BIRKELAND CENTRE FOR SPACE SCIENCE

Regions, currents and energy flow in the solar-wind-magnetosphere system

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Outline

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Plasma regions in the magnetosphere
- Overview of the plasma regions in the Earth's magnetosphere
- Magnetopause – magnetic shielding and pressure balance
- Plasma sheet and magnetotail

Currents in the magnetosphere and ionosphere
- Magnetopause currents
- Ring current
- Tail currents
- Ionospheric currents: Pedersen and Hall
- Field aligned currents, Birkeland region 1 and 2

The Energy flow the Earth's magnetosphere/ionosphere,
- Available energy in the solar wind
- Reconnection, the solar wind dynamo and the epsilon parameter

The energy sinks in the system
- Ring current increase (UR) – Dst index
- Joule heating of the ionosphere (UJ) – AE index
- Particle precipitation (UA) – AL index

Energy budget
- Short intervals
- For12 years
- New energy coupling function

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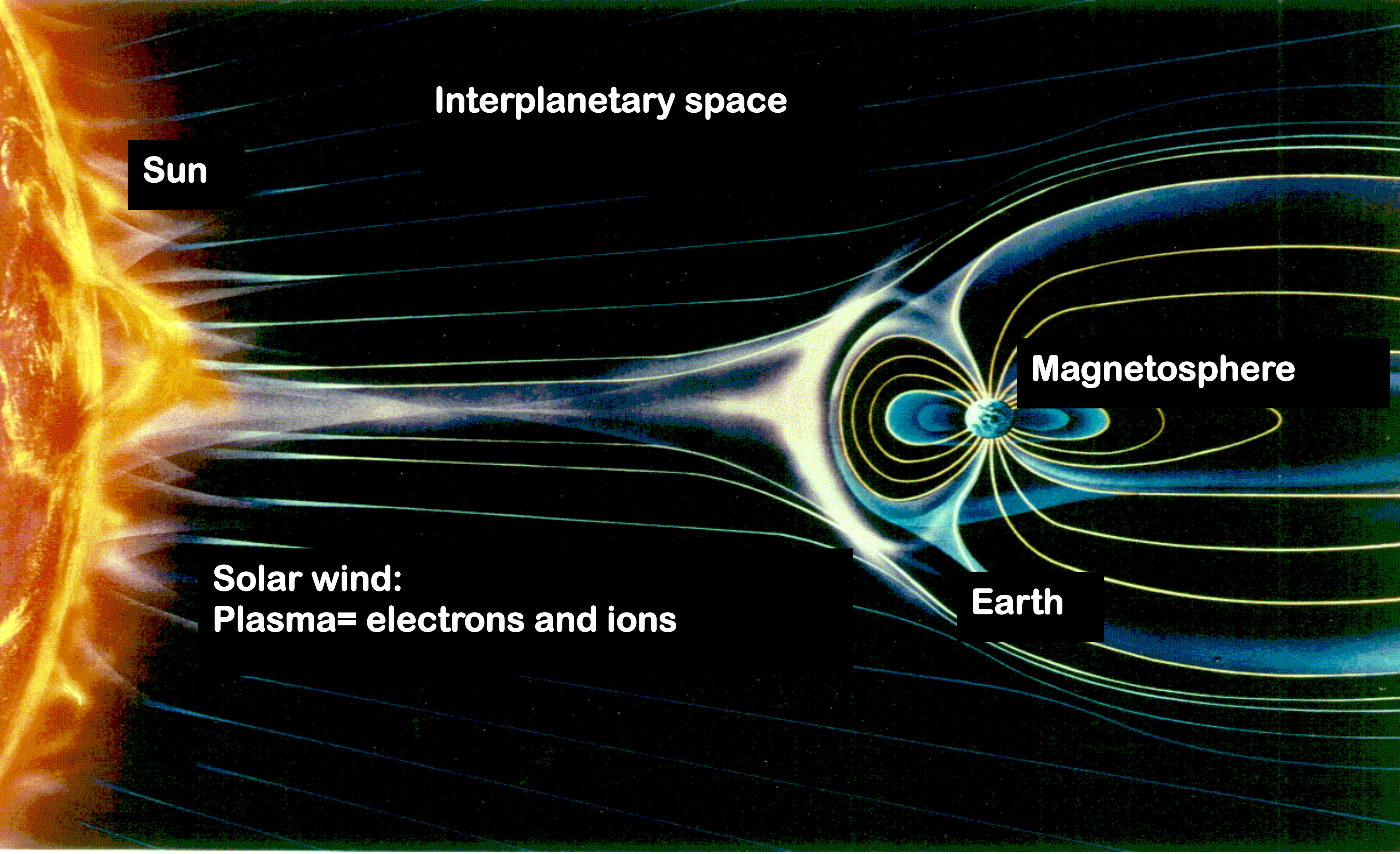
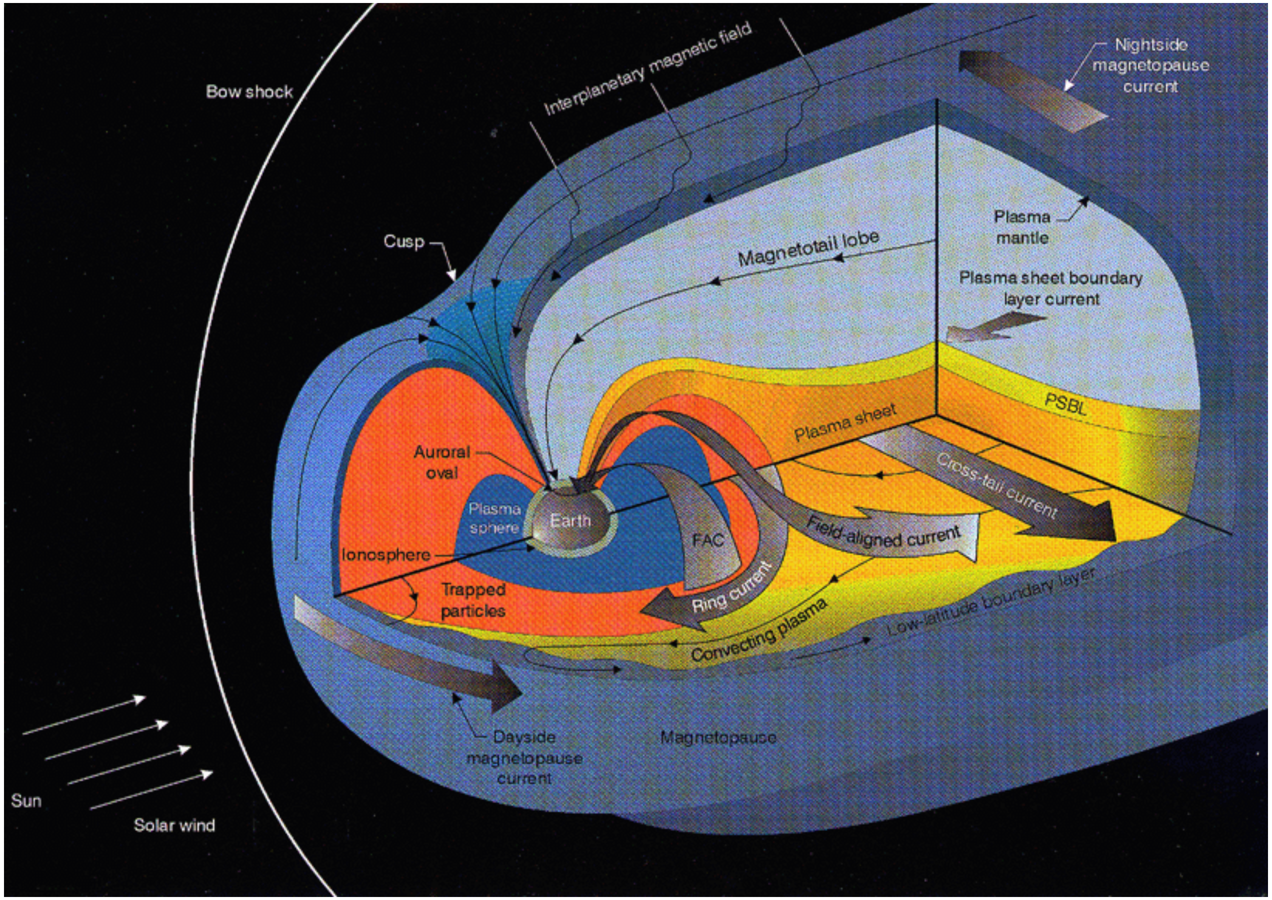


Frozen-in concept: No collision: magnetic field is´frozen´ in the plasma
Interplanetary medium
Earth's magnetosphere

Solar wind and plasma regions



Typical magnitudes

Flow speed	**Flow direction**	**Particle number density**	**Average thermal energy**	**Intensity of B_{IMF}**
300-800 km/sec	Nearly parallel to the Earth Sun line	3-20 cm-3	kTe < 100 eV kTp < 50 eV	1-30 nT

Solar wind

Typical magnitudes

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mp= 1.67 10^{-27} kg
me= 9.1 10^{-31} kg
k=1.38 10^{-23} J/K
μ_0= 4π 10^{-7} H/m

