Magnetospheric Physics

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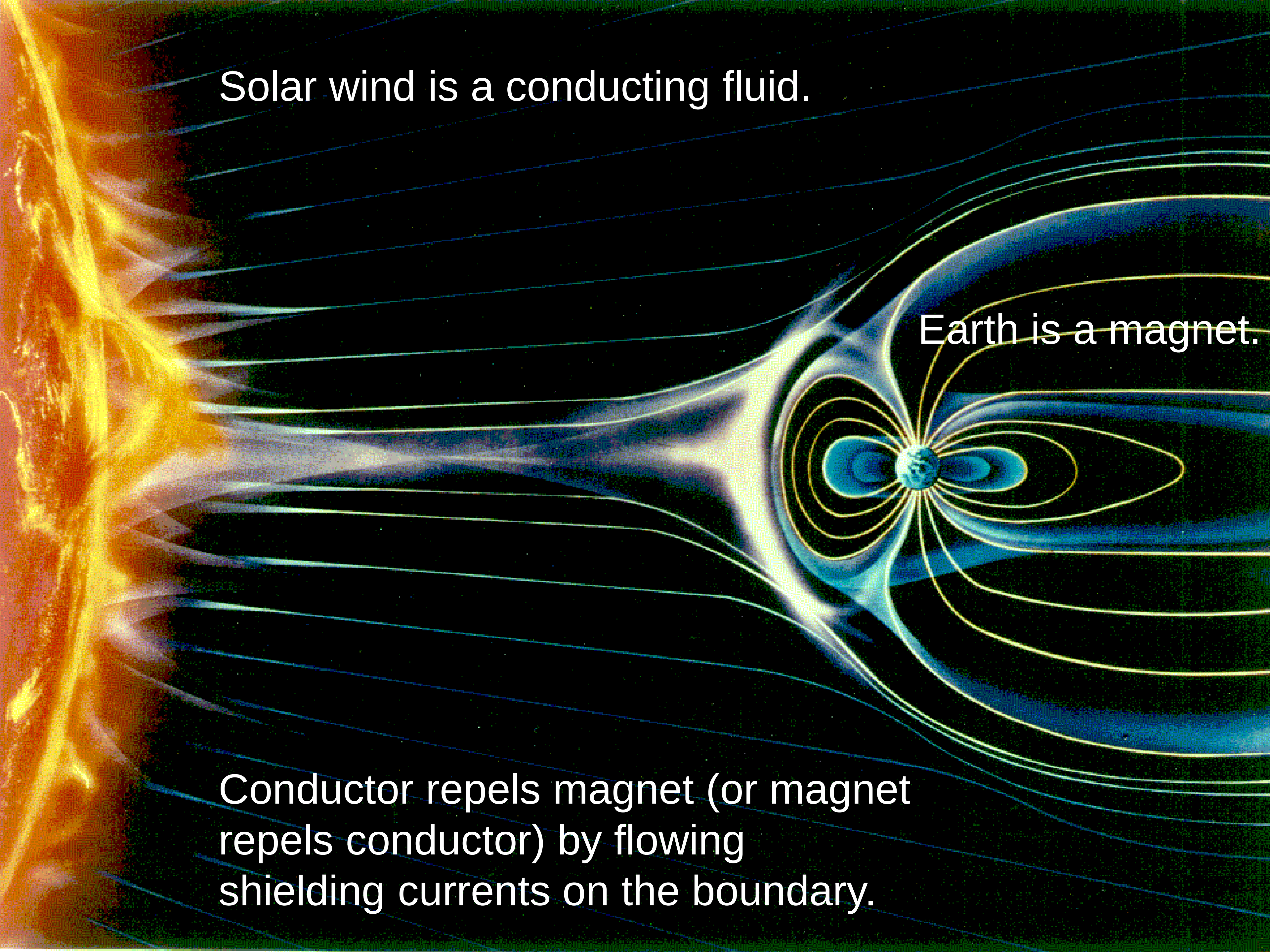
Outline

Fundamentals of

1. large-scale structure and magnetic field topology of the magnetosphere
2. convection in the magnetosphere-ionosphere system


Solar wind is a conducting fluid.
Earth is a magnet.
Conductor repels magnet (or magnet repels conductor) by flowing shielding currents on the boundary.

Vacuum model (Chapman & Ferraro)

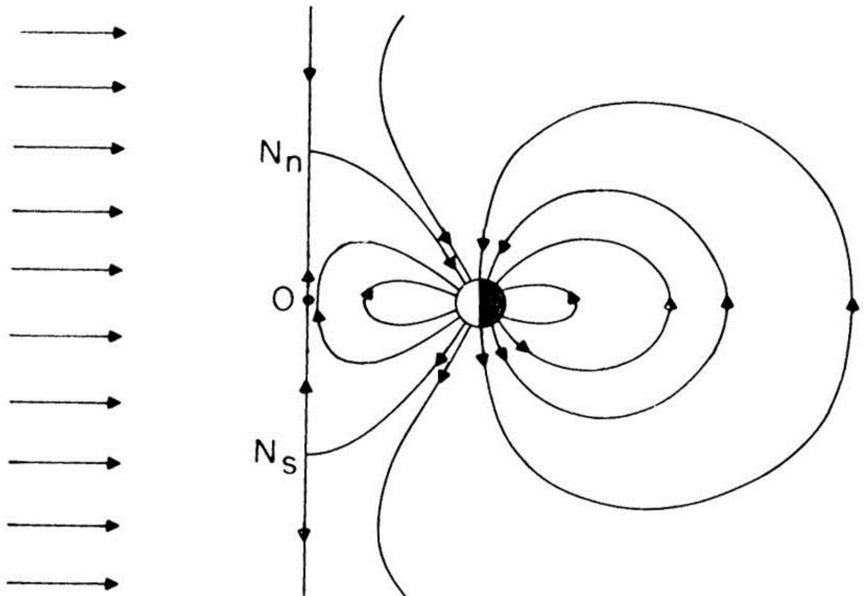
conductor B_n=0   vacuum

solar wind

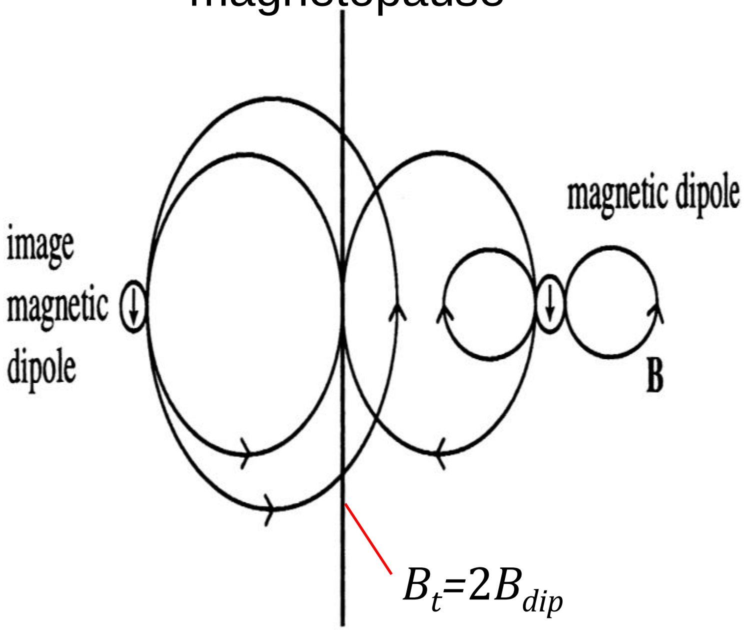
$\mathbf{u}$

ρ

p



magnetopause



Pressure balance

$$p_N = \frac{B_t^2}{2\mu_0}$$

p_N: Newtonian pressure

$$p_N = \mathbf{n}\cdot(\rho\mathbf{u}\mathbf{u} + p\mathbf{I})\cdot\mathbf{n}$$

$\mathbf{n}$: boundary normal

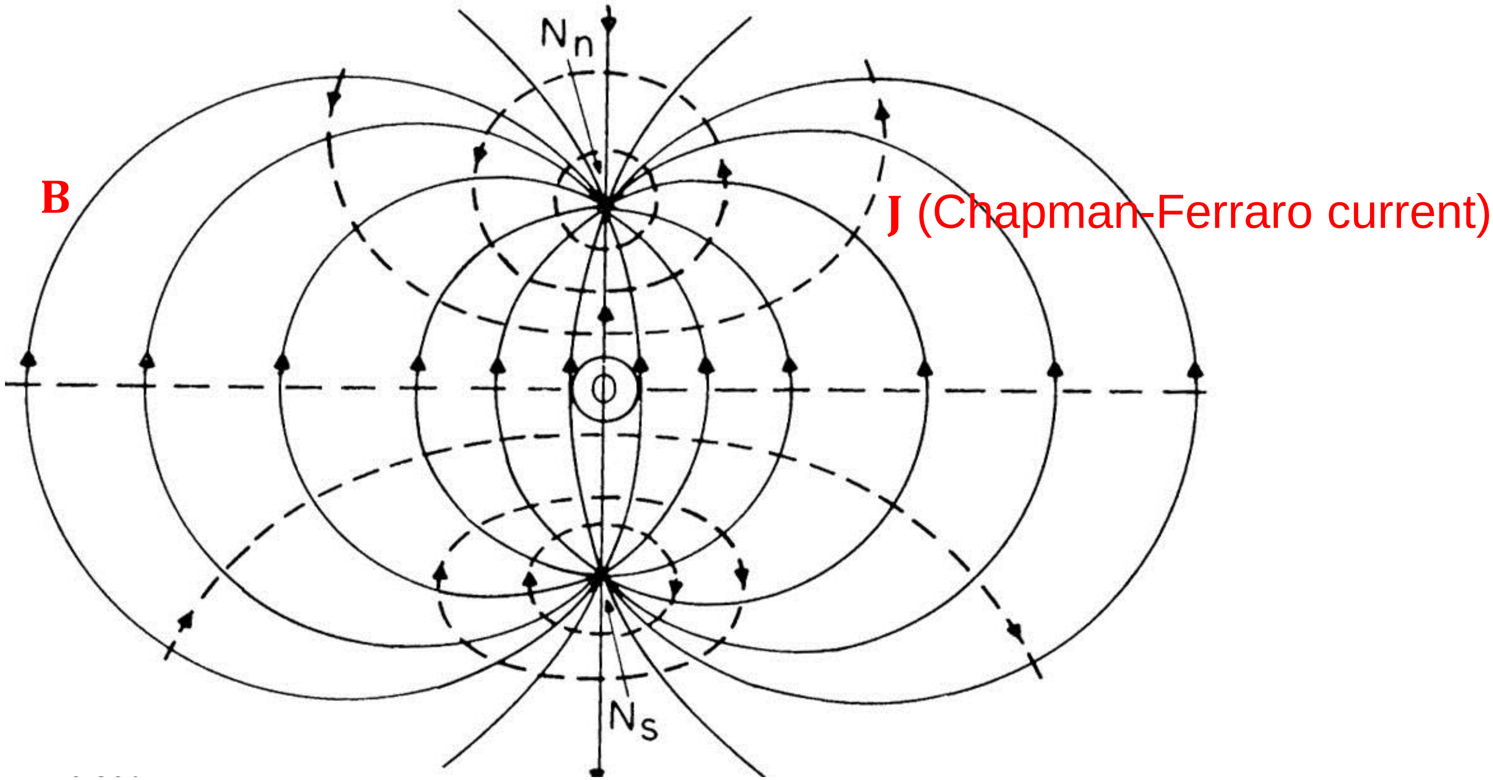
In the case of cold plasma beam that elastically reflects off the boundary

$$p_N = 2\rho u^2$$

In general

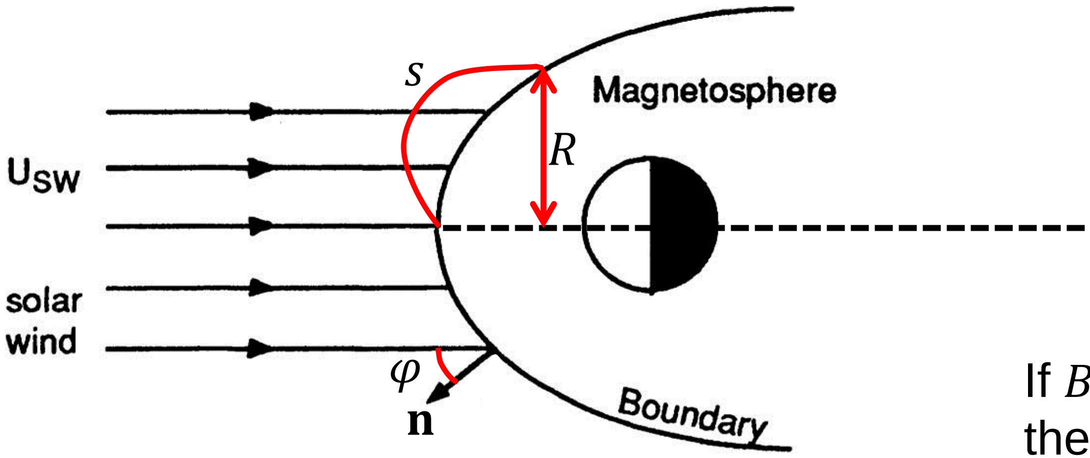
$$p_N = K\rho u^2 \qquad (0 < K \leq 2)$$

