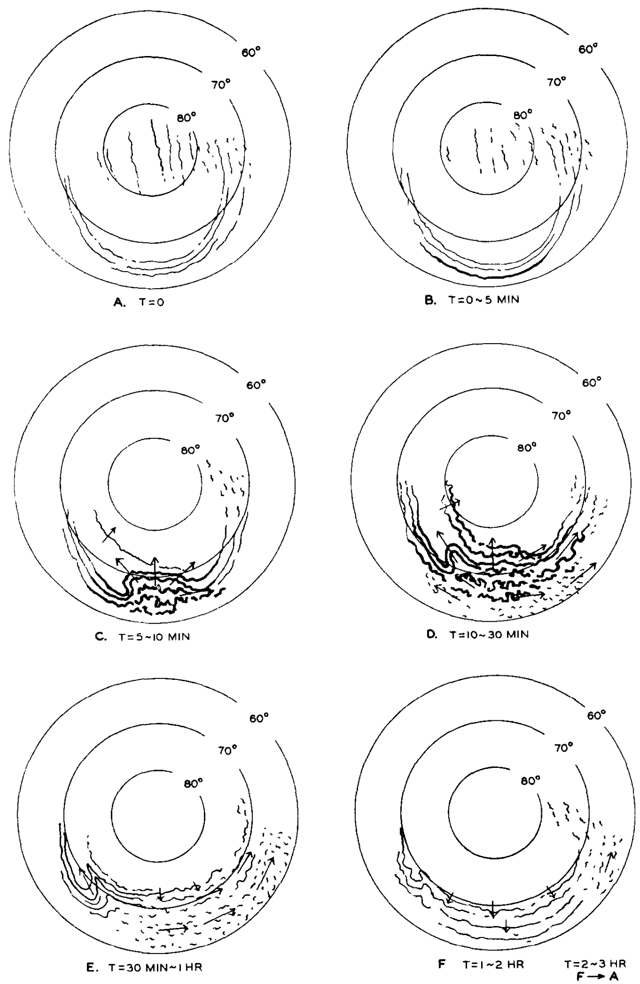
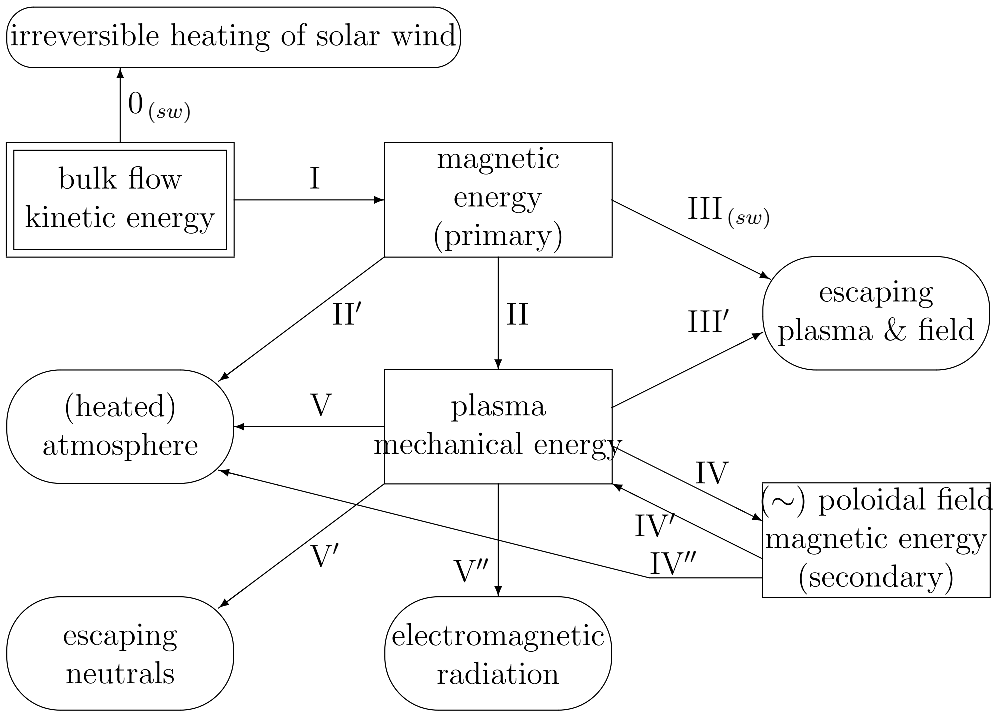