Kinetic energy, thermal energy and magnetic energy

$$E_{sw} = \frac{1}{2} N m_p v^2{}_{sw}$$

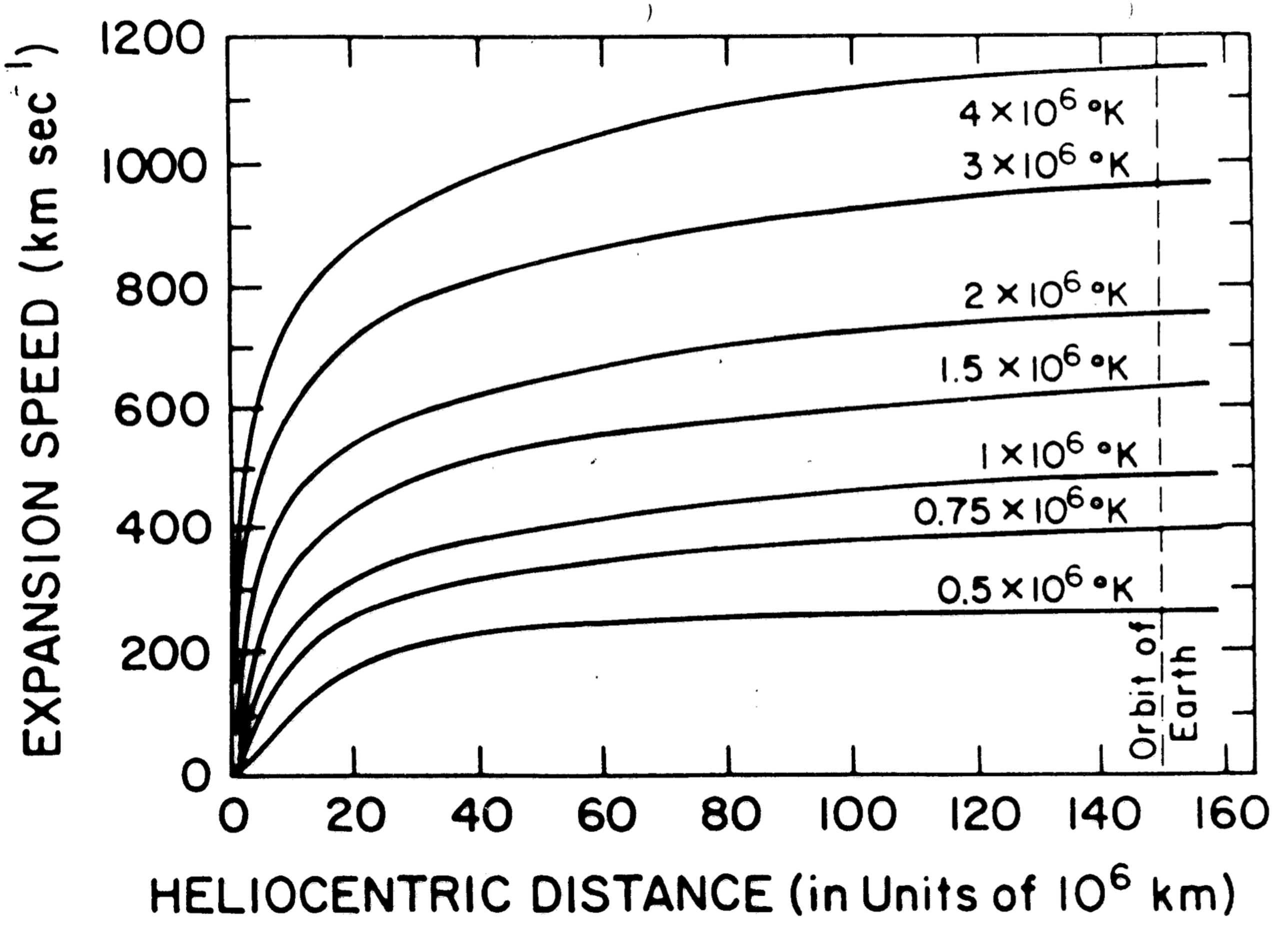
$$E_{Tp} = \frac{3}{2} N k T_p = \frac{1}{100} E_{sw}$$

$$E_B = \frac{B^2}{2\mu_0} = \frac{1}{70} E_{sw}$$

$$E_{Te} = \frac{3}{2} N k T_e = \frac{1}{50} E_{sw}$$

Solar wind speed

Modeled solar wind speed assuming isotherm gas (Parker 1958)

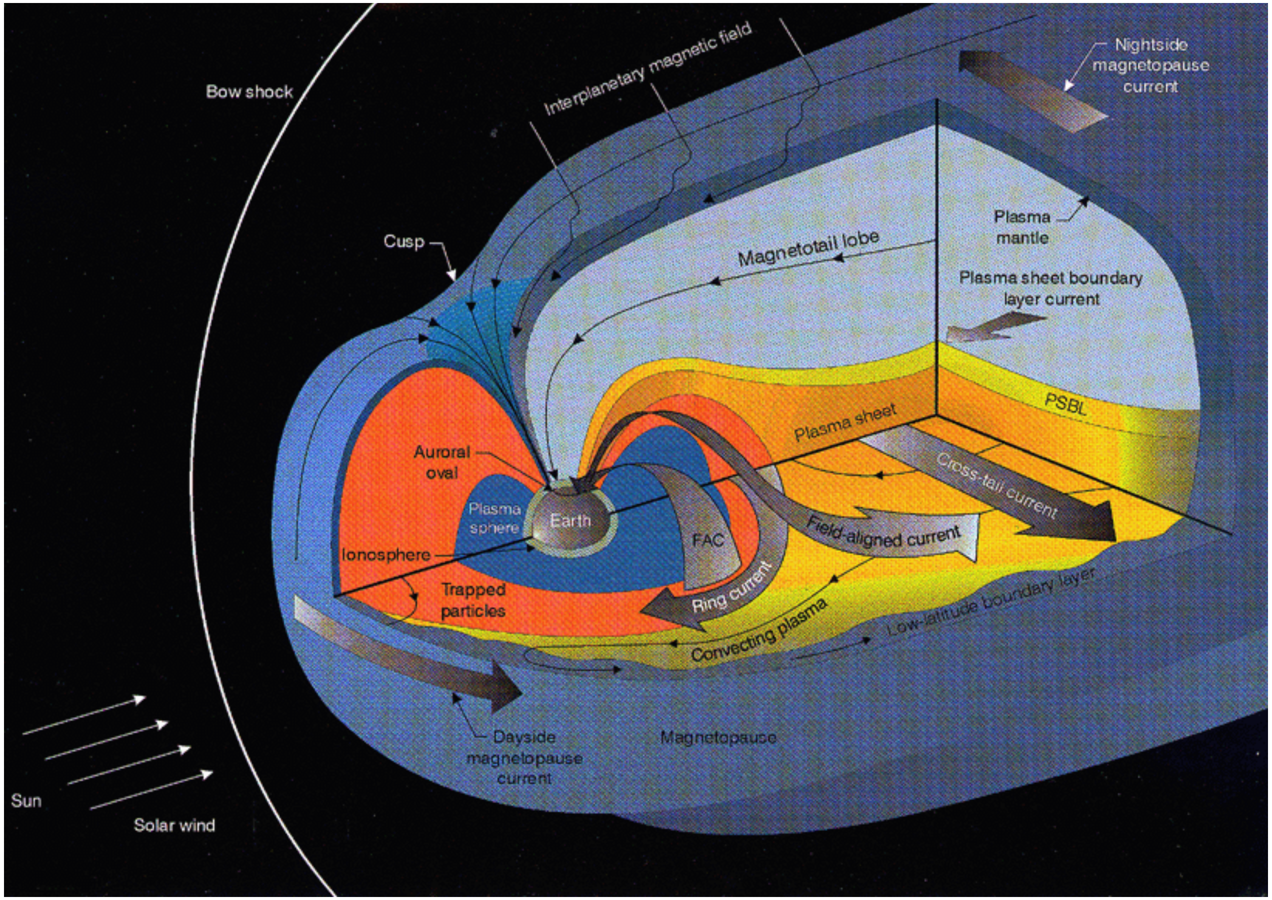


Hydrodynamic gas

No viscosity
No magnetic field

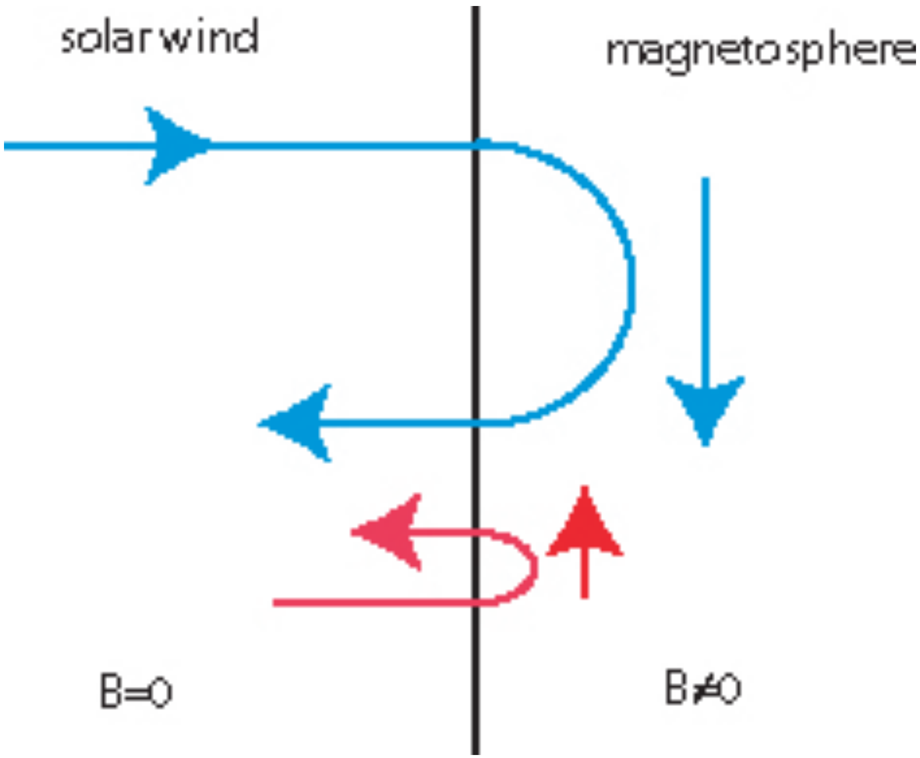
Only:
pressure,
gravity

Magnetopause



Pressure balance between solar wind and magnetosphere

The magnetic boundary



Magnetic force

$$F = qv \times B$$

Gyro radius

$$m\frac{dv}{dt} = m\frac{v^2}{r} = qvB$$

$$r = \frac{mv}{qB}$$

Magnetic shielding
Magnetopause current – Eastward (compression)

Magnetopause and pressure balance

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$$(p_{sw} + \frac{B_{IMF}{}^2}{2\mu_0}) = (p_m + \frac{B_m{}^2}{2\mu_0})$$