Chapman-Ferraro current



The role of Chapman-Ferraro current is to confine the Earth's magnetic field in a volume and at the same time to prevent the solar wind from penetrating into that volume.

Realistic shape

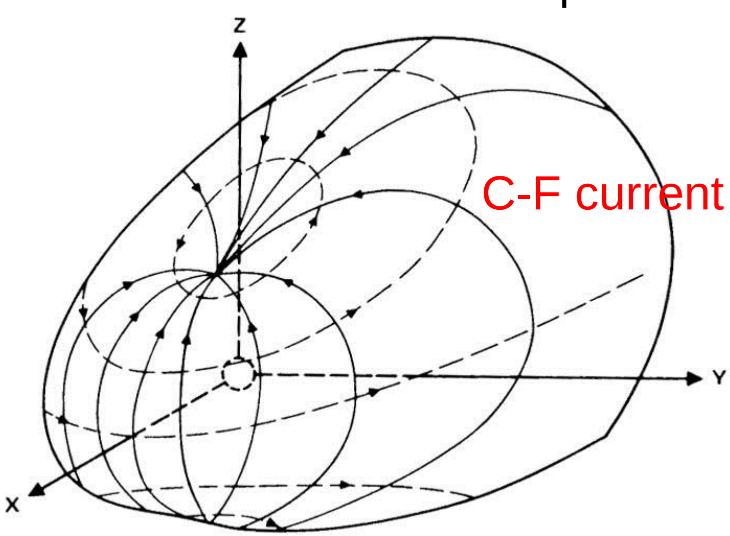


s: distance from the subsolar point along the boundary

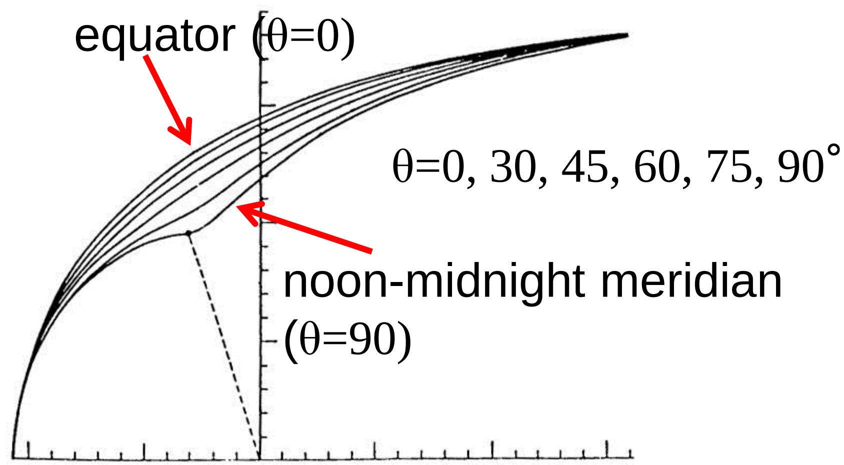
$$\begin{cases} P_N = K\rho u^2 \cos^2\varphi \\ p_N = \dfrac{B_t^2}{2\mu_0} \\ \dfrac{dR}{ds} = \cos\varphi \end{cases}$$

If B_t is given as a function of position, these equations determine the shape of the boundary.

Examples of solutions



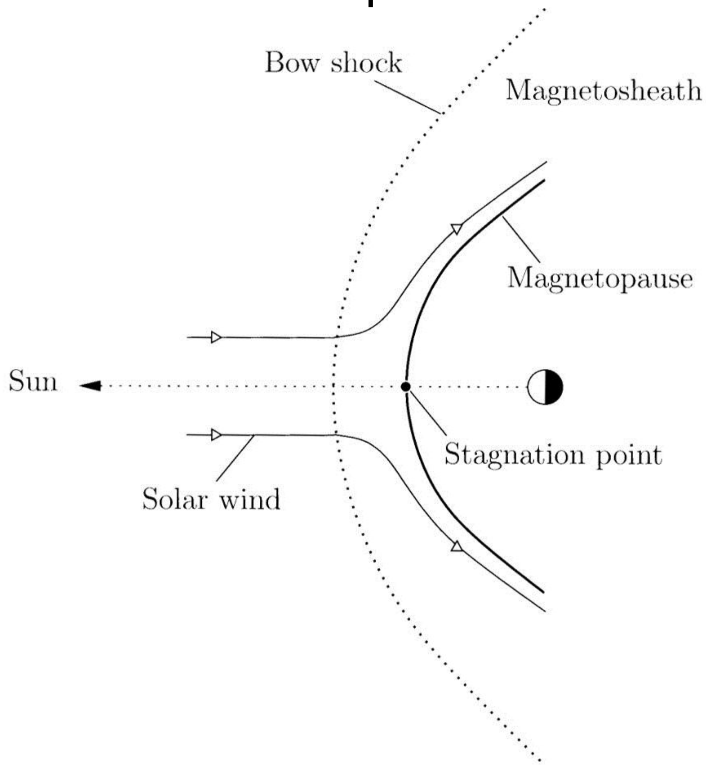
Midgley & Davis (1963)

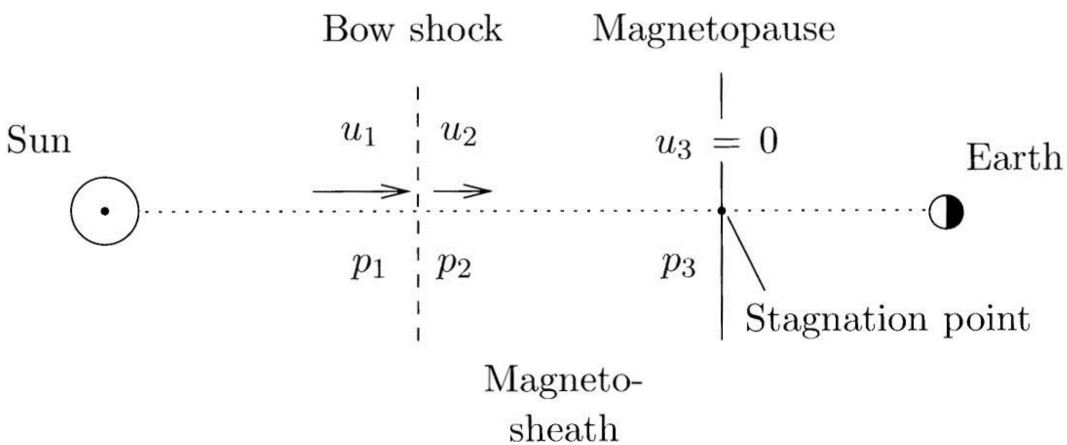


Mead & Beard (1964)

$M_A \geq 10$ Magnetic field can be neglected.

$M \geq 10$ Thermal pressure can be neglected.





bow shock → magnetosheath

$$\frac{u_2}{u_1} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{(\gamma + 1)M_1^2} \approx \frac{\gamma - 1}{\gamma + 1} = \frac{1}{4}$$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{\gamma + 1}{\gamma - 1 + \frac{2}{M_1^2}} \approx \frac{\gamma + 1}{\gamma - 1} = 4$$

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1} \approx \frac{2\gamma M_1^2}{\gamma + 1} = \frac{2}{\gamma + 1}\frac{\rho_1 u_1^2}{p_1}$$

$$= \frac{2}{\gamma + 1}\frac{\rho_1 u_1^2}{p_1} = \frac{3}{4}\frac{\rho_1 u_1^2}{p_1} \rightarrow p_2 = \frac{3}{4}\rho_1 u_1^2$$

$$M_2^2 = \frac{2 + (\gamma - 1)M_1^2}{2\gamma M_1^2 - (\gamma - 1)} \approx \frac{\gamma - 1}{2\gamma} = \frac{1}{5}$$

→ subsolar magnetopause

Bernoulli theorem

$$\frac{u_2^2}{2} + \frac{\gamma}{\gamma - 1}\frac{p_2}{\rho_2} = 0 + \frac{\gamma}{\gamma - 1}\frac{p_3}{\rho_3}$$

adiabatic $p\rho^{\gamma} = const.$

$$\frac{p_3}{p_2} = \left(1 + \frac{\gamma - 1}{2}M_2^2\right)^{\frac{\gamma}{\gamma - 1}} = \left(\frac{16}{15}\right)^{\frac{5}{2}}$$

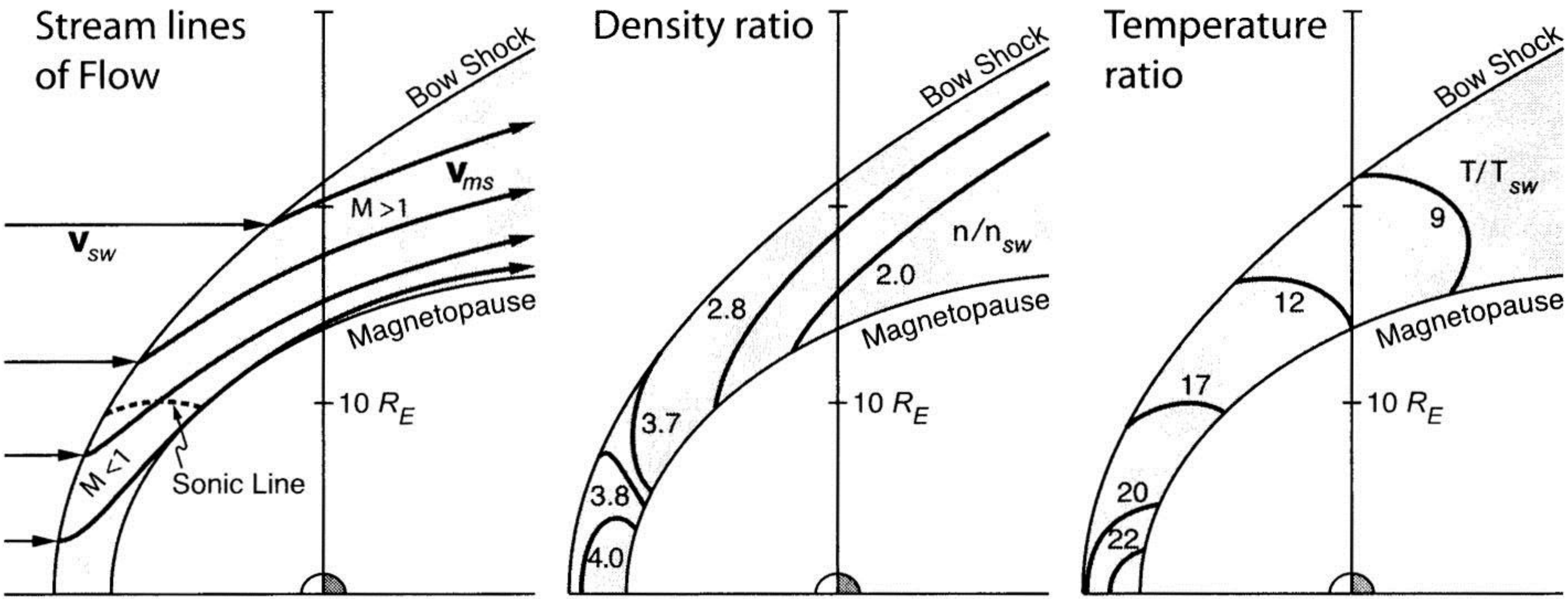
$$K = \frac{3}{4}\left(\frac{16}{15}\right)^{\frac{5}{2}} = 0.881$$

Advanced vacuum model

When φ becomes large, the thermal pressure of the solar wind cannot be negligible.