Figure 13: **Schematic diagram of the auroral substorm. View from above the north pole, circles of constant geomagnetic latitude, Sun toward the top (Akasofu, 1964)**



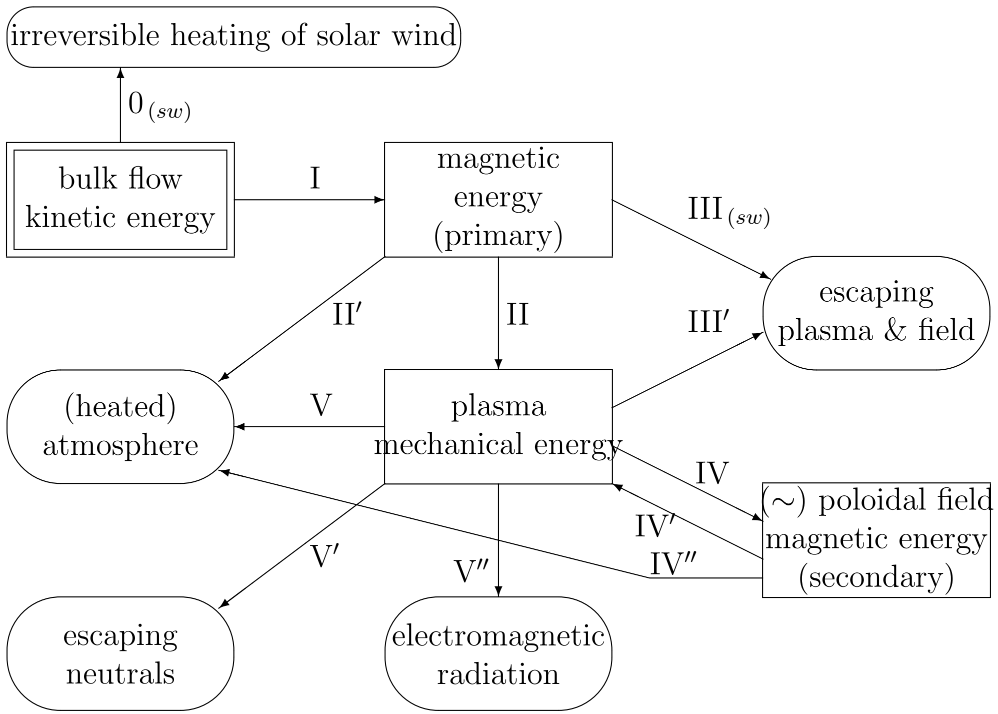
$\mathcal{P}_{total} \sim \frac{1}{2}\rho_{sw}(V_{sw})^3 A_T$ **total power supplied by the solar-wind energy source**

$\mathcal{P}_{0_{(sw)}} \sim (1-\delta)\,\frac{1}{2}\rho_{sw}(V_{sw})^3 A_T$ **from pressure (Chapman-Ferraro) force on magnetosphere**

$\mathcal{P}_{\mathrm{I}} \sim \left({B_T}^2/8\pi\right)\, A_T\, V_{sw}$ **from magnetic tension force of magnetotail**

$\mathcal{P}_{\mathrm{II}}$, $\mathcal{P}_{\mathrm{II}'}$ **estimated empirically (e.g., Burton et al. formula, ϵ parameter, etc.)**

find in general $\mathcal{P}_{\mathrm{II}} + \mathcal{P}_{\mathrm{II}'} \sim O(\frac{1}{10})\mathcal{P}_{\mathrm{I}}$