It comes from:

$$m\frac{dv}{dt} = F$$

For ions and electrons

$$m_i n_i \frac{dv_i}{dt} = q_i n_i (E + v_i \times B) - \nabla p_i$$

$$m_e n_e \frac{dv_e}{dt} = q_e n_e (E + v_e \times B) - \nabla p_e$$

Add and notice

$$q = q_i = -q_e \qquad J = nq(v_i - v_e) \qquad \rho_m = m_i n_i + m_e n_e$$

$$\rho_m \frac{dv}{dt} = J \times B - \nabla p \qquad\qquad n = n_i = n_e$$

Magnetopause and pressure balance

Equilibrium:

$$\rho_m \frac{dv}{dt} = 0 = J \times B - \nabla p$$

Ampere

$$J = \frac{\nabla \times B}{\mu_0}$$

Combine

$$\frac{(\nabla \times B) \times B}{\mu_0} = \nabla p$$

Vector identity and assume straight homogenous B

$$\nabla(p + \frac{B^2}{2\mu_0}) = 0$$

And we get the pressure balance

$$(p_{sw} + \frac{B_{IMF}{}^2}{2\mu_0}) = (p_m + \frac{B_m{}^2}{2\mu_0})$$

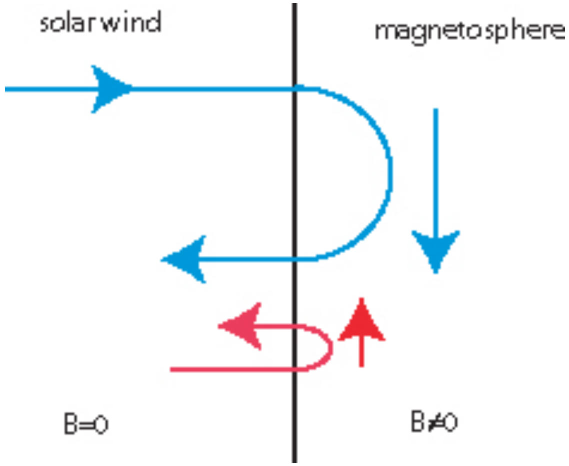
Magnetopause and pressure balance

$$(p_{sw} + \frac{B_{IMF}^{\ 2}}{2\mu_0}) = (p_m + \frac{B_m^{\ 2}}{2\mu_0})$$

$$p_{sw} = \frac{B_m^{\ 2}}{2\mu_0}$$

Reflecting particles at the magnetopause:

$$p_{sw} = 2Nm_p v^2$$

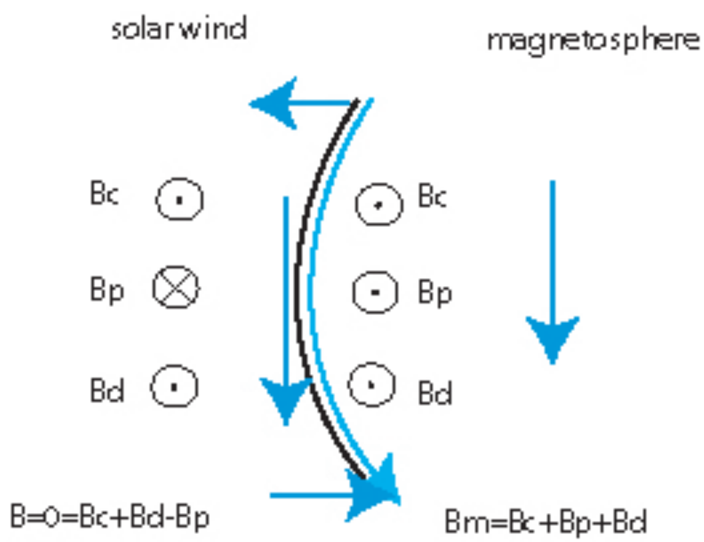


Magnetopause and pressure balance, cont

$$B_d = \frac{\mu_0 M}{4\pi \cdot r^3}$$

Dipole magnetic field,
M is Earth's dipole moment

$$B_m = 2B_d$$



Magnetopause and pressure balance, cont

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$$p_{sw} = \frac{B_m^{\ 2}}{2\mu_0}$$

$$2Nm_p v^2 = \frac{(2B_d)^2}{2\mu_0} = \frac{2}{\mu_0}\left(\frac{\mu_0 M}{4\pi r^3}\right)^2$$

$$r = \sqrt[6]{\frac{\mu_0 M^2}{16\pi^2 N m_p v^2}}$$

$M=8\ 10^{22}$ A m^2 .

Typical solar wind parameters:

$N=10\ 10^6\ m^{-3}$

$m_p=1.67\ 10^{-27}$ kg

$v=400\ 10^3$ m/s

r= 51600 km = **8.1 Re**

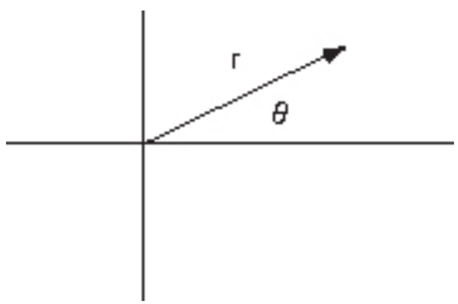
If one use $p=Nm_p v^2$, one gets **9.1 Re**

Magnetopause, empirical determination

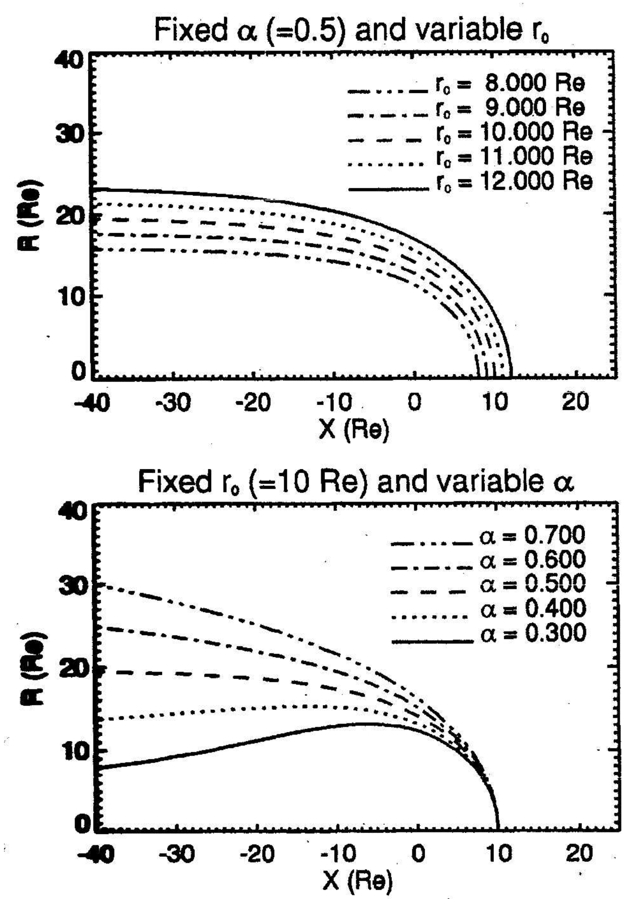
Shue et al., 1997

Representation

$$r = r_0\left(\frac{2}{1+\cos\theta}\right)^{\alpha}$$



$$\alpha = 0.5 \quad \theta = 0 \quad r = r_0, \quad \theta \to 180 \quad r \to \infty$$



Sun

Figure 1. Graphical representation of equation (1). The radial distance r varies with r_0 and α. The top panel shows fixed α (= 0.5) and variable r_0. The bottom panel shows fixed r_0 (= 10 R_e) and variable α. Note that $R = \sqrt{Y_{GSE}^2 + Z_{GSE}^2} = \sqrt{Y_{GSM}^2 + Z_{GSM}^2}$, which is independent of GSE and GSM coordinates.

Magnetopause, empirical determination

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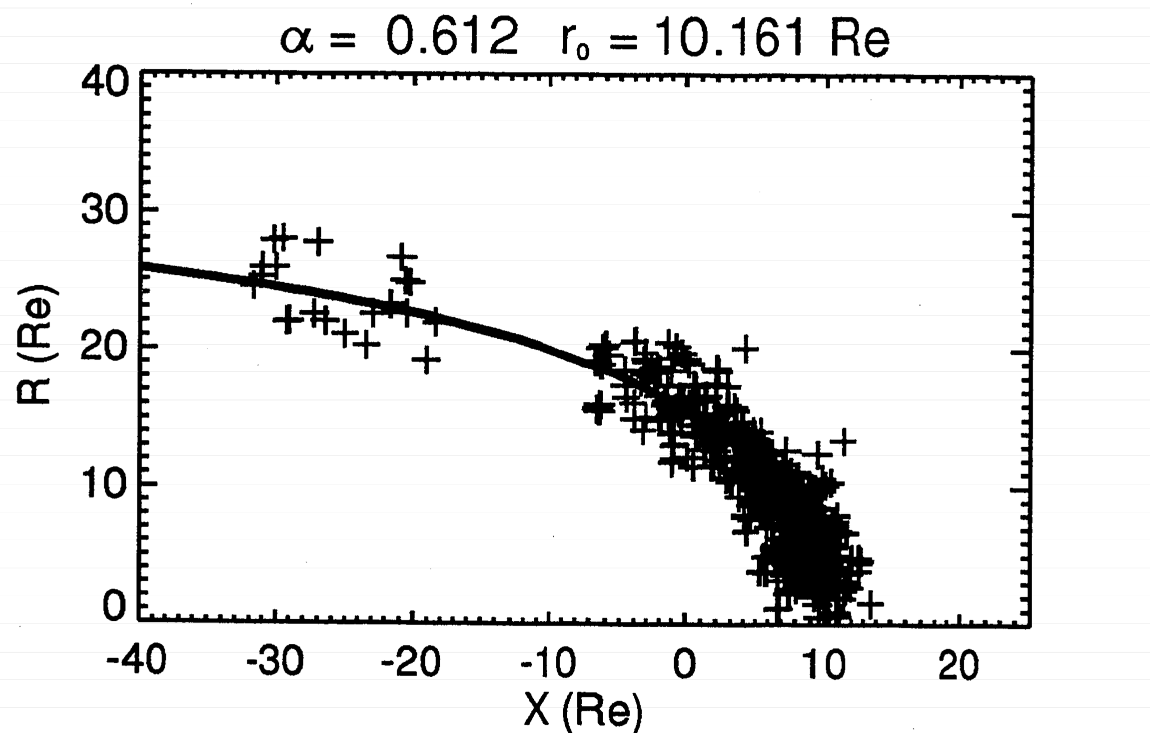
$$r = r_0 \left(\frac{2}{1+\cos\theta}\right)^{\alpha}$$