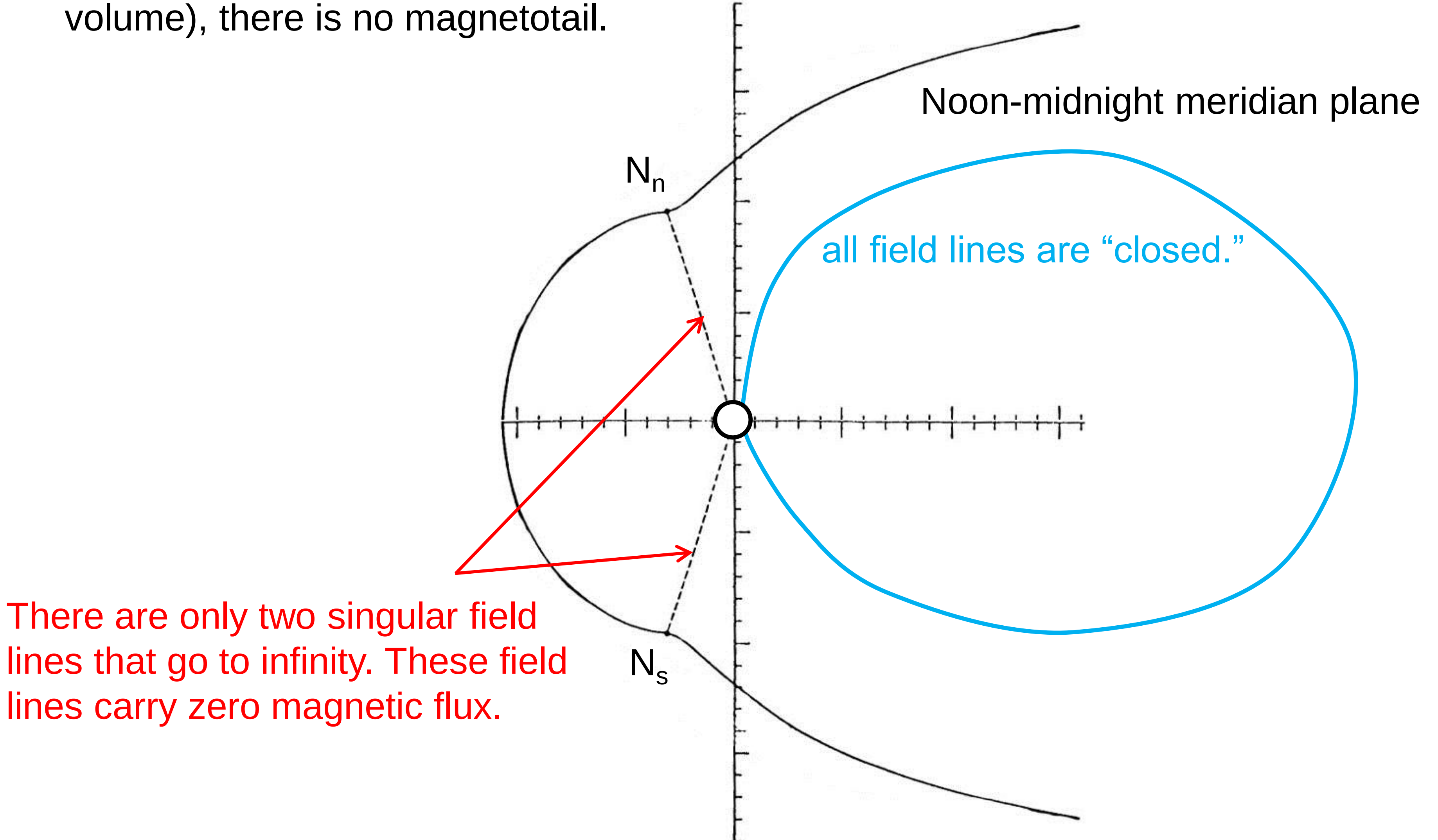
$$P_N = K\rho u^2 \cos^2\varphi + p_{SW}$$

Numerical calculation for M=8 (Spreiter et al., 1966)

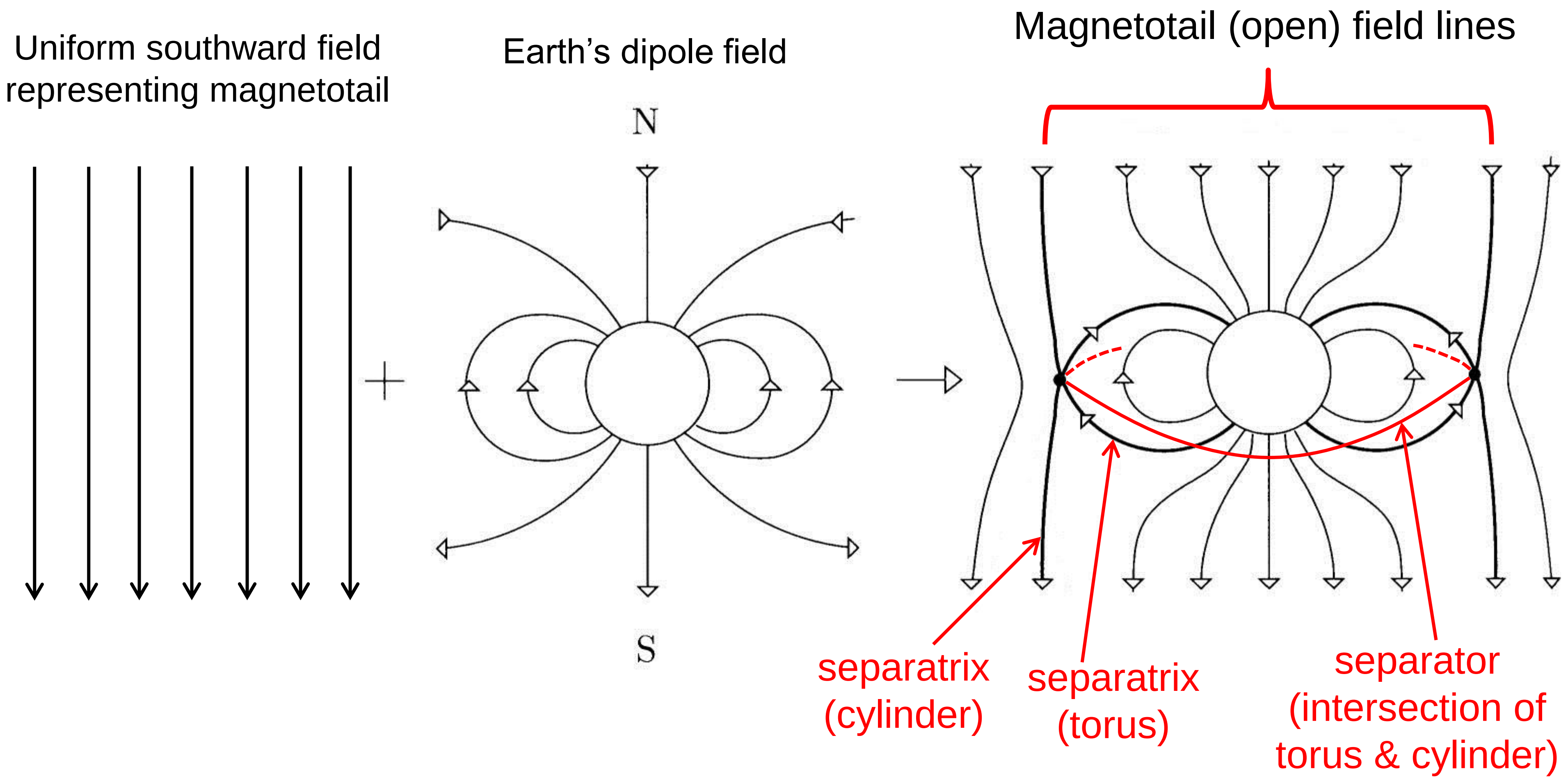


Magnetotail

- Magnetotail may be defined as the region that conveys a finite magnetic flux from the Earth to infinity. Ionospheric projection of the magnetotail is called the polar cap.
- In the Chapman-Ferraro models (a vacuum magnetosphere confined to a volume), there is no magnetotail.

