The Physics of Magnetospheric Variability

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ABSTRACT. Many widely used methods for describing and understanding the magnetosphere are based on balance conditions for quasi-static equilibrium (this is particularly true of the classical theory of magnetosphere/ionosphere coupling, which in addition presupposes the equilibrium to be stable); they may therefore be of limited applicability for dealing with time-variable phenomena as well as for determining cause-effect relations. The large-scale variability of the magnetosphere can be produced both by changing external (solar-wind) conditions and by non-equilibrium internal dynamics. Its developments are governed by the basic equations of physics, especially Maxwells equations combined with the unique constraints of large-scale plasma; the requirement of charge quasi-neutrality constrains the electric field to be determined by plasma dynamics (generalized Ohm's law) and the electric current to match the existing curl of the magnetic field. The structure and dynamics of the ionosphere/magnetosphere/solar-wind system can then be described in terms of three interrelated processes: (1) stress equilibrium and disequilibrium, (2) magnetic flux transport, (3) energy conversion and dissipation. This provides a framework for a unified formulation of settled as well as of controversial issues concerning, e.g., magnetospheric substorms and magnetic storms.

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.

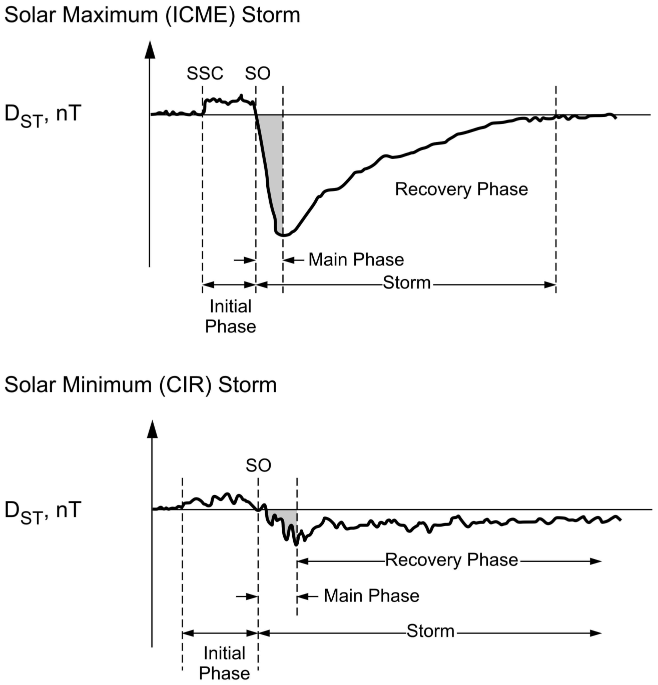


Figure 1: **Schematic time history of geomagnetic field variation for two typical magnetic storms. Time range: several days. Vertical variation range: $\sim 100 - 200$ nT. SSC: storm sudden commencement. SO: storm onset (adapted from Tsurutani *et al.*, 2006).**