Magnetopause, empirical determination

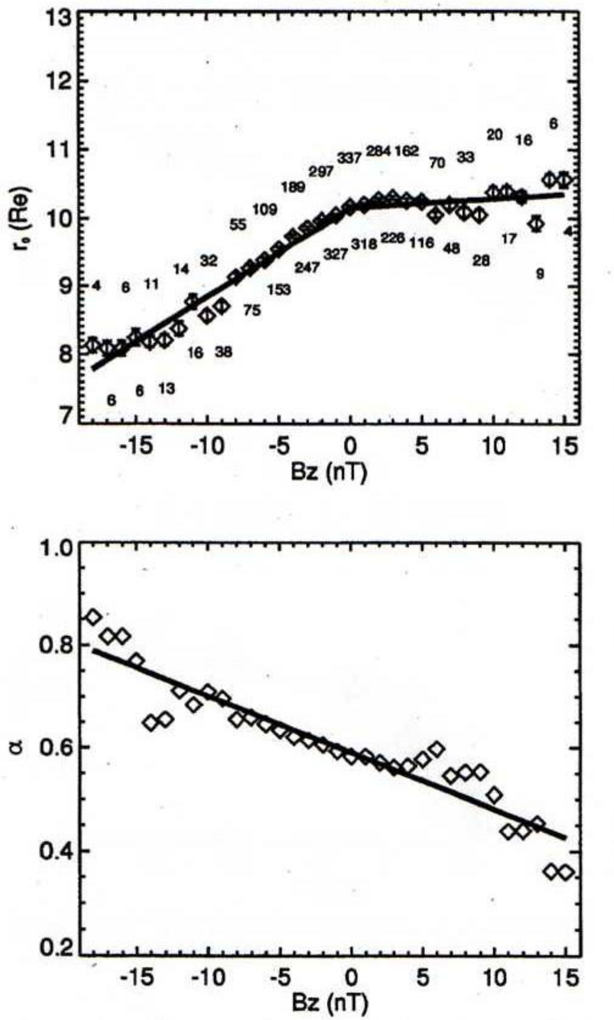


Figure 8. The variation of r_0 and α with B_z. This relation is for $D_p = 1.915$ nPa. The diamond symbols represent the best-fit values of r_0 and α. The error bar shows the probable error of the best-fit value. The solid lines show the fits. The number indicated above or below each error bar shows the number of data points for each bin.

$$r = r_0\left(\frac{2}{1+\cos\theta}\right)^{\alpha}$$

$$r_0 = (11.4 + 0.013B_z)\,p_{sw}^{-\frac{1}{6.6}},\ for B_z \geq 0$$

$$r_0 = (11.4 + 0.14B_z)\,p_{sw}^{-\frac{1}{6.6}},\ for B_z < 0$$

$$\alpha = (0.58 - 0.010B_z)(1 + 0.010p)$$

Magnetopause, empirical determination

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$$r_0 = (11.4 + 0.14 B_z) p^{-\frac{1}{6.6}}, for B_z \leq 0$$

$$p_{sw} = N m_p v^2$$

Same solar wind parameters:

$N = 10\ 10^6\ m^{-3}$
$m_p = 1.67\ 10^{-27}$ kg
$v = 400\ 10^3$ m/s

B_Z= 0 nT r_0= 9.8 Re
B_Z= -5 nT r_0= 9.2 Re

Compared with 8.1 Re
Or 9.1 Re

Plasma sheet and magnetotail

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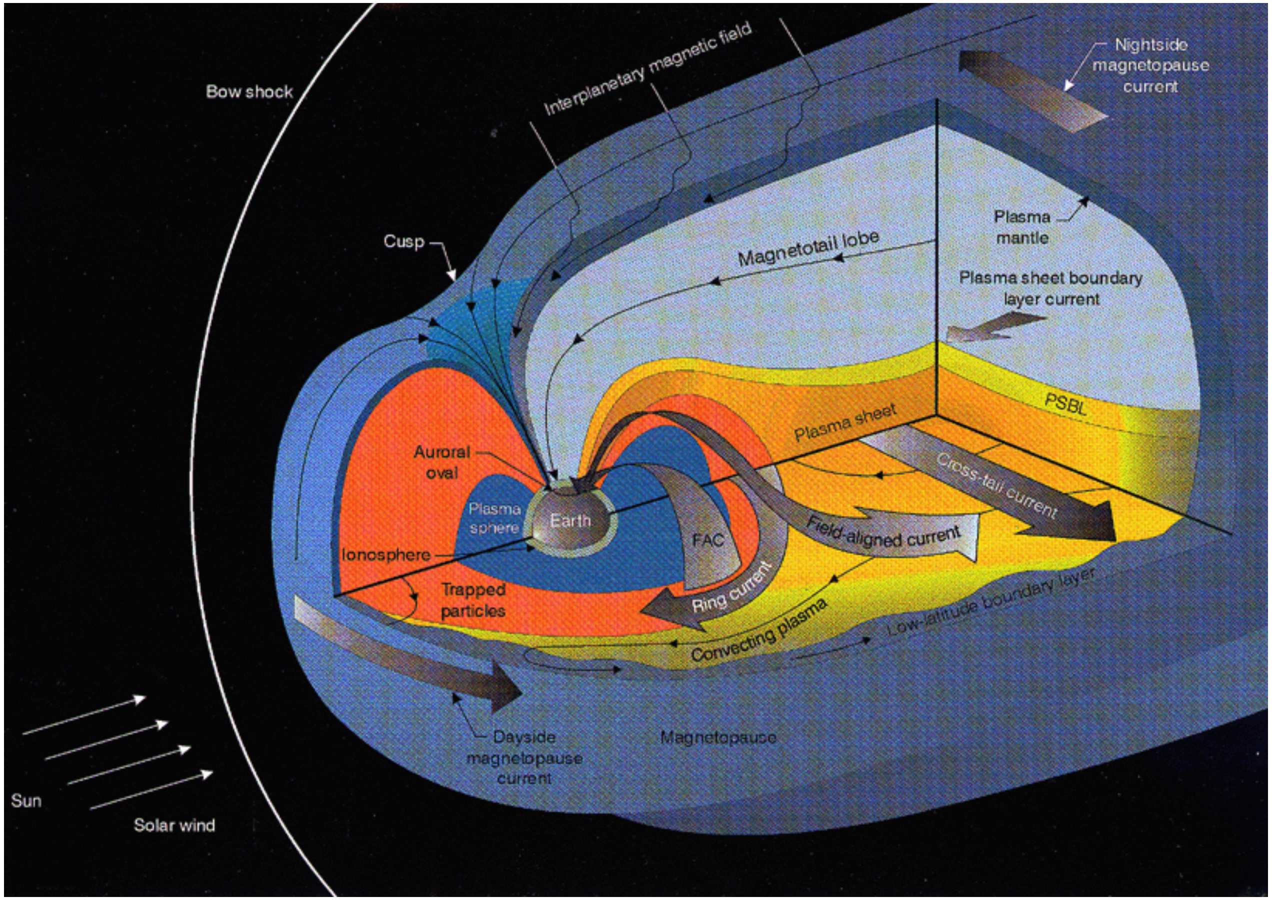

Plasma sheet with weak field and dense plasma
Lobe with low plasma density and stronger field
Stretched magnetotail with current sheet

$$(p_{sh} + \frac{B_{sh}^{2}}{2\mu_0}) = (p_l + \frac{B_l^{2}}{2\mu_0})$$

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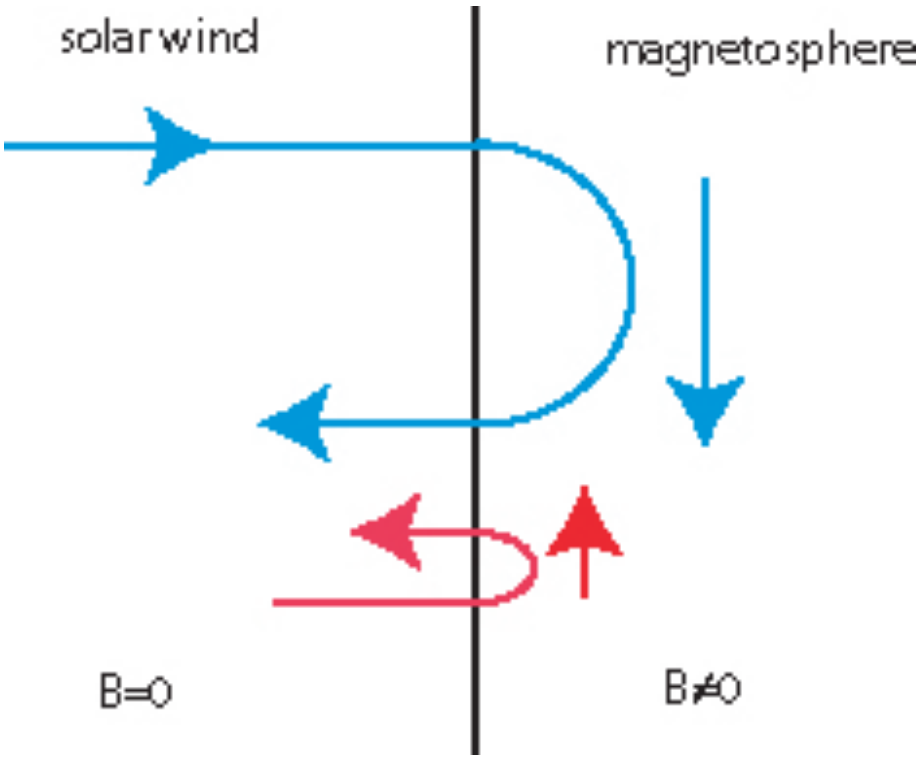
Magnetopause current