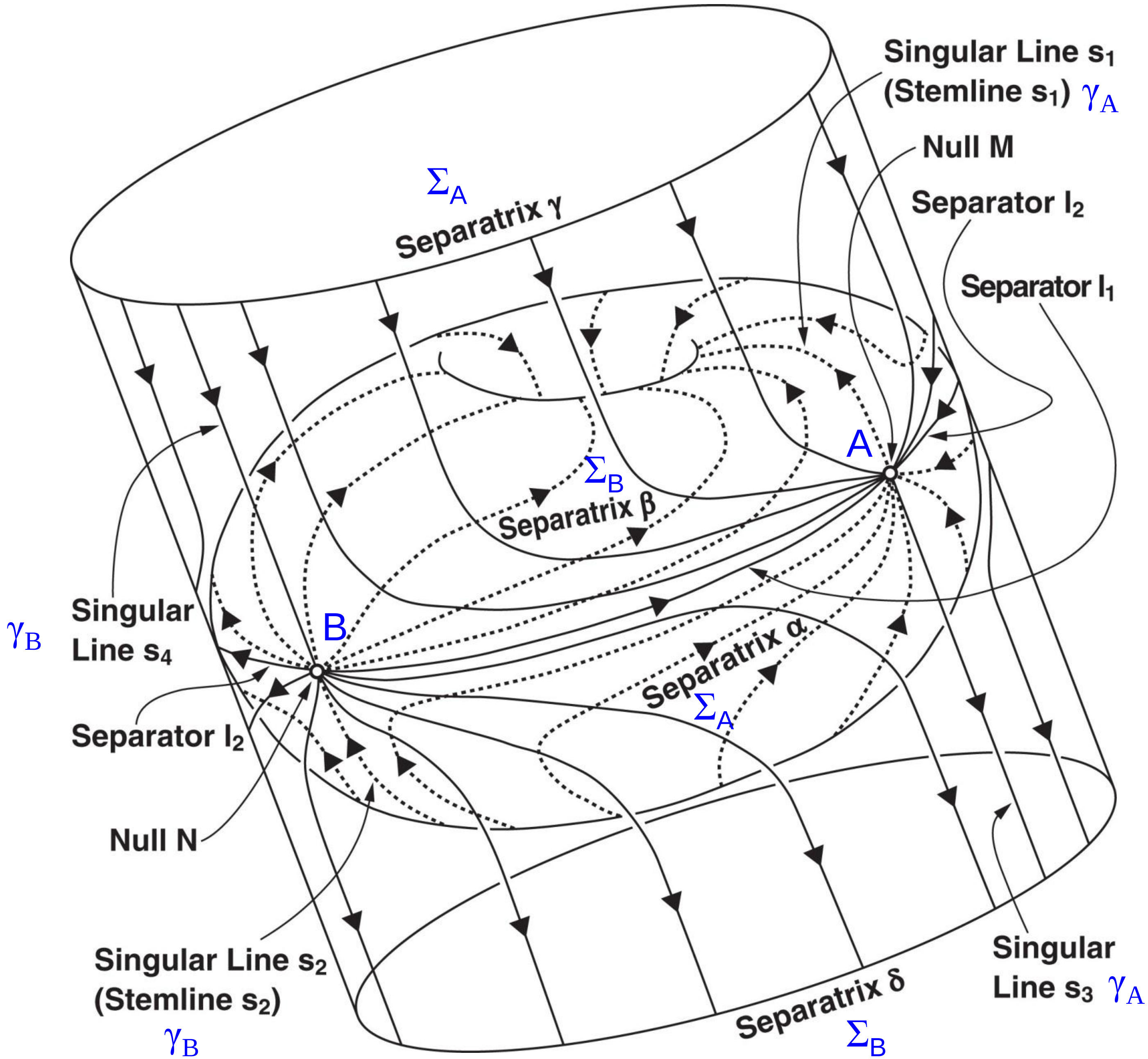


Adding a magnetotail

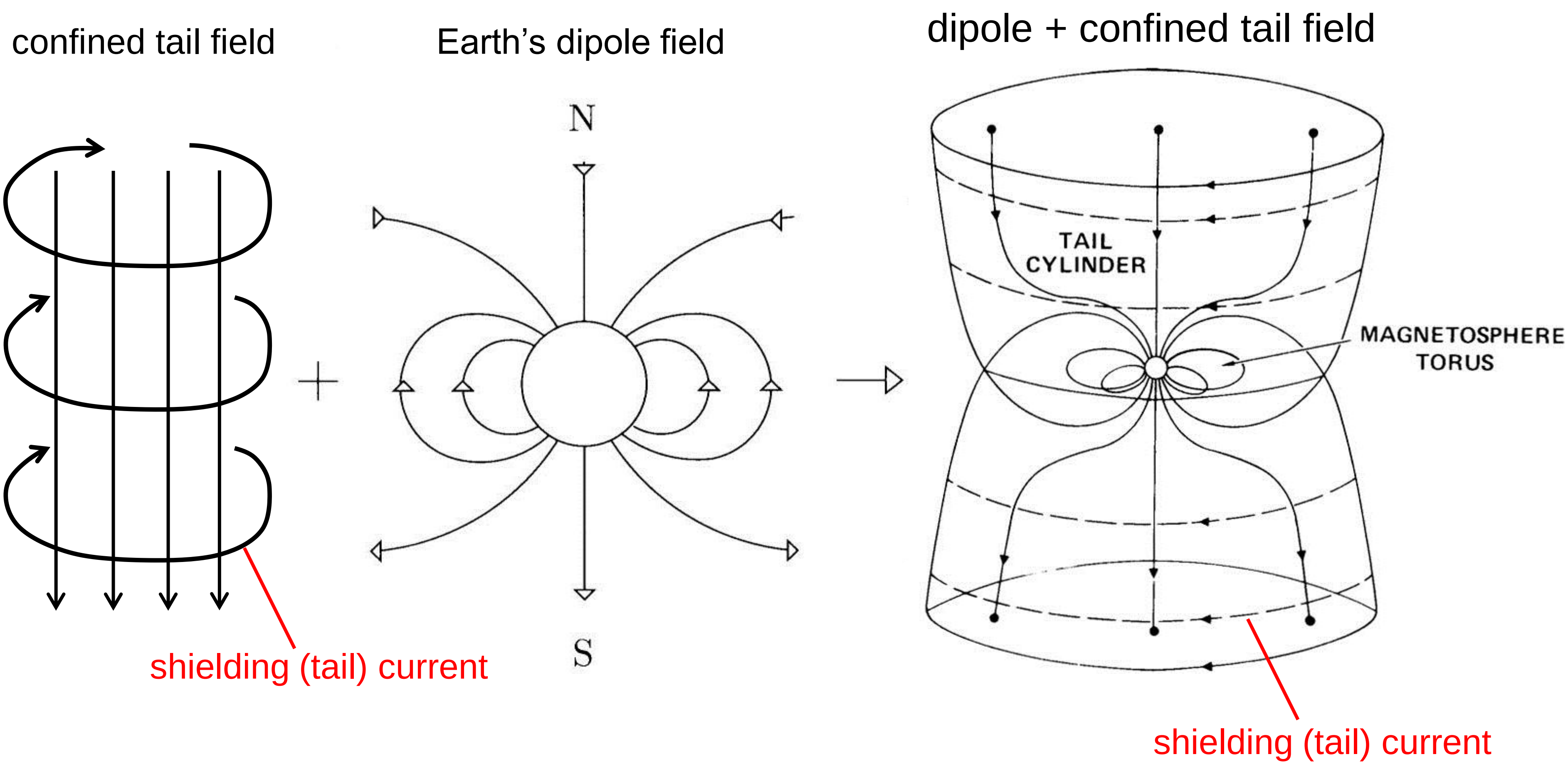


- Separatrix: magnetic surface that demarcates topologically different regions. It consists of field lines.
- Separator: intersection of separatrices. It is also a field line connecting two magnetic nulls.

Superposition of dipole and nonparallel uniform fields

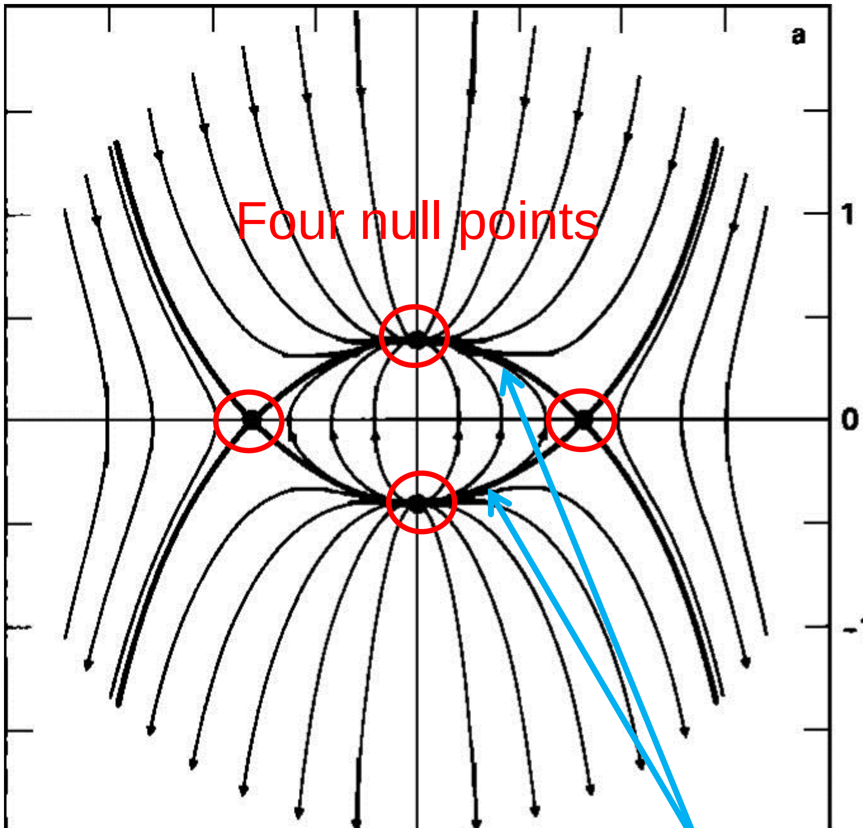


Confined magnetotail (non-vacuum model)



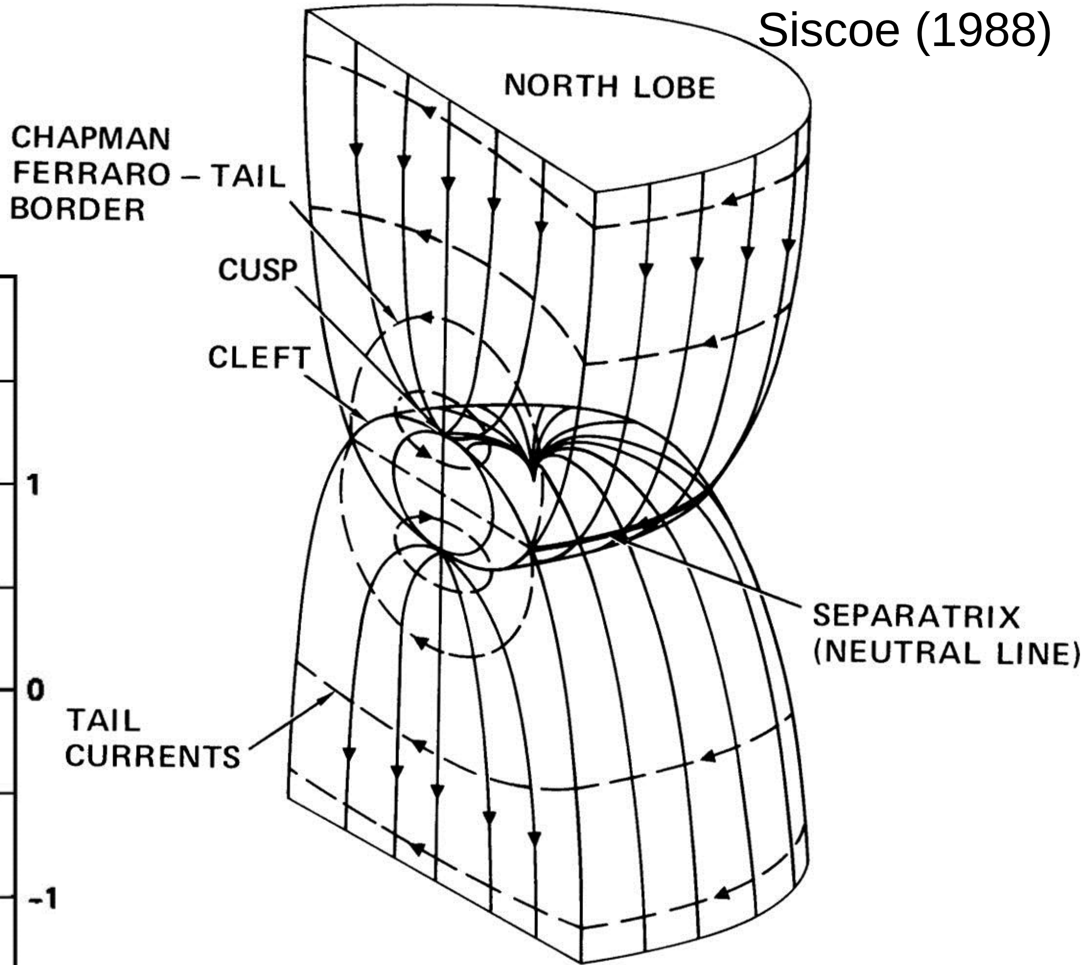
Confined tail flattened against an image plane

dipole + uniform field + image
Crooker (1985)



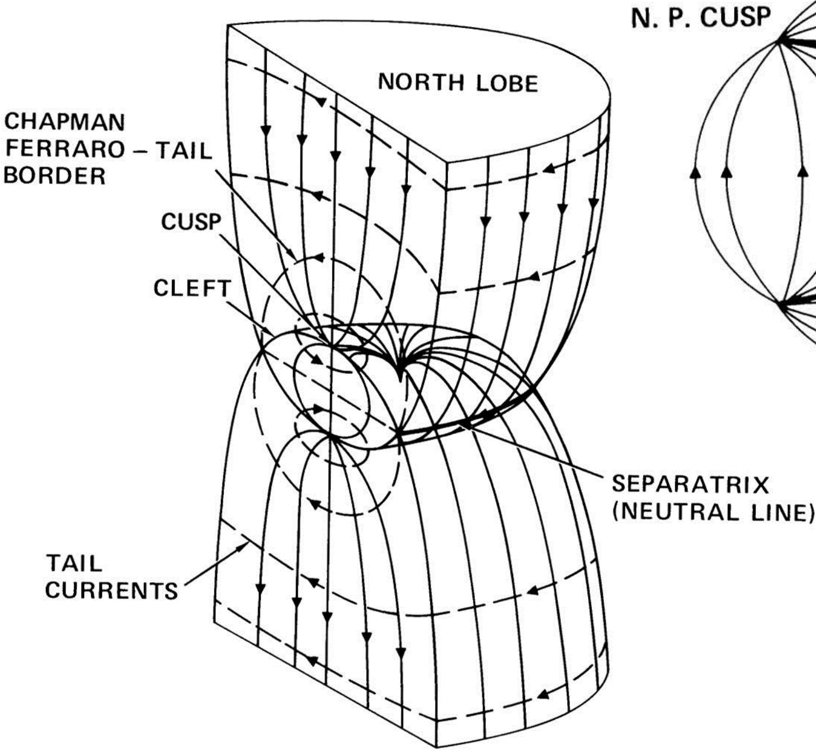
The separator splits into two.