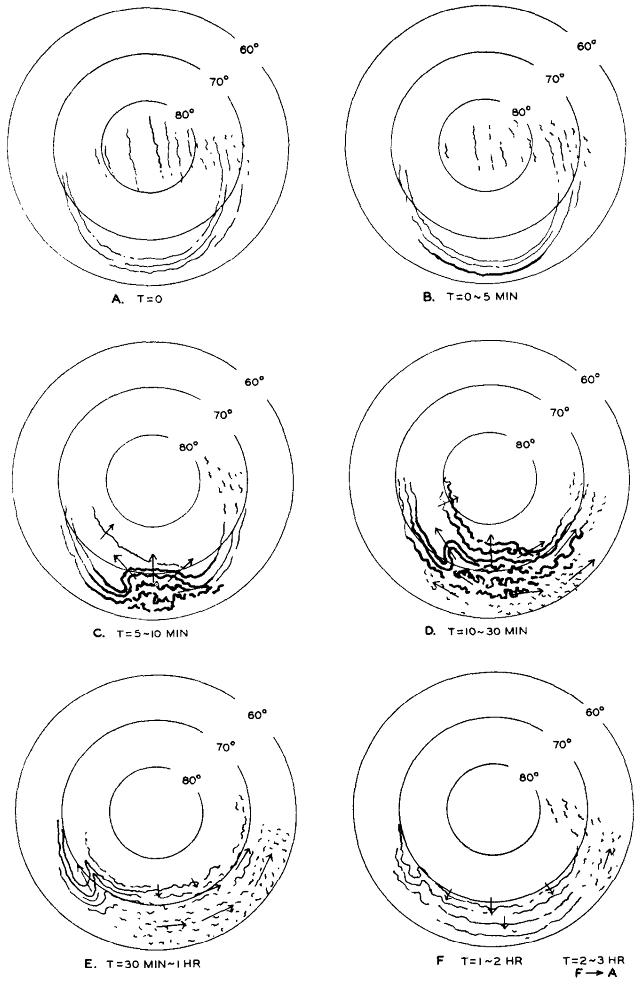
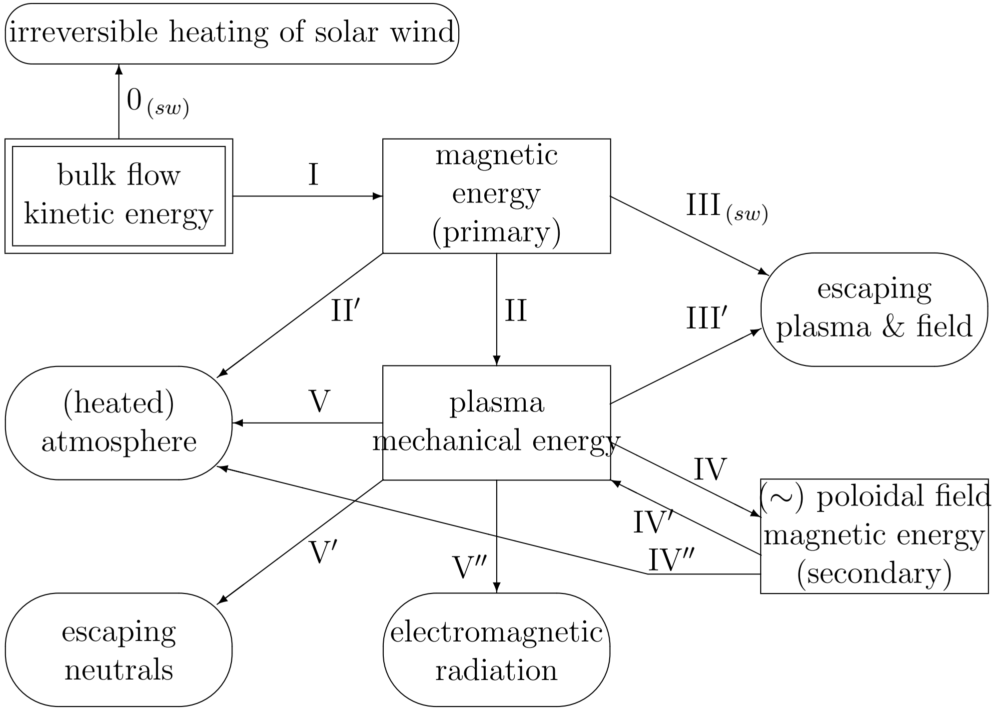


Figure 2: **Schematic diagram of the auroral substorm. View from above the north pole, circles of constant geomagnetic latitude, Sun toward the top (Akasofu, 1964)**