Magnetic force

$$F = qv \times B$$

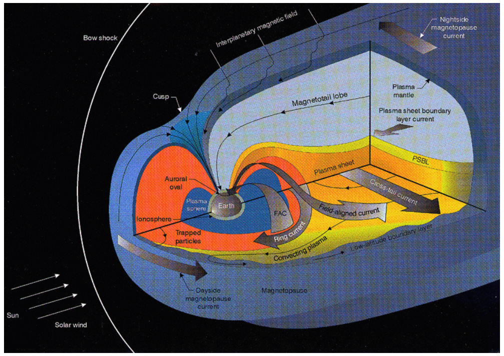
Gyro radius

$$m\frac{dv}{dt} = m\frac{v^2}{r} = qvB$$

$$r = \frac{mv}{qB}$$

Magnetic shielding

Magnetopause current – Eastward current



Particle motion in the magnetosphere

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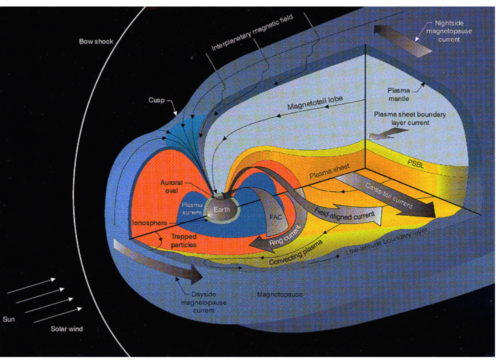
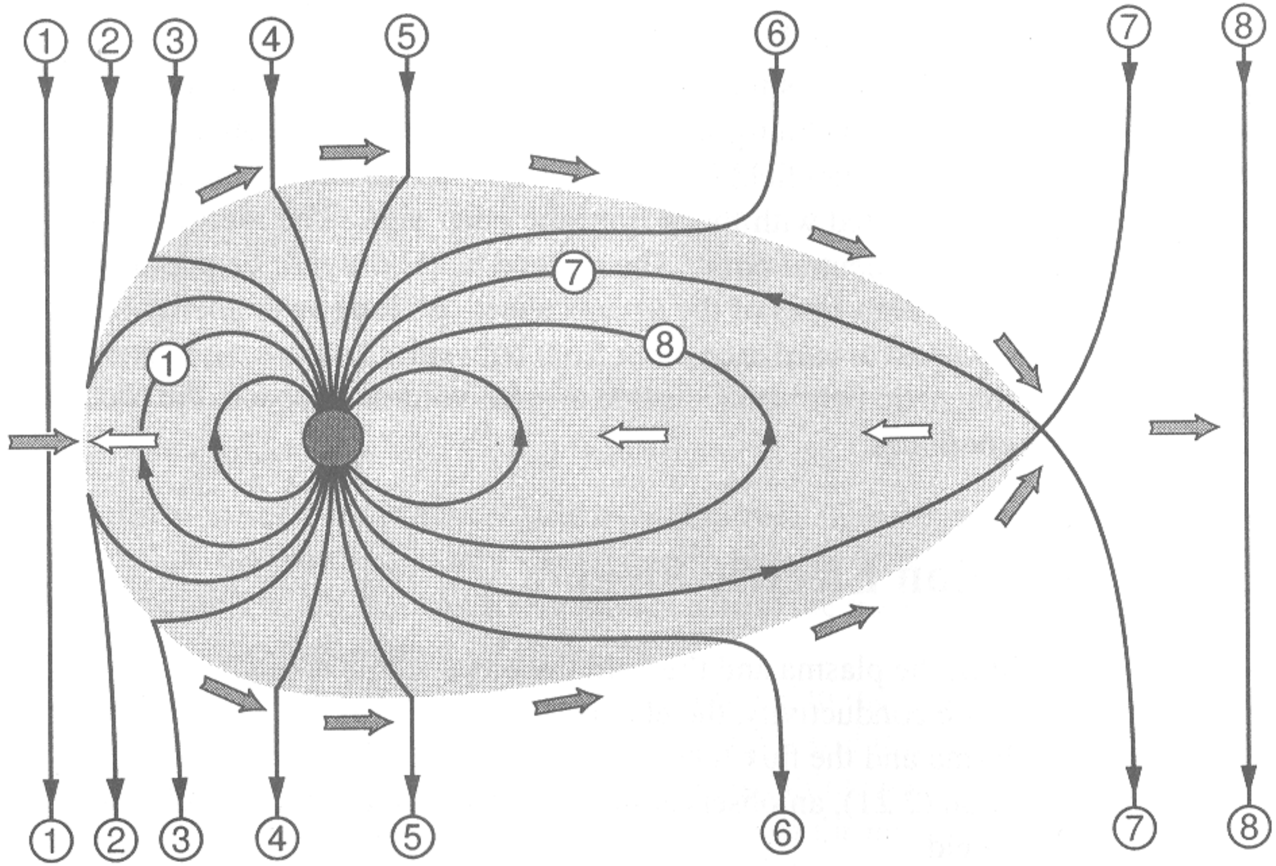
how do particles enter the inner magnetosphere





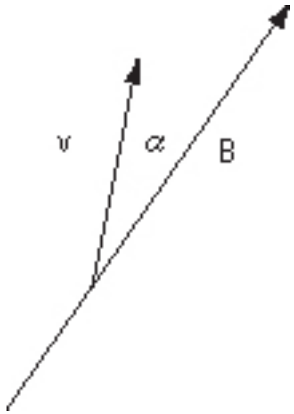
Dungey cycle

Particle motion, cont

To describe drift paths:
General drift of particles in E and B

$$v_d = \frac{E \times B}{B^2} + \frac{K}{qB^3}(1 + \cos^2 \alpha) B \times \nabla B$$

α=pitch angle

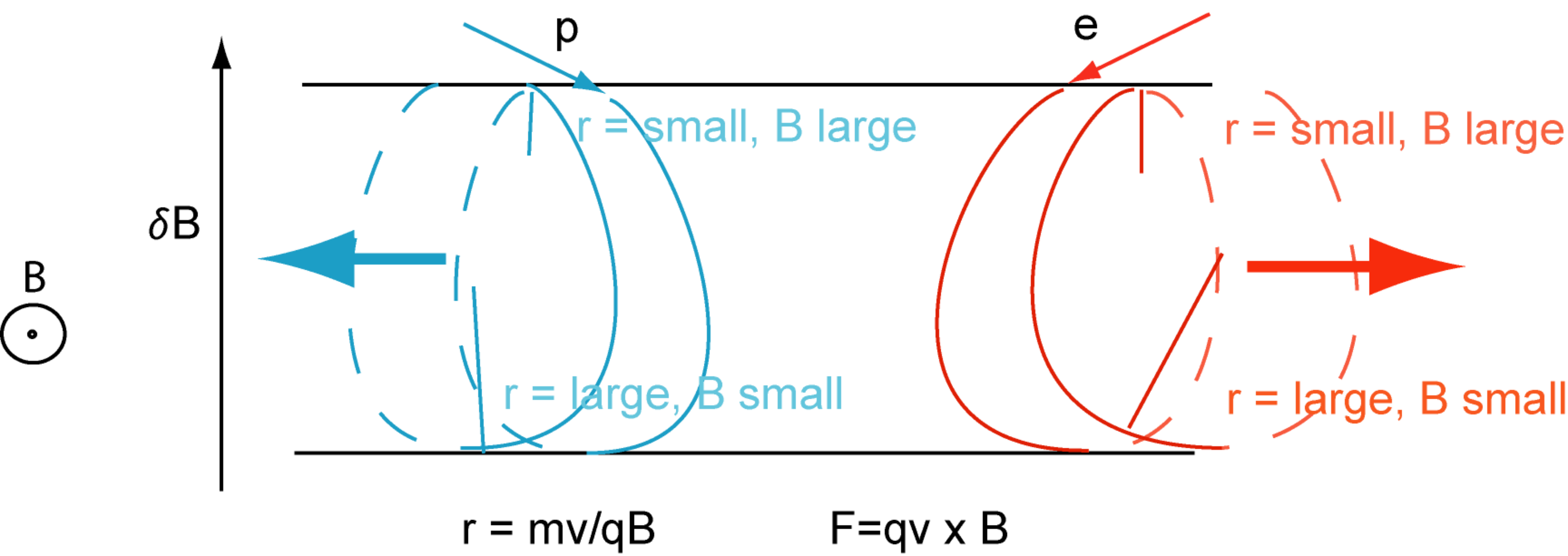


General drift velocity in E and inhomogenous B

Magnetic drift

$$v_d = \frac{K}{qB^3} B \times \nabla B$$

General drift velocity in inhomogenous B



Electrons and protons drift OPPOSITE direction
Only higher energies

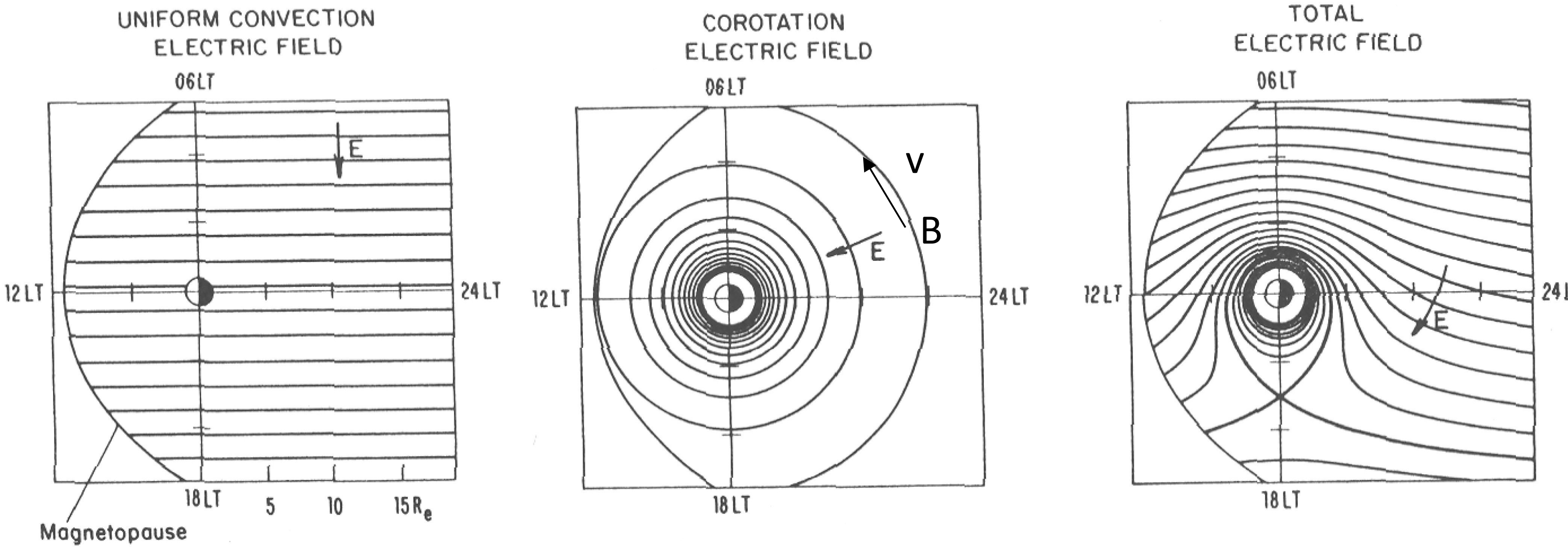
Drift paths and injection to ring current