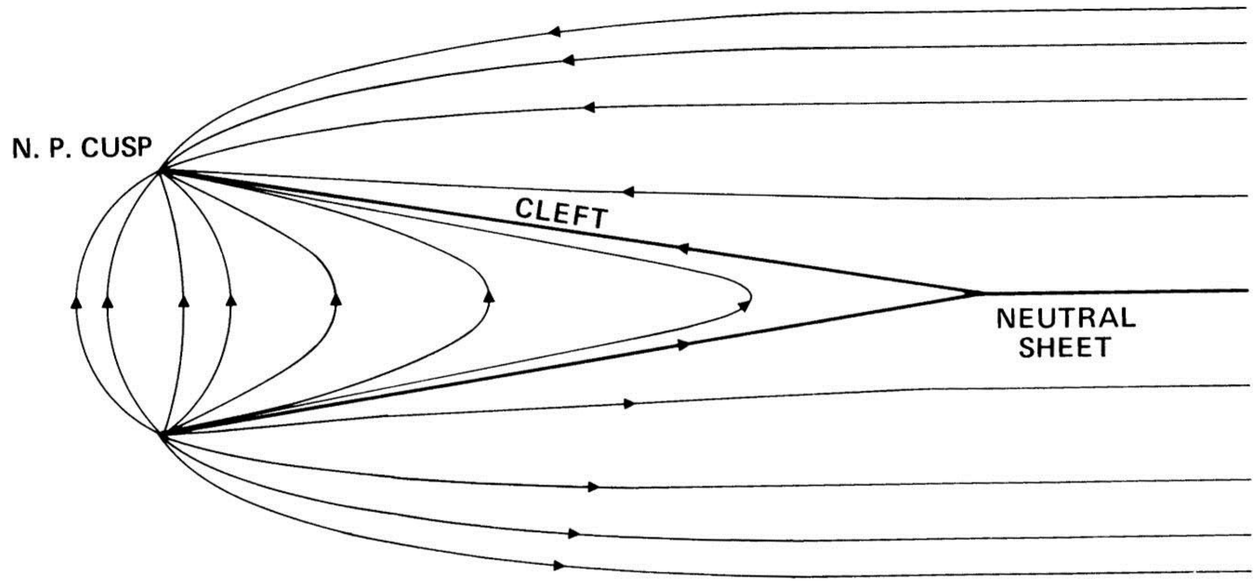
dipole + confined tail + image
Siscoe (1988)



The C-F current is confined on the dayside. However, the C-F and tail currents are continuous on the magnetopause.

Final procedure is to mold the magnetosphere into a realistic shape.

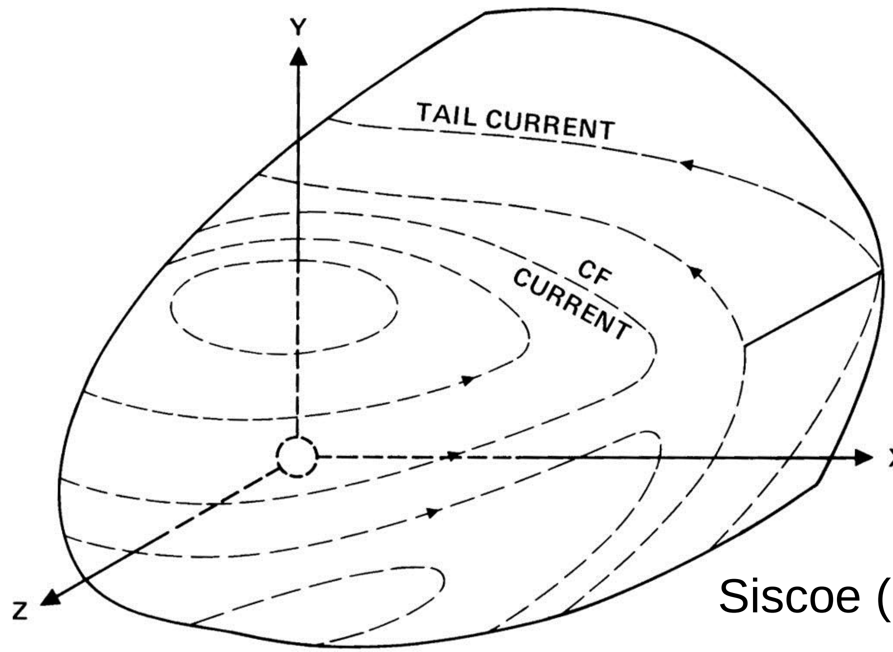




The magnetosphere is “closed” in the sense that the magnetopause is a tangential discontinuity.

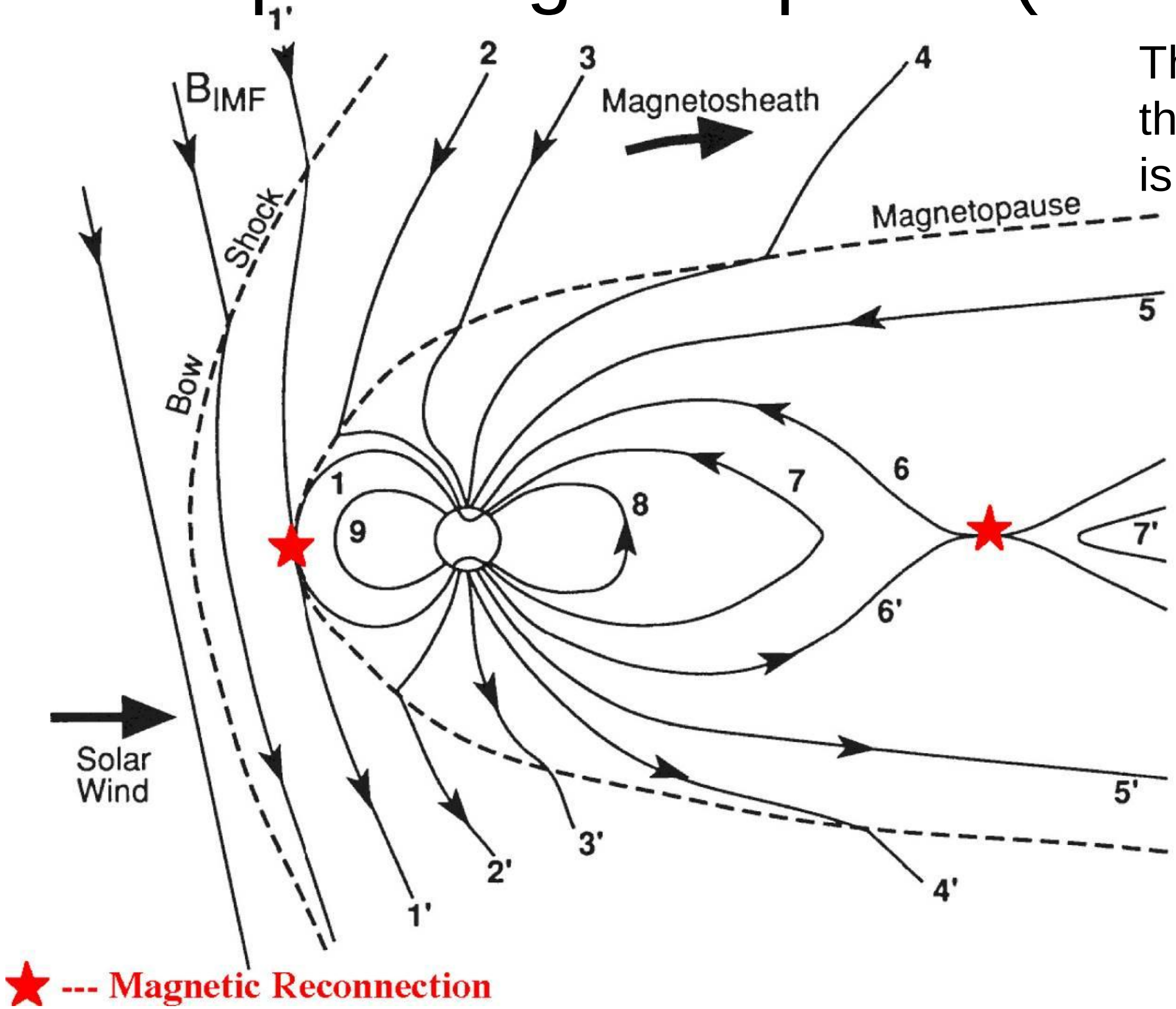
↓

Connection to interplanetary magnetic field comes into play.