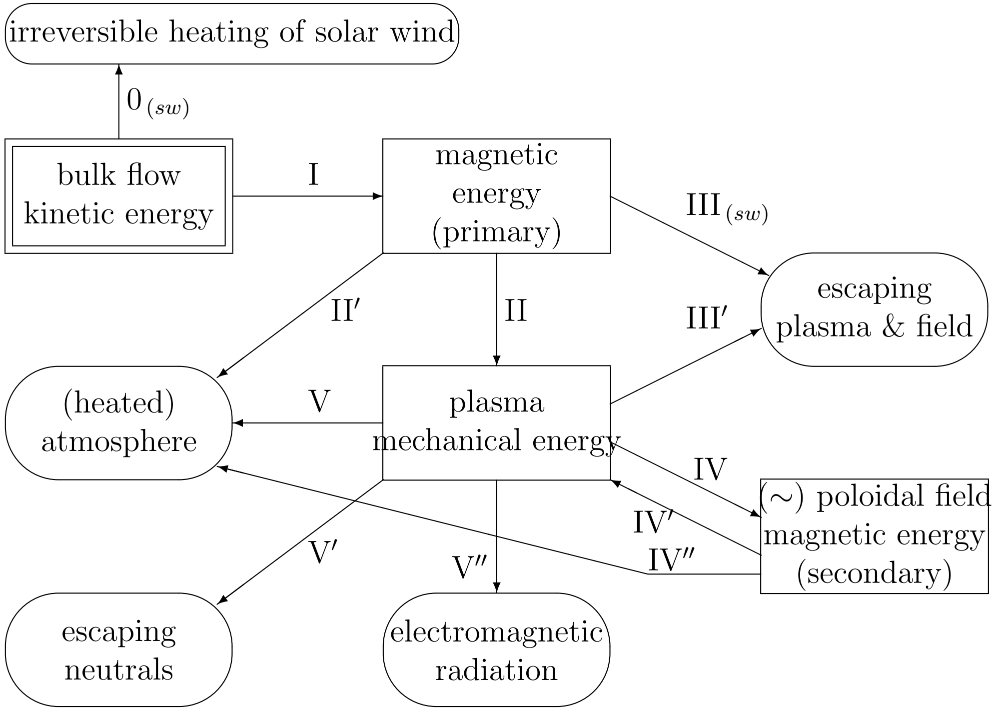
$\mathcal{P}_{total} \sim \frac{1}{2}\rho_{sw}(V_{sw})^3 A_T$ **total power supplied by the solar-wind energy source**

$\mathcal{P}_{0_{(sw)}} \sim (1-\delta)\,\frac{1}{2}\rho_{sw}(V_{sw})^3 A_T$ **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 $\mathcal{P}_{\mathrm{II}} + \mathcal{P}_{\mathrm{II}'} \sim O(\frac{1}{10})\mathcal{P}_{\mathrm{I}}$



irreversible heating of solar wind

$0_{(sw)}$

bulk flow kinetic energy

I

magnetic energy (primary)

$\mathrm{III}_{(sw)}$

escaping plasma & field

II'

II

III'

(heated) atmosphere

V

plasma mechanical energy

IV

($\sim$) poloidal field magnetic energy (secondary)

IV'

IV''

V'

V''

escaping neutrals

electromagnetic radiation

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** $\mathcal{P}_{\mathrm{II}'}$