$$E' = E + v \times B = 0$$

$$E = -v \times B$$

$$E = -v \times B$$

When plasma moves with B, an E-field in stationary system

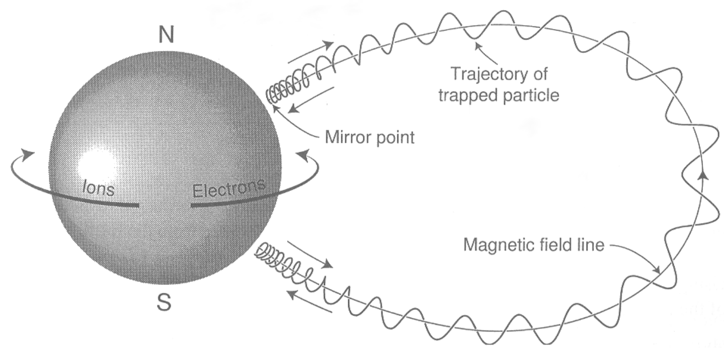


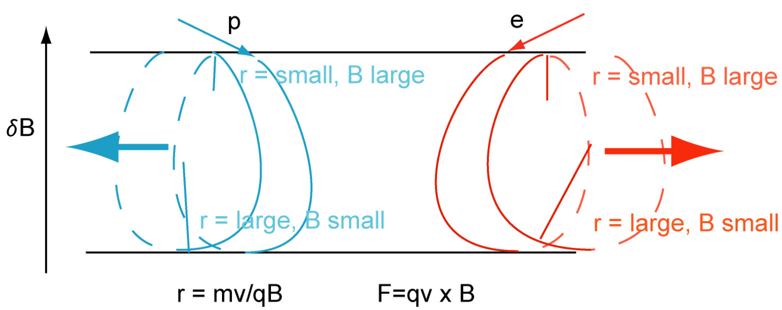
$$v_d = \frac{E \times B}{B^2}$$

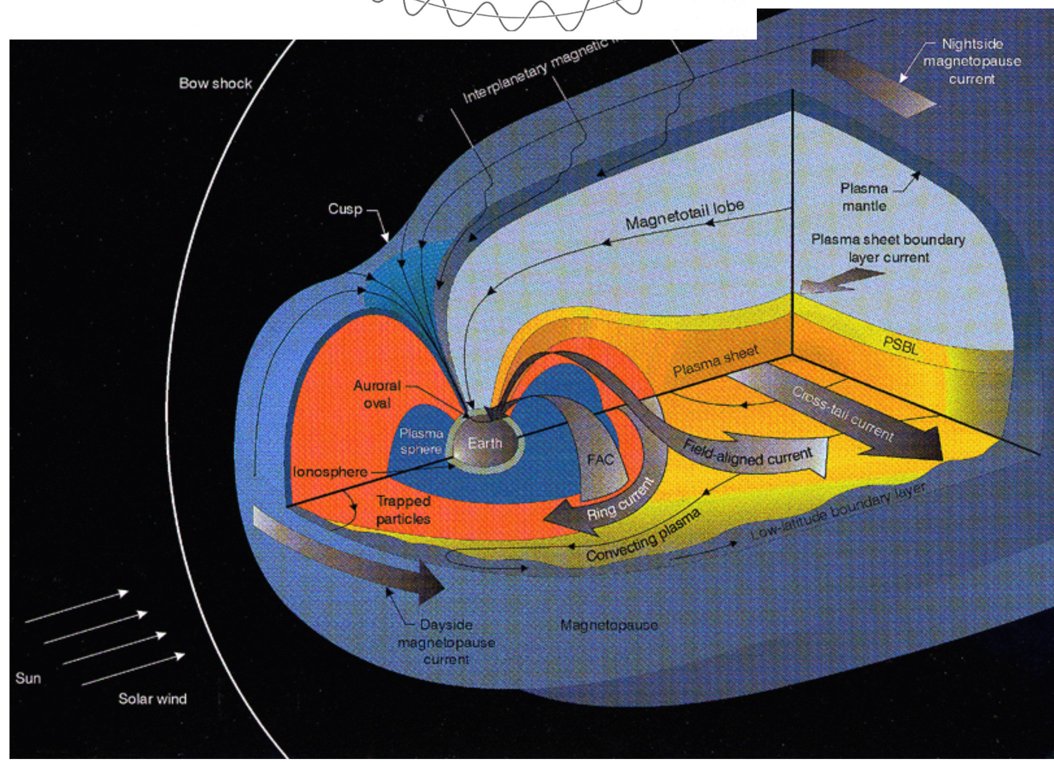
General drift velocity in E and B

Gradient drift and Ring current

$$v_d = \frac{K}{qB^3} B \times \nabla B$$

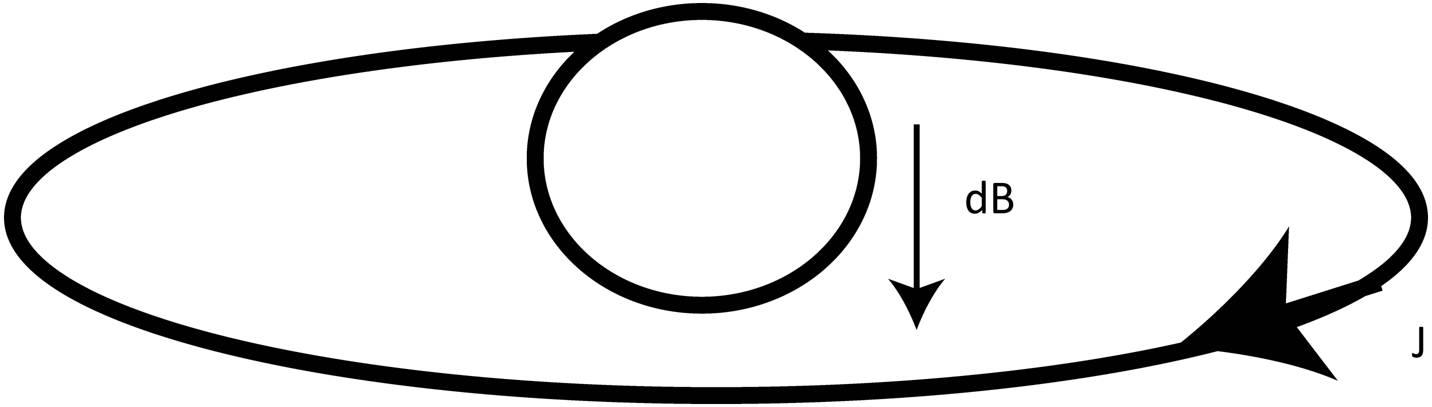






Energetic particles:
Ions to the west (dusk) and electrons to the east (dawn)

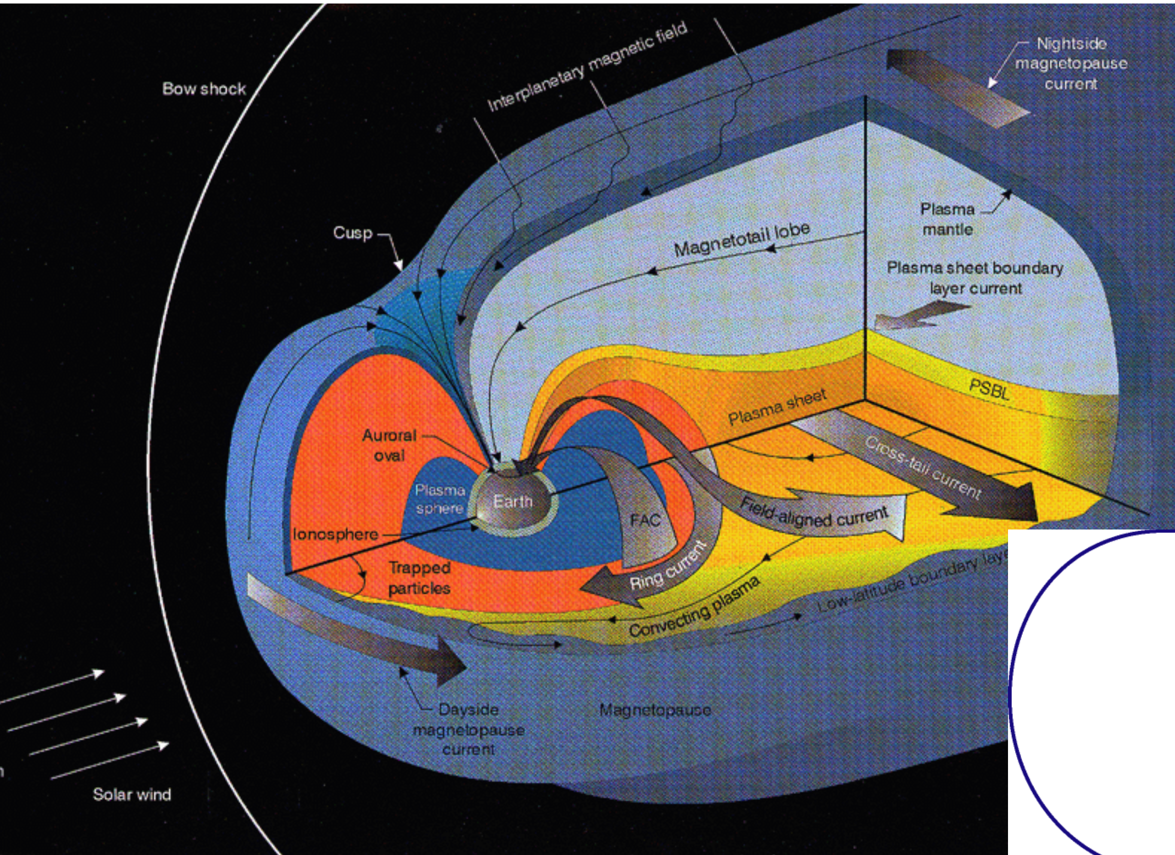
Ring current



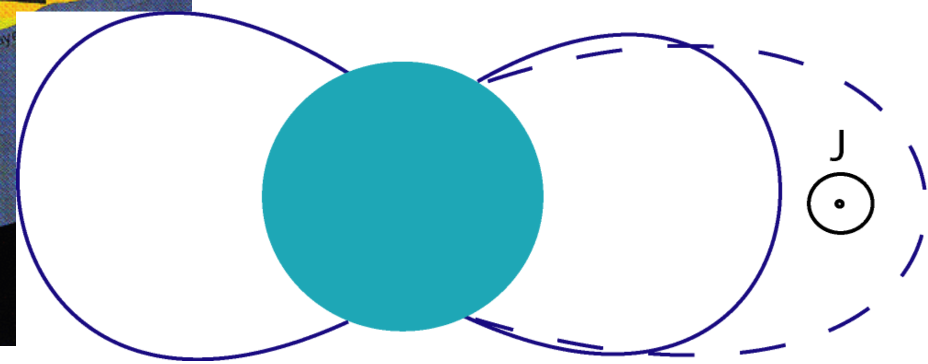
$$v_d = \frac{K}{qB^3} B \times \nabla B$$