Magnetospheric substorm:

growth phase **— $\mathcal{P}_{\mathrm{I}}$ enhanced,**

$\mathcal{P}_{\mathrm{I}} > [\mathcal{P}_{\mathrm{II}} + \mathcal{P}_{\mathrm{II}'} + \mathcal{P}_{\mathrm{III}_{(\mathrm{sw})}}]$

expansion phase **— $\mathcal{P}_{\mathrm{II}}$ and $\mathcal{P}_{\mathrm{II}'}$**

(also $\mathcal{P}_{\mathrm{III}_{(\mathrm{sw})}}$, $\mathcal{P}_{\mathrm{III}'}$) enhanced

Magnetic storm:

stored

plasma mechanical energy

enhanced

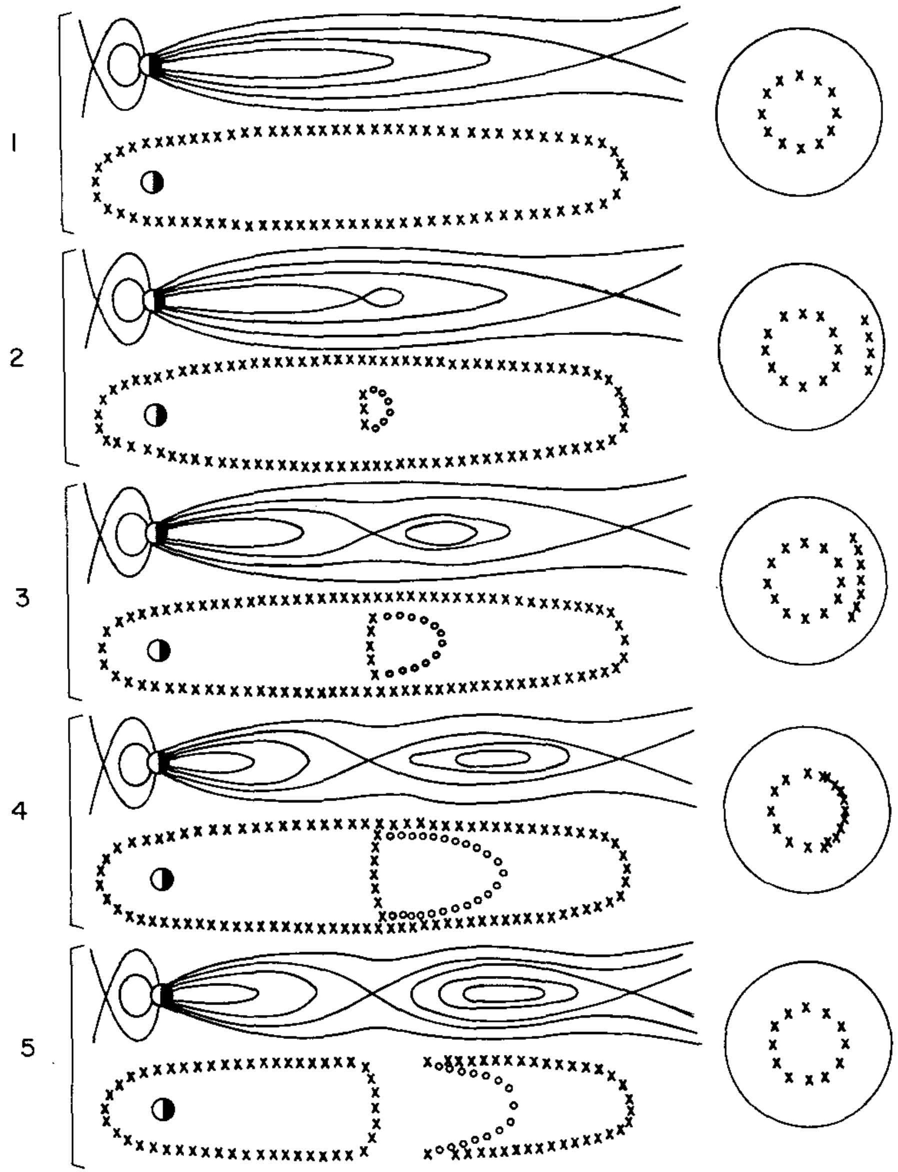


Figure 14: **Possible changes of the magnetic field topology: Earth.**

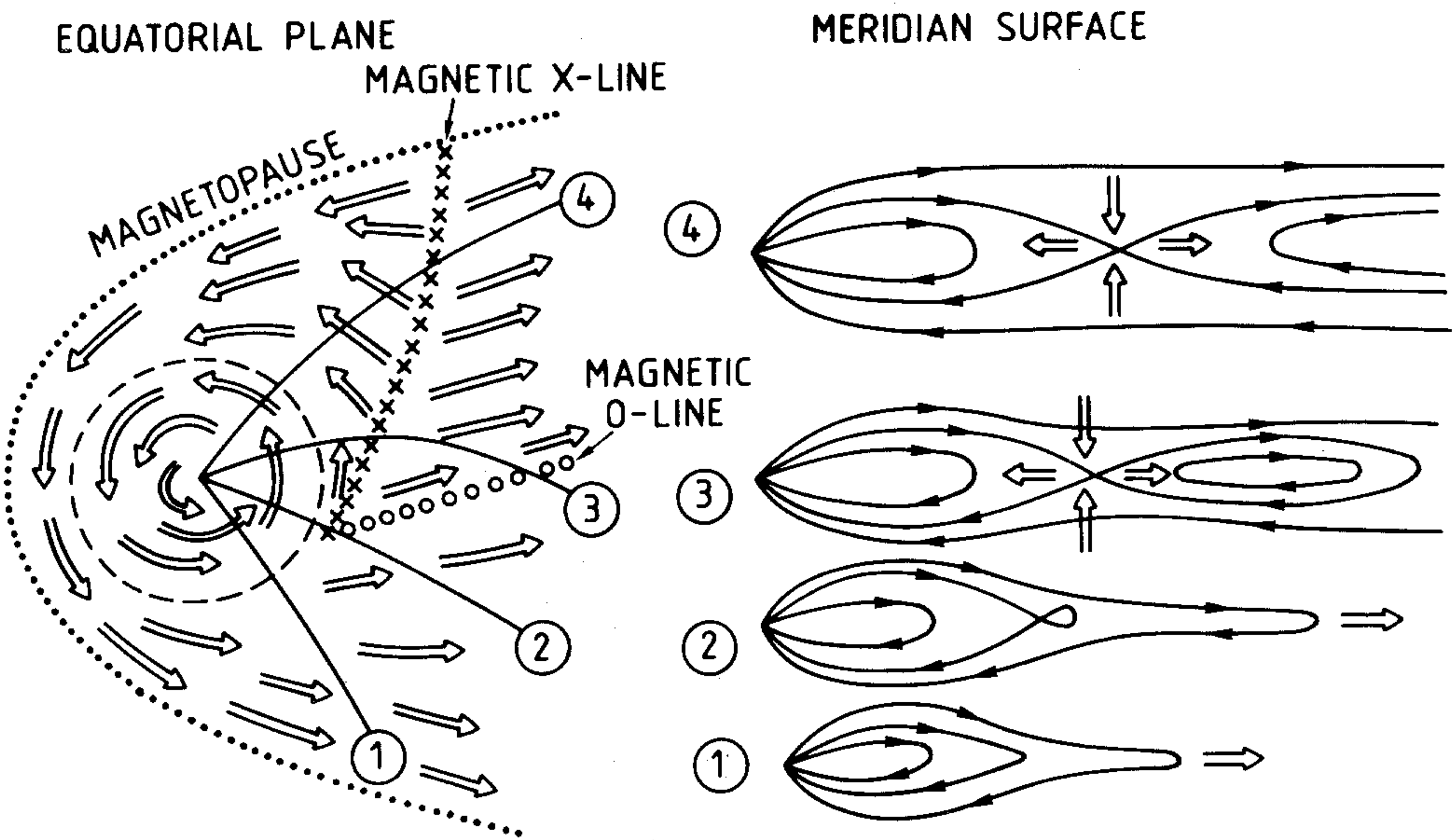


Figure 15: **Qualitative sketch of planetary wind flow and magnetic topology.**

***What constitutes a magnetospheric substorm?* I**

Phenomena at Earth:

1. • **Geomagnetic disturbances**
  (“polar elementary storm”, magnetic bay...)