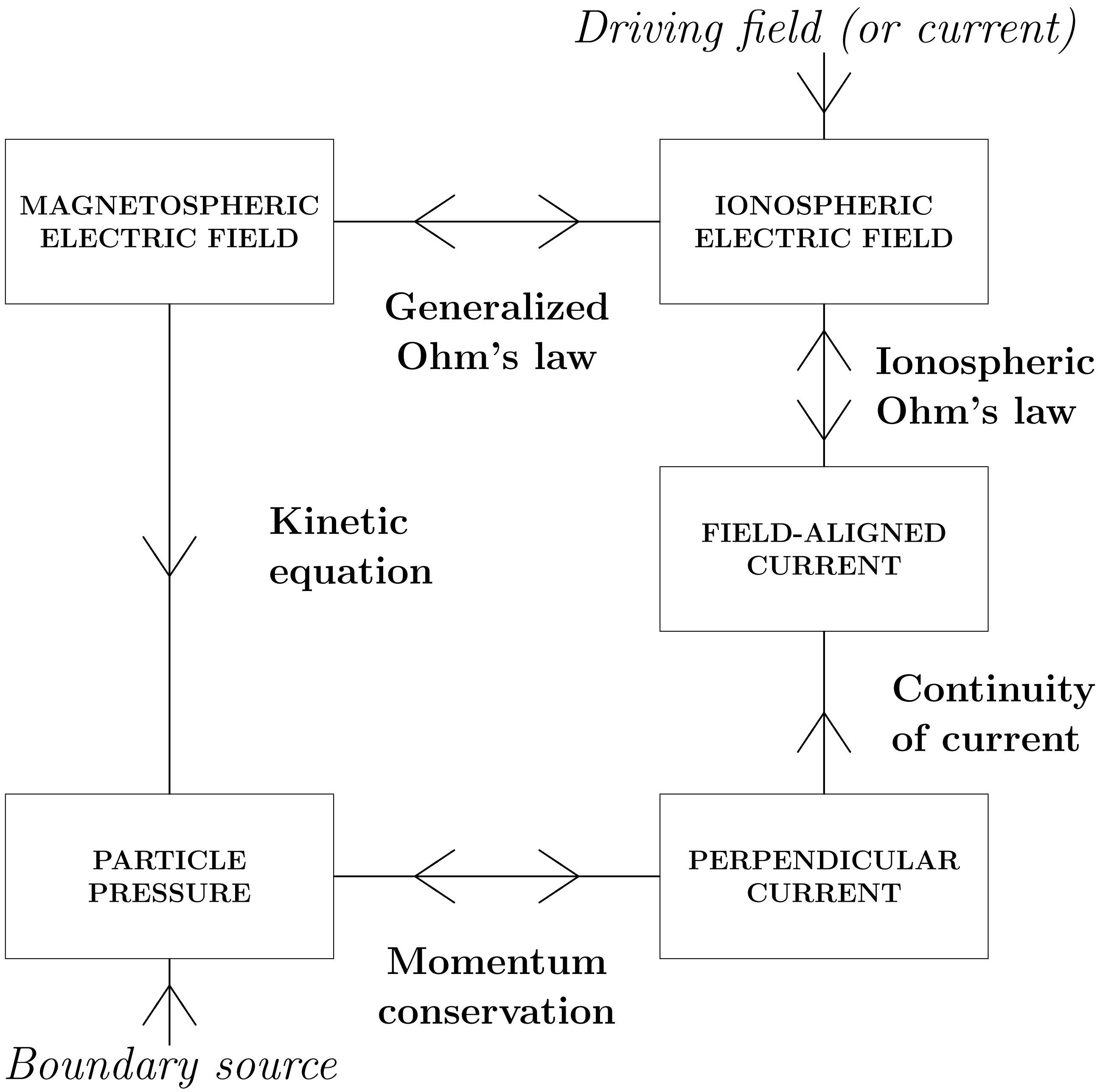
(also $\mathcal{P}_{\mathrm{III}_{(\mathrm{sw})}}$**,** $\mathcal{P}_{\mathrm{III}'}$**) enhanced**

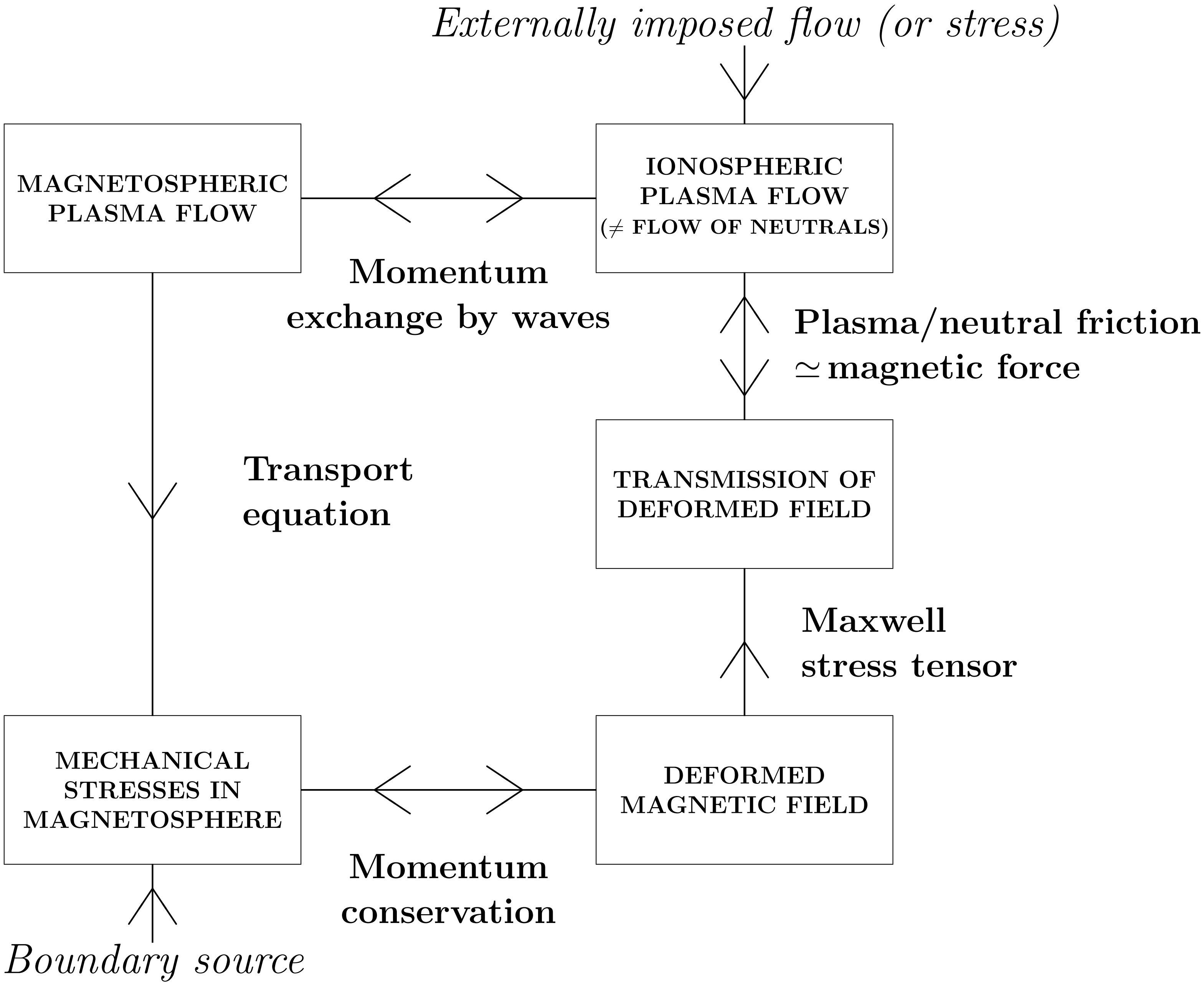
Magnetic storm:

stored

plasma mechanical energy

enhanced


Driving field (or current)
MAGNETOSPHERIC ELECTRIC FIELD
IONOSPHERIC ELECTRIC FIELD
Generalized Ohm's law
Ionospheric Ohm's law
FIELD-ALIGNED CURRENT
Kinetic equation
Continuity of current
PARTICLE PRESSURE
PERPENDICULAR CURRENT
Momentum conservation
Boundary source



Externally imposed flow (or stress)

MAGNETOSPHERIC PLASMA FLOW

IONOSPHERIC PLASMA FLOW (≠ FLOW OF NEUTRALS)

Momentum exchange by waves

Plasma/neutral friction
$\simeq$ magnetic force

Transport equation

TRANSMISSION OF DEFORMED FIELD

Maxwell stress tensor

MECHANICAL STRESSES IN MAGNETOSPHERE

DEFORMED MAGNETIC FIELD

Momentum conservation

Boundary source

Electrodynamics of large-scale ($\tau >> {\omega_p}^{-1}$, $\mathcal{L} >> \lambda_e$) plasmas

1. **The electric field is determined directly by the generalized Ohm's law (neglecting the $\partial \mathbf{J}/\partial t$ term): a combination of flows and kinetic tensors of the various particle species (in the ionosphere and the magnetosphere, predominantly $-\mathbf{V}_e \times \mathbf{B}/c$).**
2. **The time derivative of the magnetic field is determined by the curl of the electric field, hence equivalently by the curl of the generalized Ohm's law.**
3. **The current density is determined by the curl of the magnetic field.**
4. **Particle motions are determined by forces acting on them, in the usual way (the constraint implied by [3] is enforced by the electric field of [1]). The time derivative of the plasma bulk flow is determined by the difference between magnetic and mechanical stresses.**
5. **In stable quasi-equilibrium, the magnetic field becomes deformed so as to balance the mechanical stresses. In particular, the ionospheric Pedersen and Hall currents result from the deformation that balances the friction of differential plasma/neutral bulk flow.**

If $c\nabla \times \mathbf{B} - 4\pi\mathbf{J} = \partial\mathbf{E}/\partial t \neq 0$: resulting E produces

change of B **and** **change of J**

{via $\partial\mathbf{B}/\partial t = -c\nabla \times \mathbf{E}$ }
on time scale $\tau_1 \sim \mathcal{L}/c$