Energetic ions

Tail current

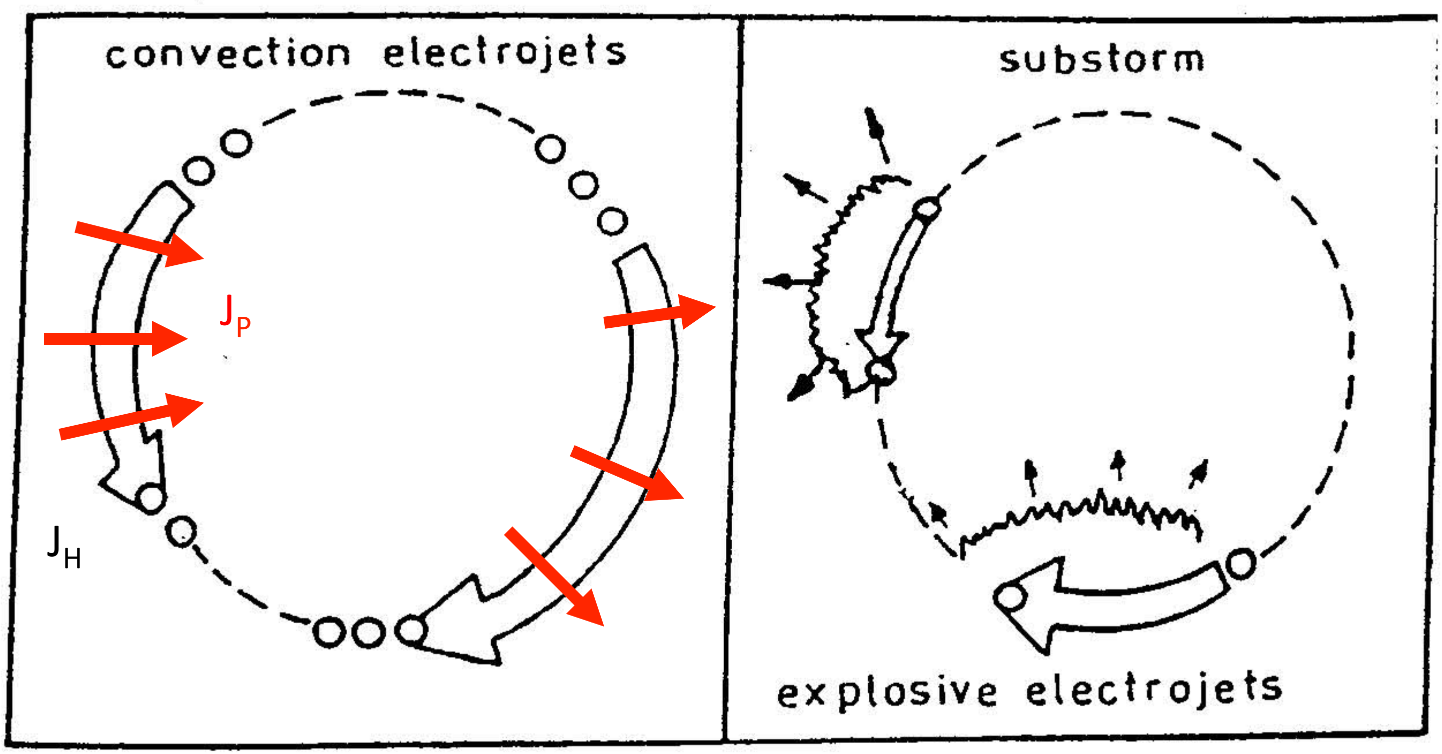


$$J = \frac{1}{\mu_0} \nabla x B$$



Tail current is consistent with the stretched configuration of the mangetotail
They close with the magnetopause currents

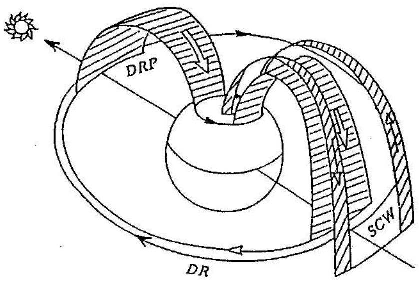
Polar ionospheric currents

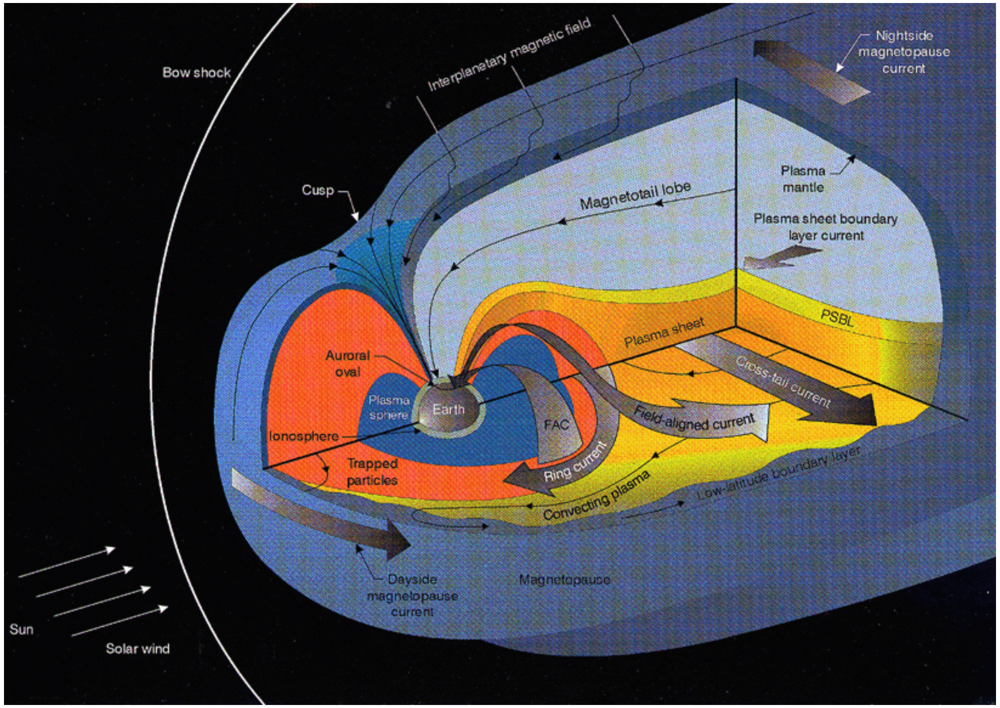


Hall currents – east-west, below 130 km

Pedersen currents – north- south, above 130 km

Birkeland currents (Field-aligned currents)





Field aligned currents are essential for the magnetosphere-ionosphere coupling

Birkeland currents (Field-aligned currents)

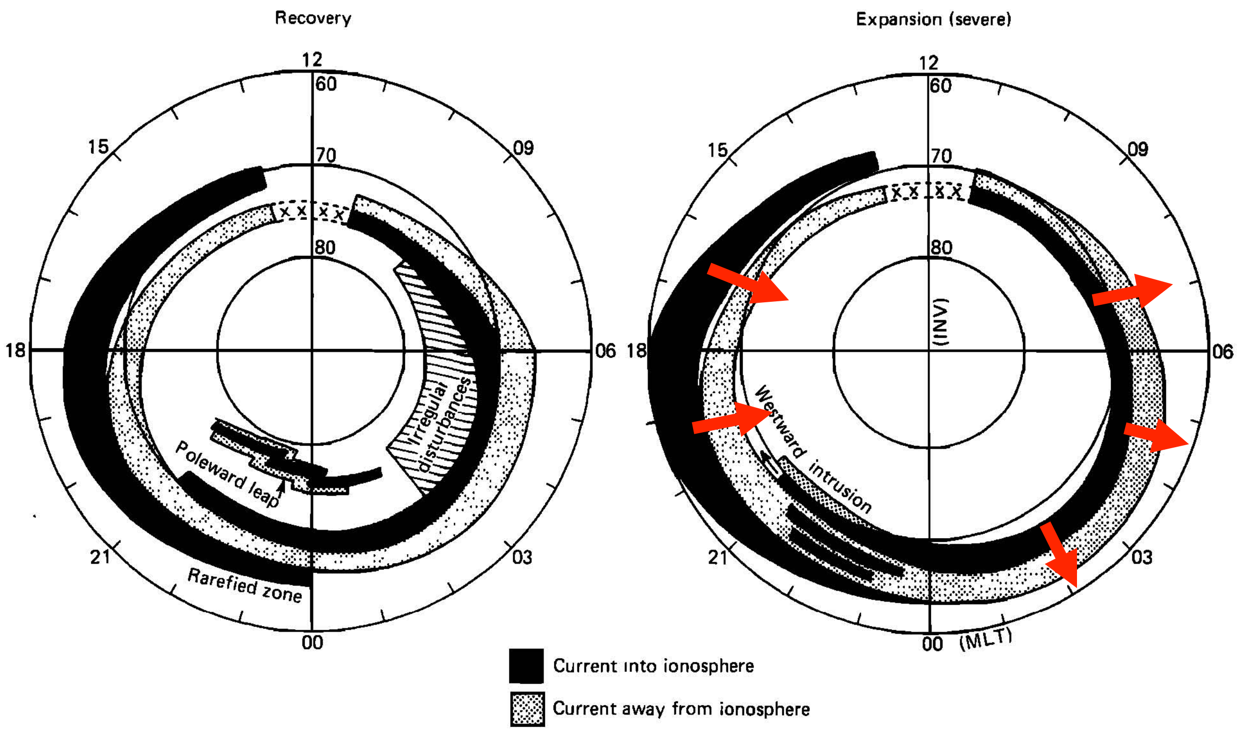
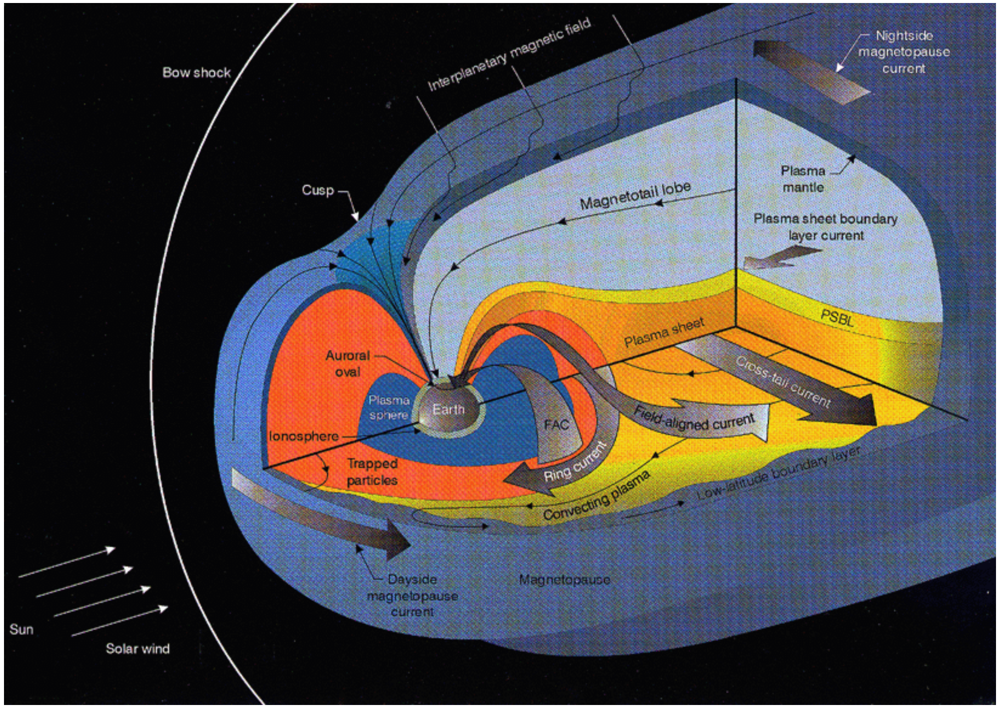