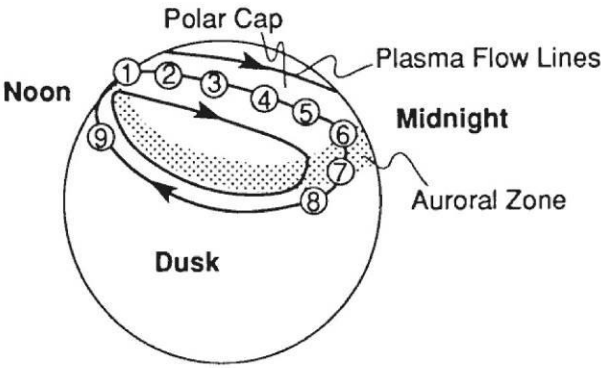
Siscoe (1988)

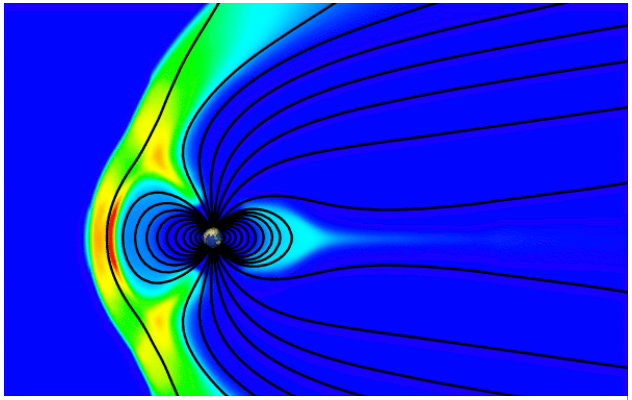
Open magnetosphere (Dungey cycle)



The magnetosphere is “open” in the sense that the magnetopause is a rotational discontinuity.

two-cell convection





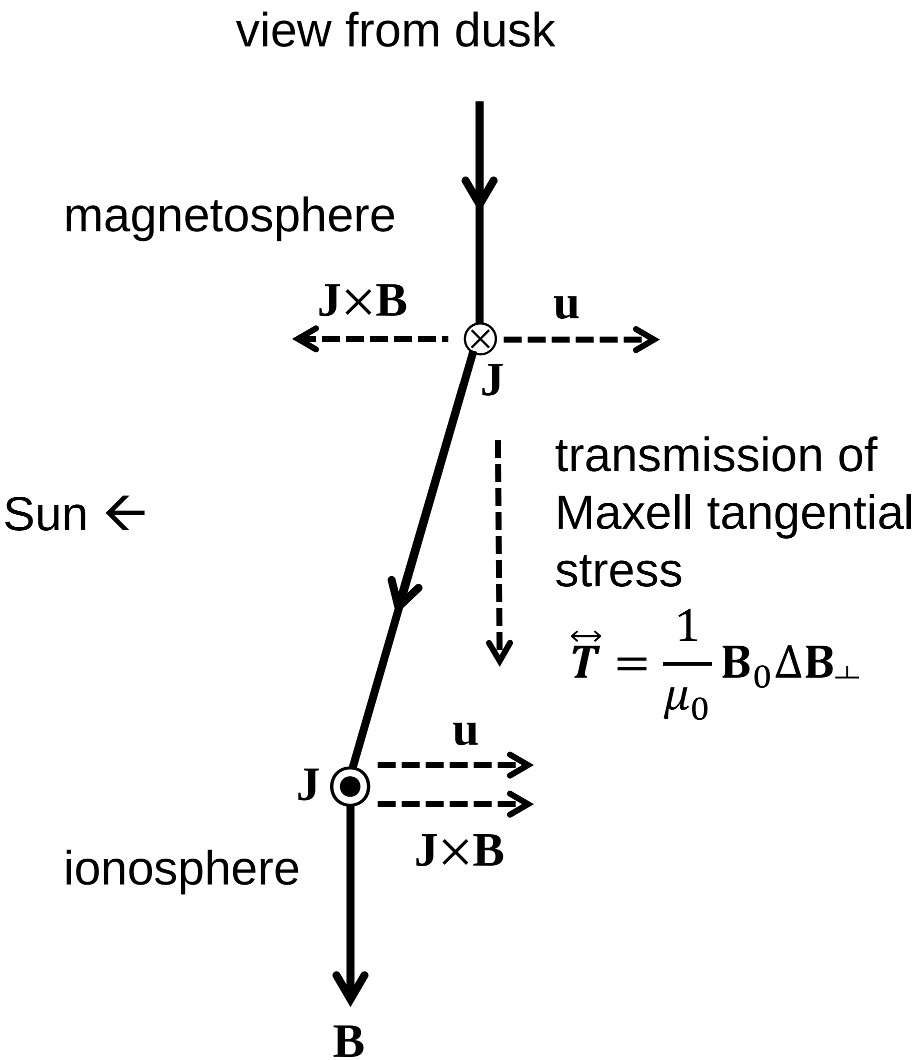
Caveat

The figure gives an impression that the solar wind drags ionospheric plasmas to excite two-cell convection. However, this is not necessarily a correct view. Ionosphere is very heavy. There are complicated processes to establish a convection system (which we cannot review in detail here).

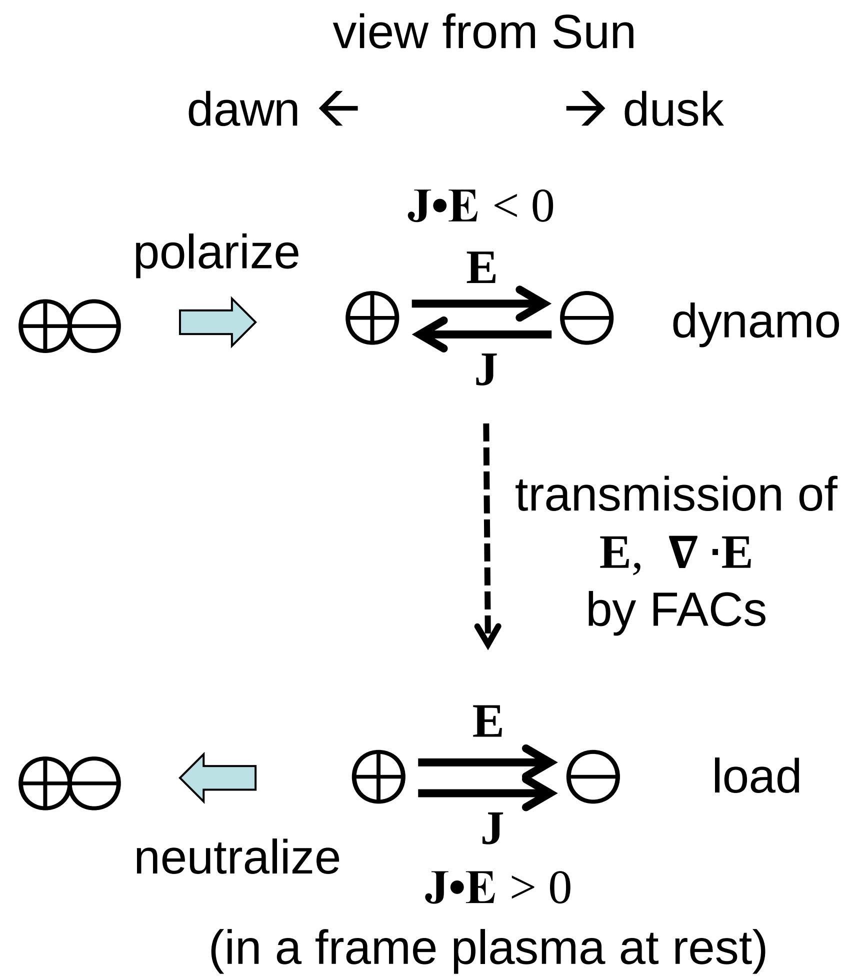
Convection as a collaboration of magnetosphere & ionosphere (1)

Momentum and energy

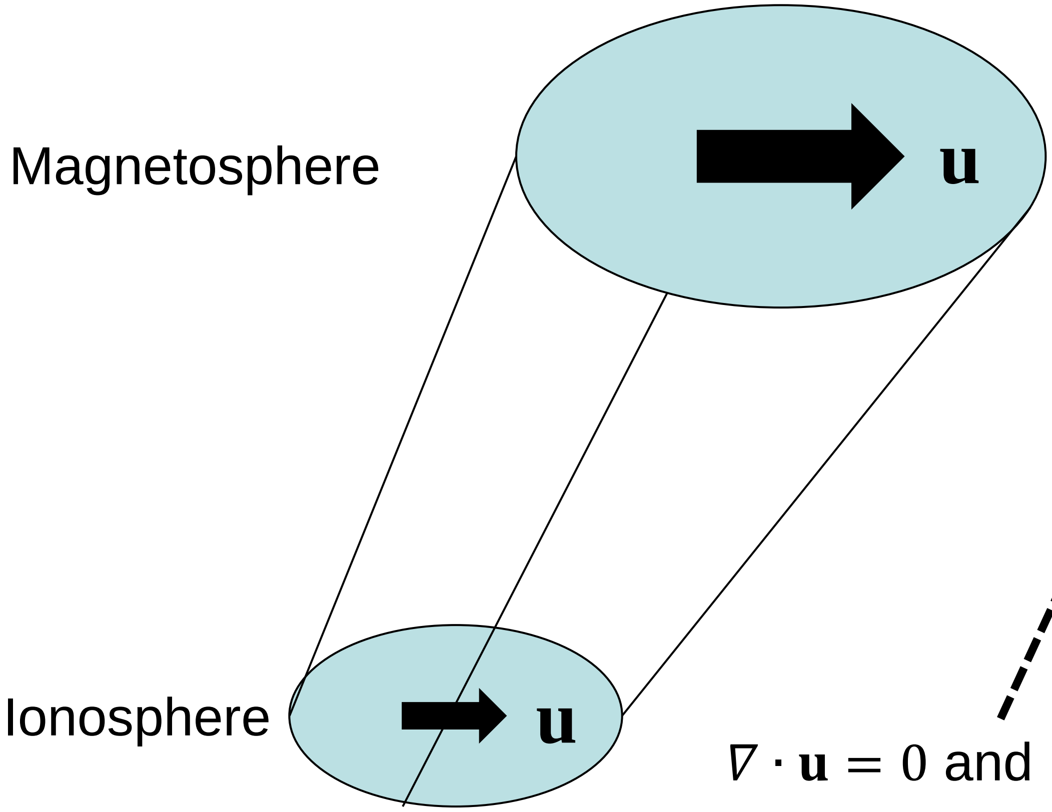
(a) (**u**, **B**) view



(b) (**E**, **J**) view



Convection as a collaboration of magnetosphere & ionosphere (2)



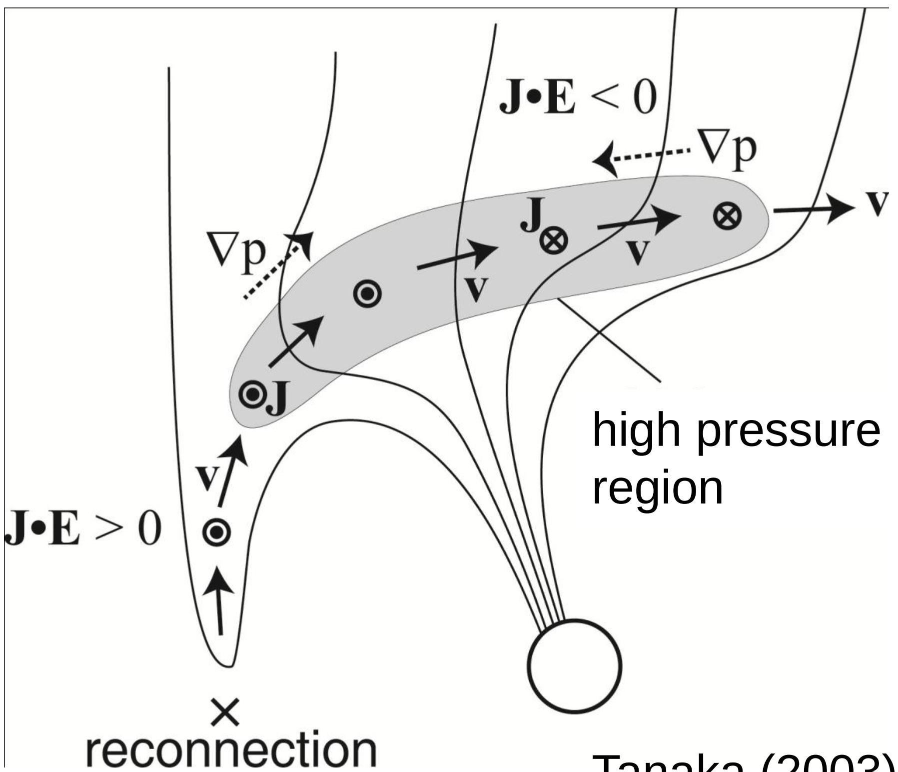
Only incompressional flow (or rotational flow) can contribute convection.