  • **Auroral breakup and and follow-on developments**
  (surge, expansion...)

2. • **Rapid enhancement of energetic charged particle intensities**
  (“injection” events, beams...)

3. • **Enhancement of magnetotail magnetic field, followed by reduction**

  • **Strong bulk flow of plasma in the magnetotail, predominantly away from Earth at larger distances**

(...can be expanded into unending detail...)

***What constitutes a magnetospheric substorm?* II**

Processes at Earth:

- **$\boxed{1}$ enhanced energy input and dissipation**
- **$\boxed{2}$ change of magnetic field configuration**
  - **from highly stretched (increased flux in magnetotail, reduced flux in nightside equatorial region)**
  - **to more nearly dipolar (increased flux on the nightside)**
  - **accompanied (most probably) by changes of magnetic topology**
- **occurring on dynamical time scales (comparable to or shorter than wave travel times)**

Main points of controversy:

- **reason for $\boxed{2}$**
- **temporal and causal relationships between $\boxed{1}$ and $\boxed{2}$**

(...can be expanded into unending detail...)

Substorms in planetary magnetospheres?

- **reports of substorms or substorm-like events in magnetospheres of other planets are based primarily on observations of the magnetic field that indicate a change from tail-like to more dipolar configuration**
- **interpretation of observed enhancements of the intensity of energetic charged particles is ambiguous — in particular, "injection" events interpreted as indicative sometimes of substorms, sometimes of interchange motions**
- **qualitative similarity to observations at Earth is often taken as conclusive indication of an event analogous to the terrestrial substorm (without asking for confirming evidence)**
- **description of changes of magnetic field topology adapted from the terrestrial model, replacing the solar wind stress on open field lines by stress from (rotationally driven) outflow of plasma**

An underlying universal process?

- **Step 1: mechanical stresses deform the magnetic field into a configuration of increased energy.**
- **Step 2: the magnetic configuration becomes unsustainable and changes quickly, releasing the energy.**
- **(Both steps are in general associated with magnetic topological changes.)**
- **In most cases, the mechanical stress is related to plasma flow, which transports magnetic flux and, with field lines attached to a massive body, increases the magnetic energy.**
- **Why the magnetic configuration becomes unsustainable and what causes the quick change remain highly disputed questions; many possibilities can be imagined, and there may not be a universal answer.**
- **A potentially universal aspect is magnetic flux return: inability to return the flux smoothly (albeit for many possible reasons) seems to play a role (for Earth at least).**

- **The solar flare is the prototype of an explosive energy release, interpreted as originating from stored magnetic energy and thereby providing the initial theoretical framework for understanding the substorm.**
- **Solar events (flares and coronal mass ejections) and magnetospheric substorms may differ considerably, however, in the specifics of the magnetic field configuration.**
- **Events in which magnetic field, plasma, and energetic charged particle intensities change similarly to what is observed at Earth during substorms occur in the magnetospheres of Mercury, Jupiter, and Saturn. That these are close analogs of the terrestrial substorm, differing only in scale (and for Jupiter and Saturn also in the dominant role of rotation instead of solar wind flow) is a plausible (although for the most part not yet confirmed) hypothesis.**
- **A universal framework for all these events can be envisaged as a two-step process, first building up and then quickly releasing the energy in the magnetic field. The first step is reasonably well understood, in principle if not in detail. For the second step, there are so many possibilities and the range of views even in the single case of Earth so extreme, that the chances of identifying a universal process — if one exists — are at present remote.**