{via $\partial\mathbf{J}/\partial t = ({\omega_p}^2/4\pi)(\mathbf{E} - \mathbf{E}^*)$}
on time scale $\tau_2 \sim {\omega_p}^{-1}$

$$\tau_1/\tau_2 = \mathcal{L}\omega_p/c = \mathcal{L}/\lambda_e \qquad \lambda_e \equiv c/\omega_p = 5\ \mathbf{km}\ (1\ \mathbf{cm}^{-3}/n_e)^{1/2}$$

- **J is determined by the motion of <u>all</u> the charged particles, and there is no** *a priori* **reason why it should equal** $(c/4\pi)\nabla \times \mathbf{B}$
- **the equality is established on time scale $\tau \simeq$ shorter of $[\mathcal{L}/c,\ {\omega_p}^{-1}]$**
- **in the ordinary EM lab environment ($\omega_p\tau \ll 1$, $\mathcal{L}\omega_p/c \ll 1$), this occurs primarily by changing B so $(c/4\pi)\nabla \times \mathbf{B}$ matches the existing J, on time scale of order $\sim \mathcal{L}/c$**
- **in a large-scale plasma ($\omega_p\tau \gg 1$, $\mathcal{L}\omega_p/c \gg 1$), this occurs primarily by changing J to match the existing $(c/4\pi)\nabla \times \mathbf{B}$, on time scale of order $\sim {\omega_p}^{-1}$**

Time scale for development of $\nabla \times \mathbf{B}$:

Initially, if $\mathbf{J}\times\mathbf{B}/c$ is out of balance with the plasma stresses by δF, plasma bulk flow begins to change:

$$\delta V \sim (\delta F/\rho)\, t$$

Changed V implies changed E; if change varies on spatial scale $\mathcal{L}$, $\nabla \times \mathbf{E}$ implies change of B:

$$\delta B \sim (B\delta V/\mathcal{L})\, t \sim (\delta F/\rho)\, t^2\, (B/\mathcal{L})$$

Resulting $(\nabla \times \mathbf{B}) \times \mathbf{B}/4\pi$ comes into stress balance after time t given by

$$\delta F \sim B\delta B/4\pi\mathcal{L} \sim (\delta F/\rho)\, t^2 \left(B^2/4\pi\mathcal{L}^2\right)$$