$\nabla \cdot \mathbf{u} = 0$ and $\nabla \times \mathbf{u} \neq 0$

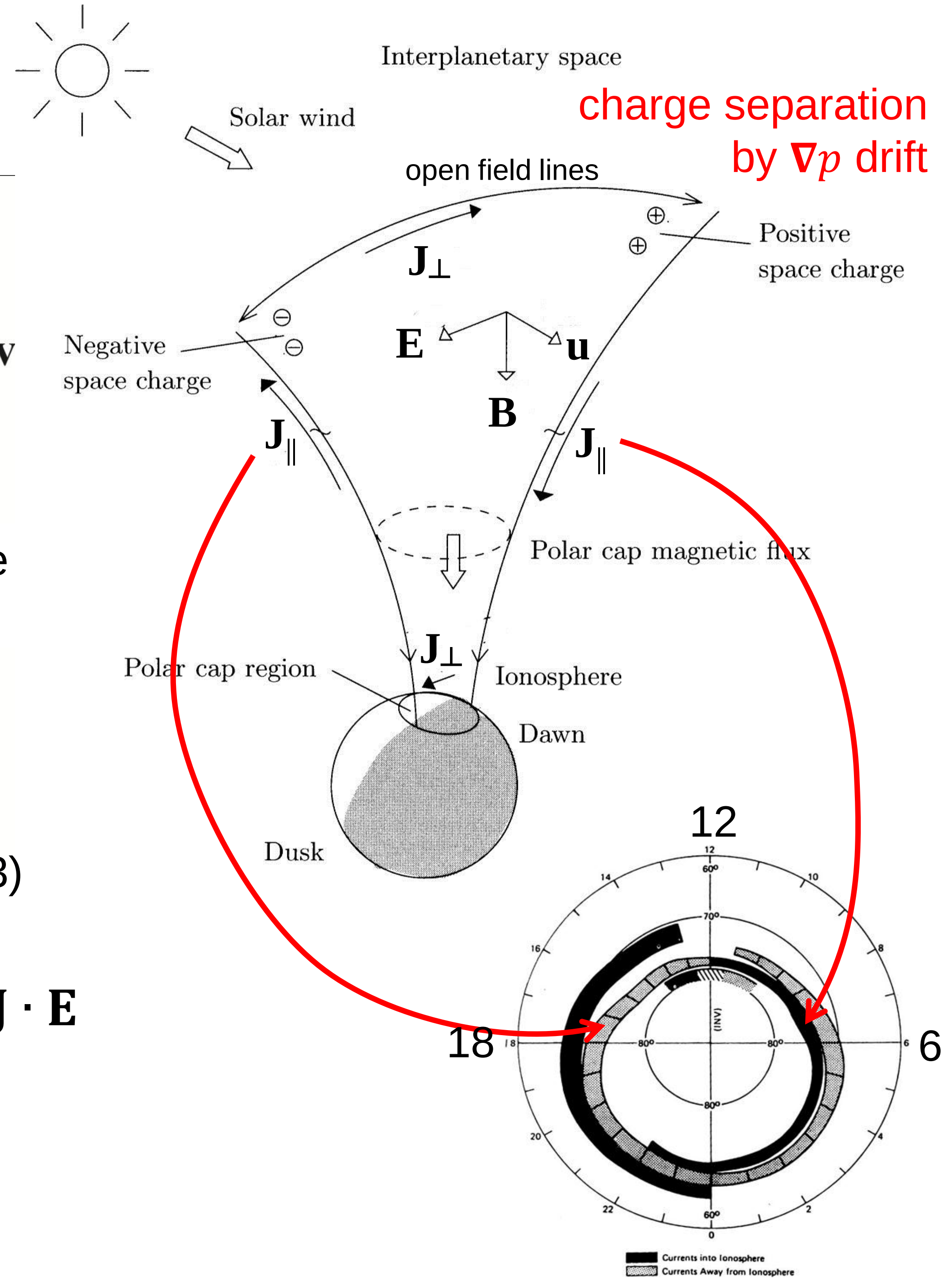
The flow tends to be stationary ($\frac{\partial}{\partial t} = 0$), and the electric field to be static.

Establishment of a self-consistent global plasma circulation in the magnetosphere-ionosphere system ("convection").

Solar wind dynamo

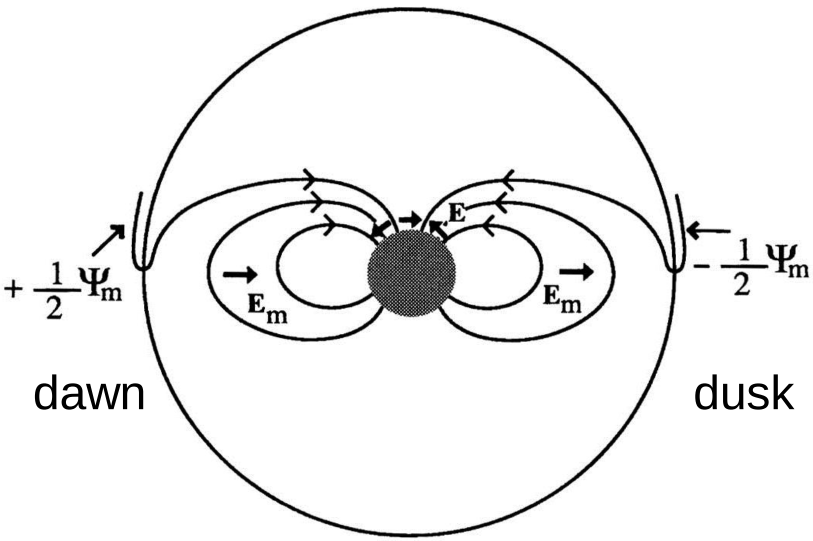


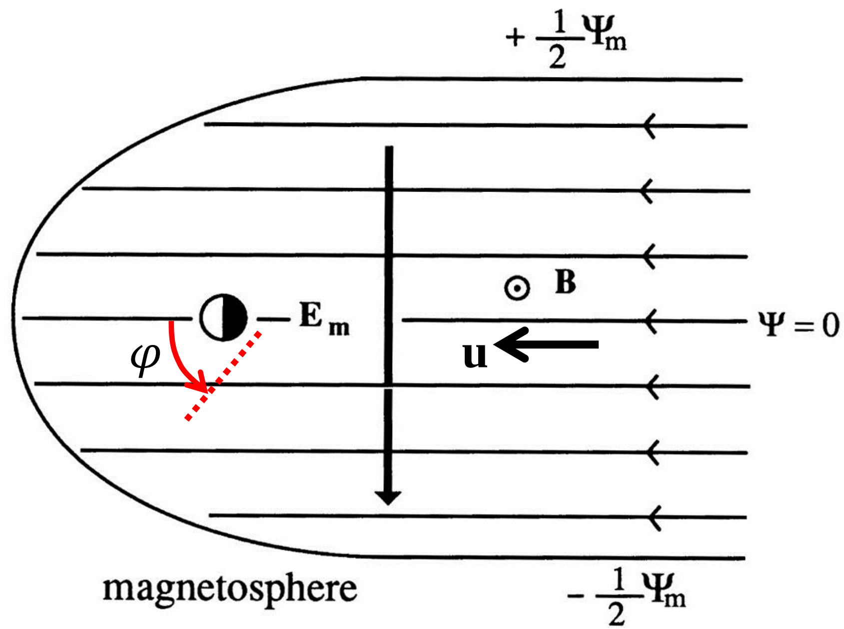
Tanaka (2003)



$$\mathbf{J} \times \mathbf{B} \approx \nabla p \longrightarrow \mathbf{v} \cdot \nabla p = \mathbf{J} \cdot \mathbf{E}$$

Convection (Electric field) in the closed field line region





$$\mathbf{u} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$\mathbf{E} = -\nabla\Psi$$

(static electric field)

Uniform dawn-to-dusk electric field

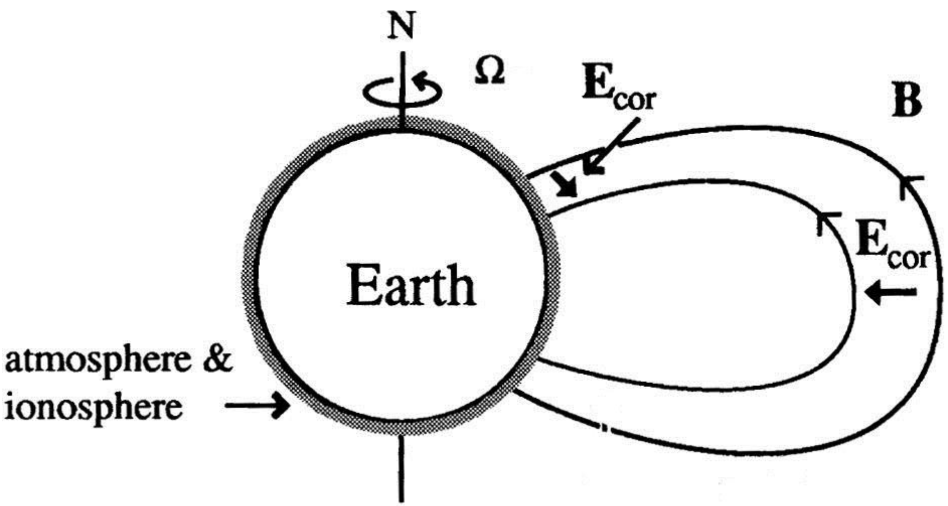
$$\Psi_m = -E_m L a \sin\varphi$$

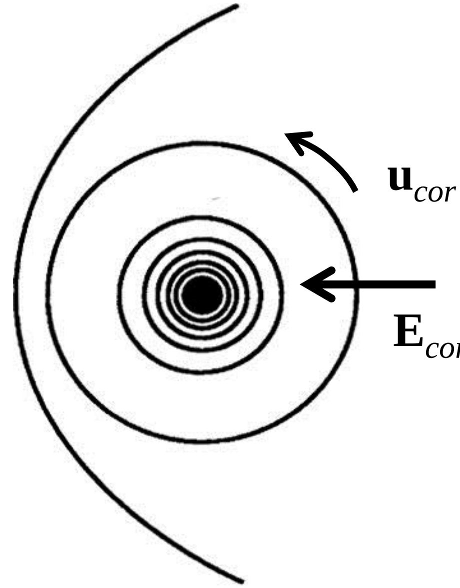
$$\mathbf{E}_m = -\nabla\Psi_m$$

a: radius of the Earth

L: geocentric distance measured by a where a field line crosses the equator

Corotation electric field in the inner magnetosphere





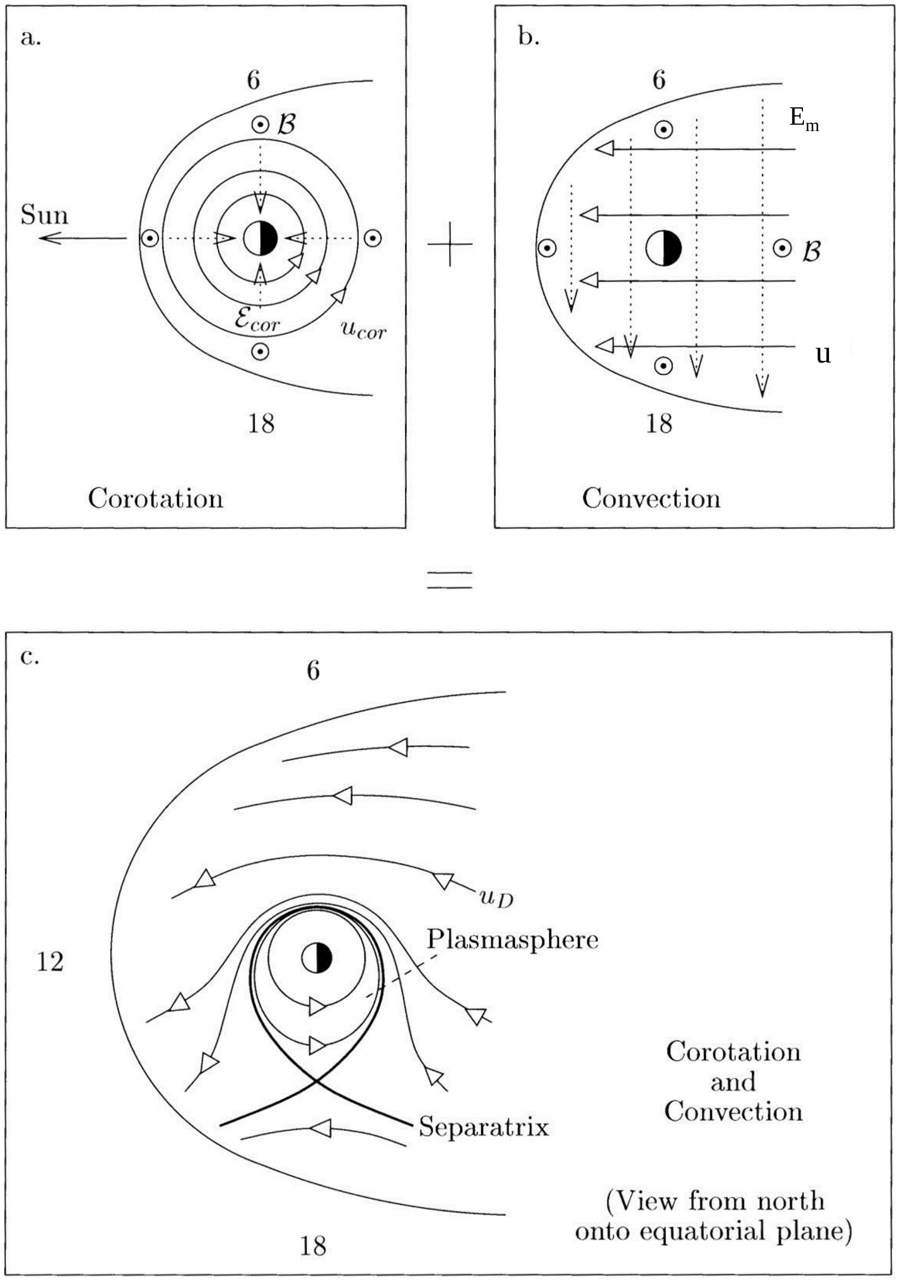
$$\mathbf{E}_{cor} = -\mathbf{u}_{cor} \times \mathbf{B} = -(\boldsymbol{\Omega} \times \boldsymbol{r}\ ) \times \mathbf{B}$$

At the equator, assuming a dipole,

$$E_{cor} = -\frac{\Omega B_0 a}{L^2}$$ radial component

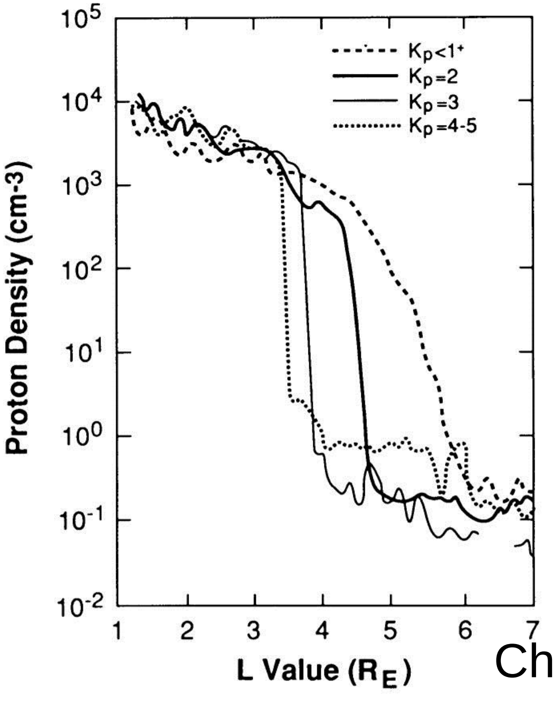
$$\Psi_{cor} = -\frac{a^2 \Omega B_0}{L}$$

Total convection



$$\Psi = \Psi_m + \Psi_{cor} = -E_m L a \sin\varphi - \frac{\Omega B_0 a^2}{L}$$

$$\mathbf{u} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



Chappell (1972)

Energetic particles in the inner magnetosphere

$$\mathbf{u}_{j\perp} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\mathbf{B}}{q_j n B^2}\times\nabla p_j$$

j = ions, electrons

- MHD ordering
  ion thermal speed ~ ExB drift >> diamagnetic drift
- Drift ordering
  ion thermal speed >> ExB drift ~ diamagnetic drift

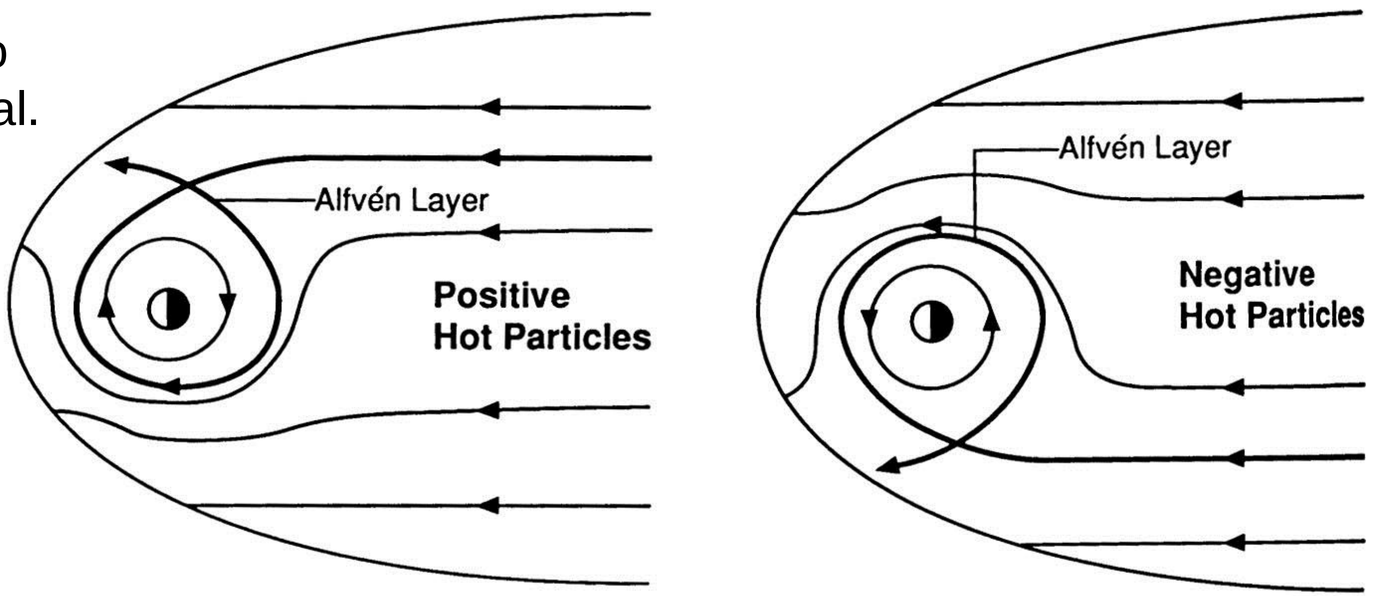
$$\mathbf{u}_{j\perp} = \frac{\mathbf{B}\times\nabla\Psi}{B^2} + \frac{\mathbf{B}\times\nabla\Psi_{\mu j}}{B^2}$$

$$\Psi_{\mu j} = \frac{\mu_j B_0}{q_j L^3}$$

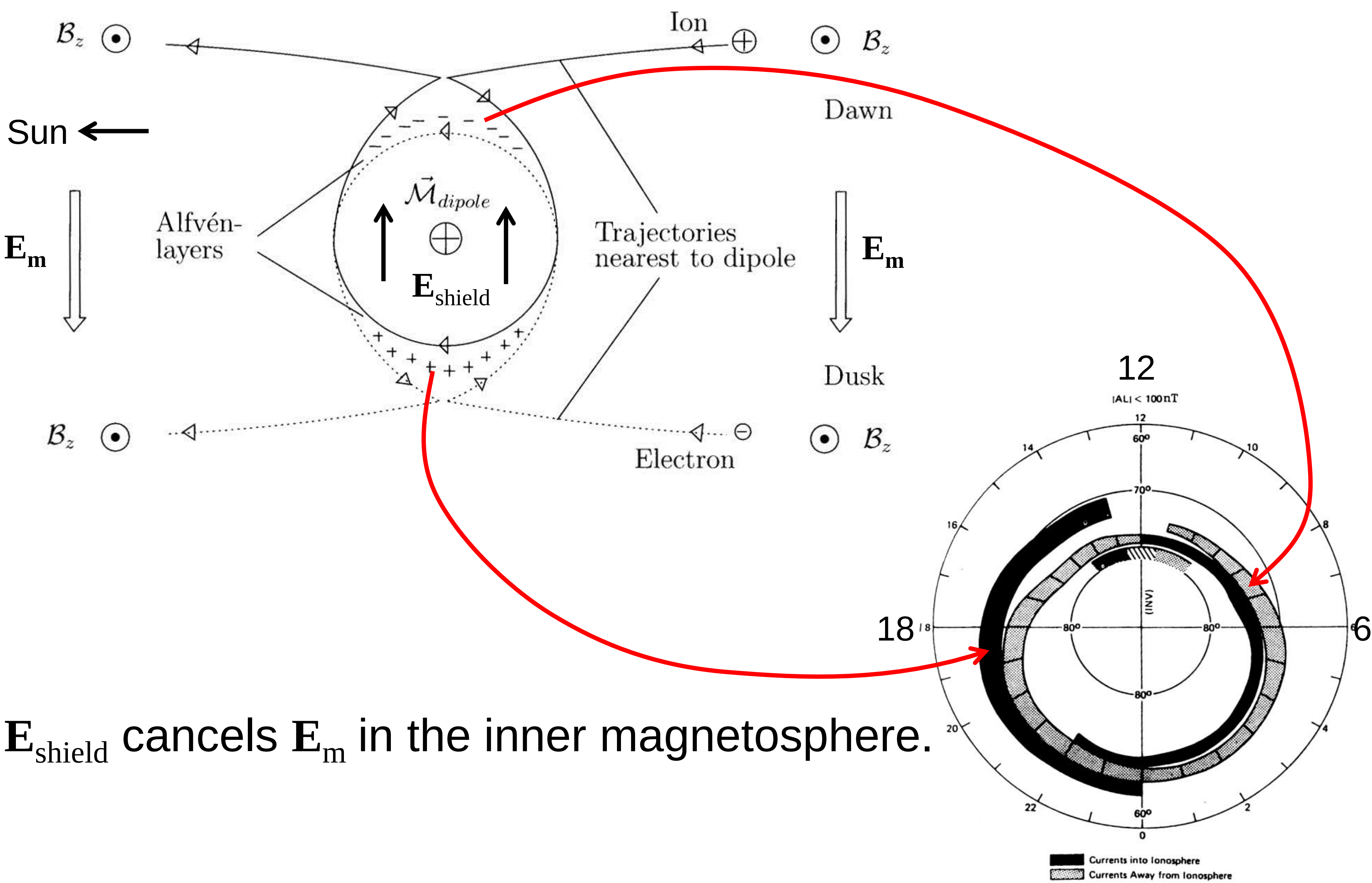
$$\mu_j = \frac{p_j}{nB} = const.$$

There is a similarity to the corotation potential.

$$\Psi_{cor} = -\frac{a^2\Omega B_0}{L}$$



Charge separation in the inner magnetosphere



$\mathbf{E}_{shield}$ cancels $\mathbf{E}_m$ in the inner magnetosphere.

Review

- What is the role of the Chapman-Ferraro current?
- What is the magnetotail?
- The idea of “convection” in the magnetosphere-ionosphere system is not simply the plasma bulk flow $\mathbf{u}$. How is it different from simple $\mathbf{u}$?
- What is a dynamo?