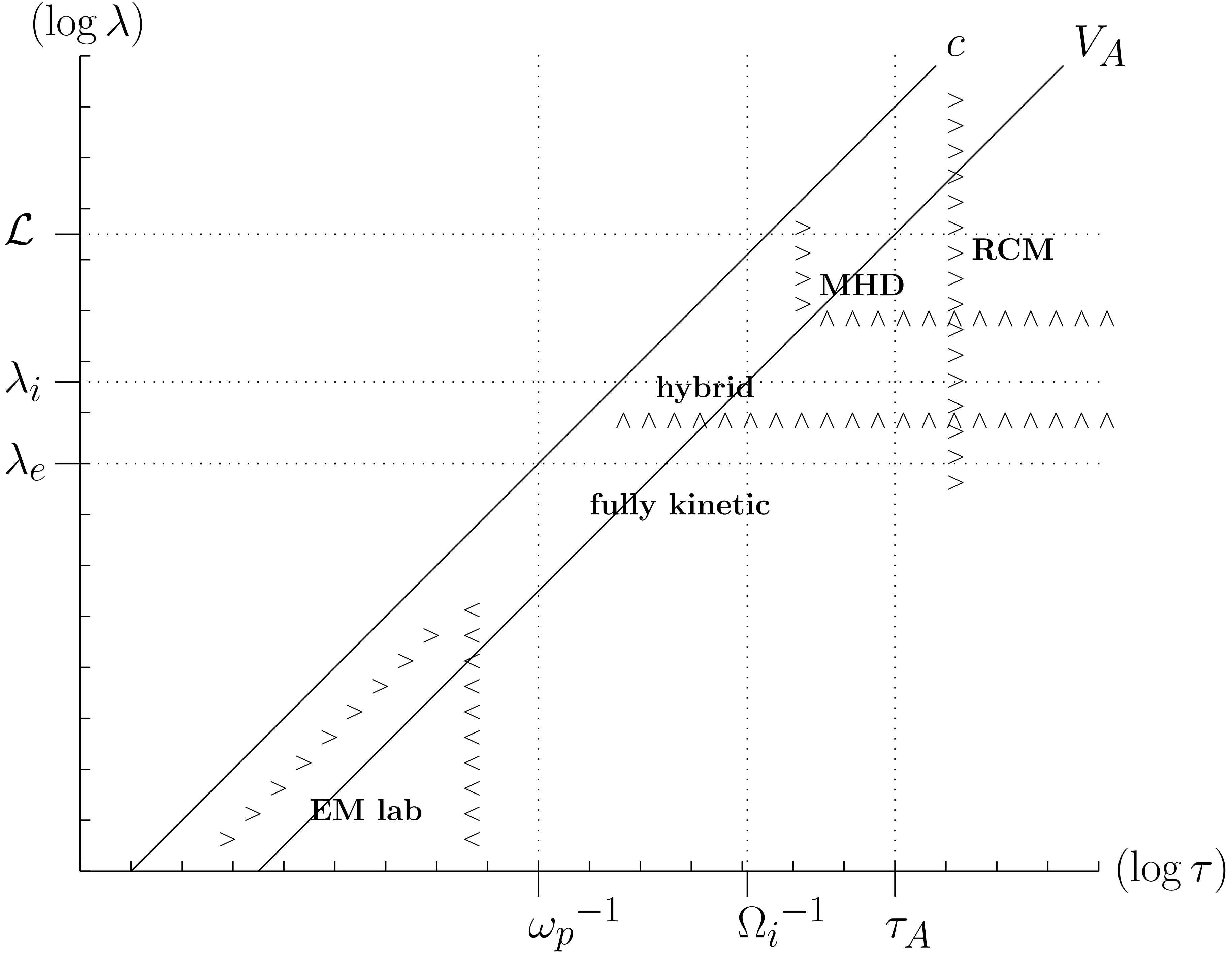
or

$$t^2 \sim \left(4\pi\rho/B^2\right) \mathcal{L}^2 = \mathcal{L}^2/{V_A}^2$$

Conclusions

- **Shaping of the magnetic field through stresses by and on the plasma determines the configuration of the solar-wind/magnetosphere/ionosphere system.**
- **Stresses are changed primarily by plasma flow, through the associated transport of magnetic flux and evolution of plasma pressure.**
- **Variable advection of magnetic flux in the solar wind seems to be the primary factor for producing large-scale variability of the Earth's magnetosphere.**
- **Magnetic storms: enhanced quasi-equilibrium storage of energy. Magnetospheric substorms: enhanced energy dissipation, connected with transitions from equilibrium to non-equilibrium. The relation between the two is not clear.**

end of presentation


$(\log\lambda)$
c
V_A
$\mathcal{L}$
λ_i
λ_e
RCM
MHD
hybrid
fully kinetic
EM lab
$(\log\tau)$
$\omega_p{}^{-1}$
$\Omega_i{}^{-1}$
τ_A

References

- Vasyliūnas, V. M.: Electric field and plasma flow: What drives what?, *Geophys. Res. Lett.*, 28, 2177–2180, 2001.
- Vasyliūnas, V. M.: Time evolution of electric fields and currents and the generalized Ohm's law, *Ann. Geophys.*, 23, 1347–1354, 2005.
- Vasyliūnas, V. M.: Relation between magnetic fields and electric currents in plasmas, *Ann. Geophys.*, 23, 2589–2597, 2005.
- Song, P., Gombosi, T. I., and Ridley, A. J.: Three-fluid Ohm's law, *J. Geophys. Res.*, 106, 8149–8156, 2001.
- Vasyliūnas, V. M., and Song, P.: Meaning of ionospheric Joule heating, *J. Geophys. Res.*, 110, A02301, doi:10.1029/2004JA010615, 2005.
- Buneman, O.: Internal dynamics of a plasma propelled across a magnetic field, *IEEE Trans. Plasma Sci.*, 20, 672–677, 1992.
- Parker, E. N.: *Conversations on Electric and Magnetic Fields in the Cosmos*, Princeton University Press, Princeton, New Jersey, 2007.