Fig. 15. Schematic diagram illustrating substorm-associated changes superimposed upon the basic distribution of field-aligned currents.

Field aligned currents are the magnetosphere-ionosphere coupling

North-south Pedersen currents will close these currents in the ionosphere

Birkeland currents (Field-aligned currents)



Birkeland region 1 current connects to the magnetpause currents

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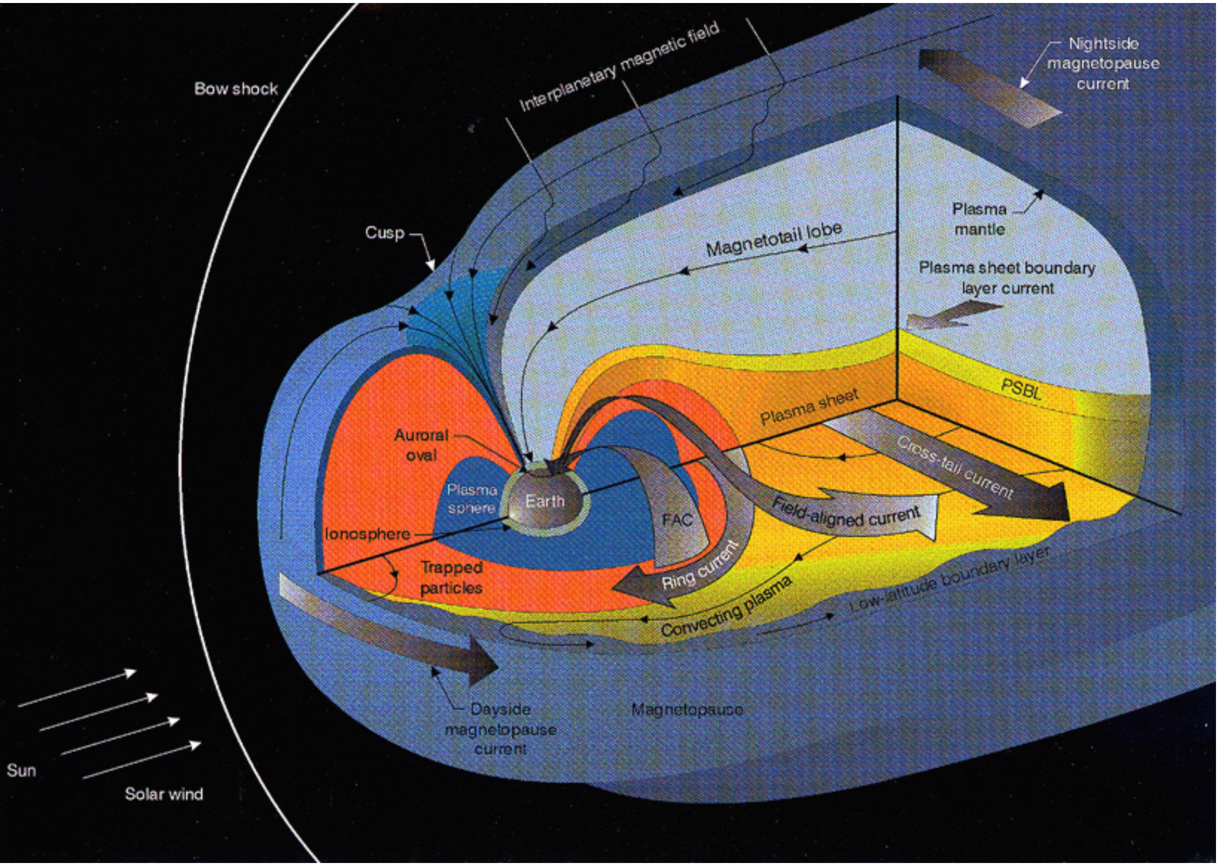
Repetition: Plasma and currents in the system

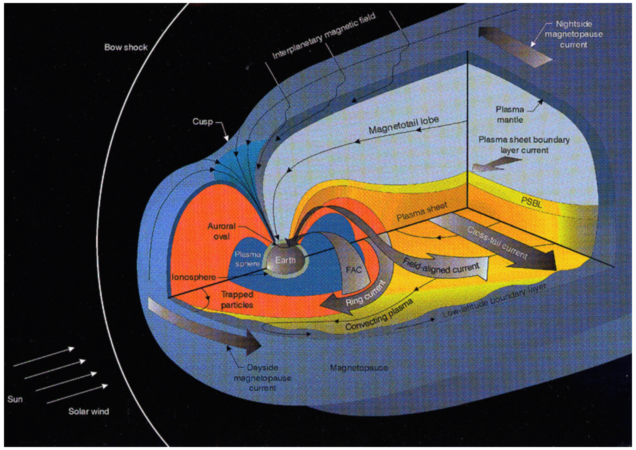


•Solar wind
•Magnetopause (boundary and current)
•Plasma sheet and magnetotail

•Magnetopause currents
•Ring current
•Tail currents
•Ionospheric currents: Pedersen and Hall
•Field aligned currents, Birkeland region 1 and 2

The source of energy:How much energy is available

$$U_{sw} = \frac{1}{2} \rho v^3 A$$



Kinetic energy is usually orders of magnitude
Larger than

- Magnetic energy
- Thermal energy

Remember: almost efficient shielding – only 1% into system

Entry of energy

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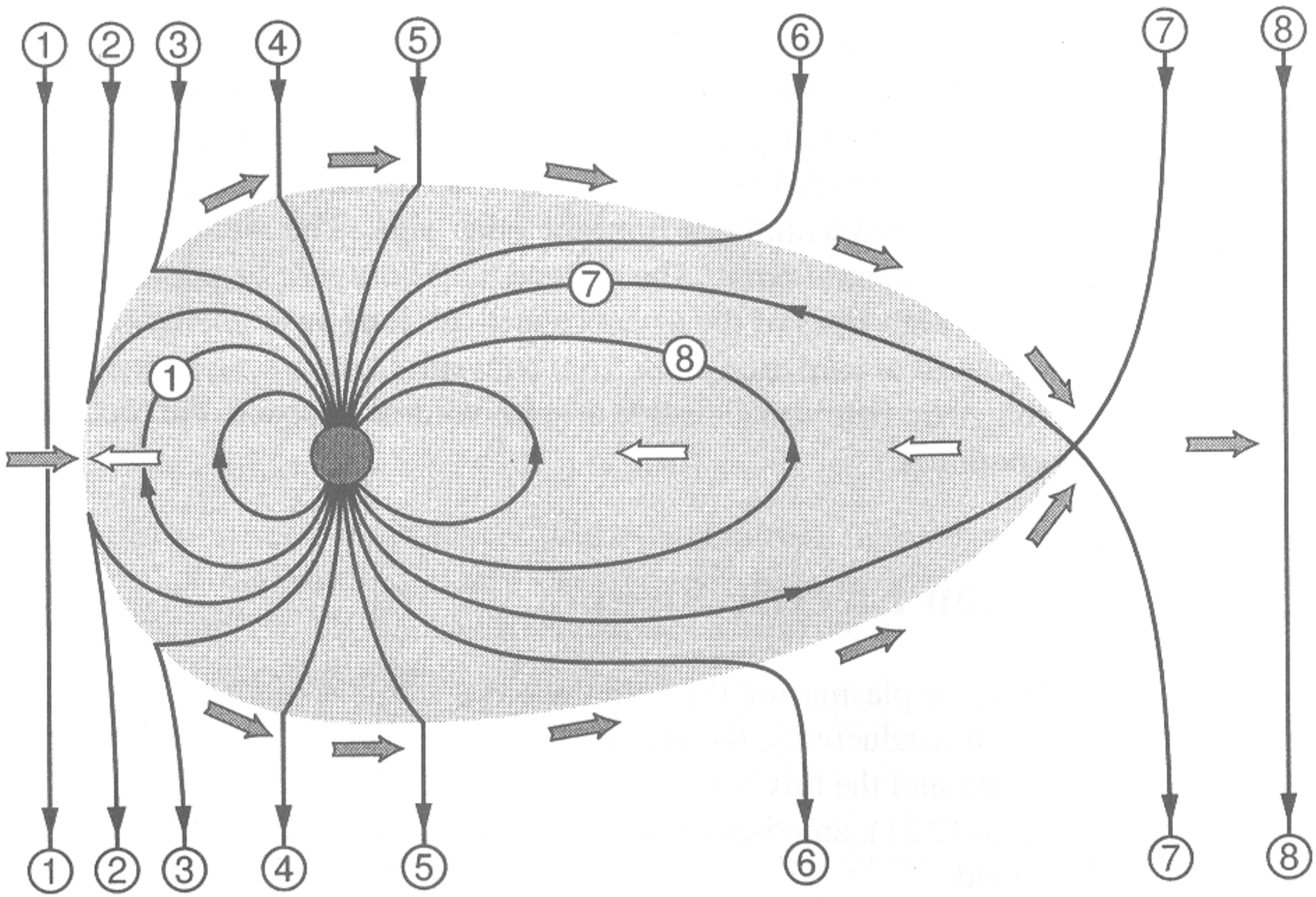
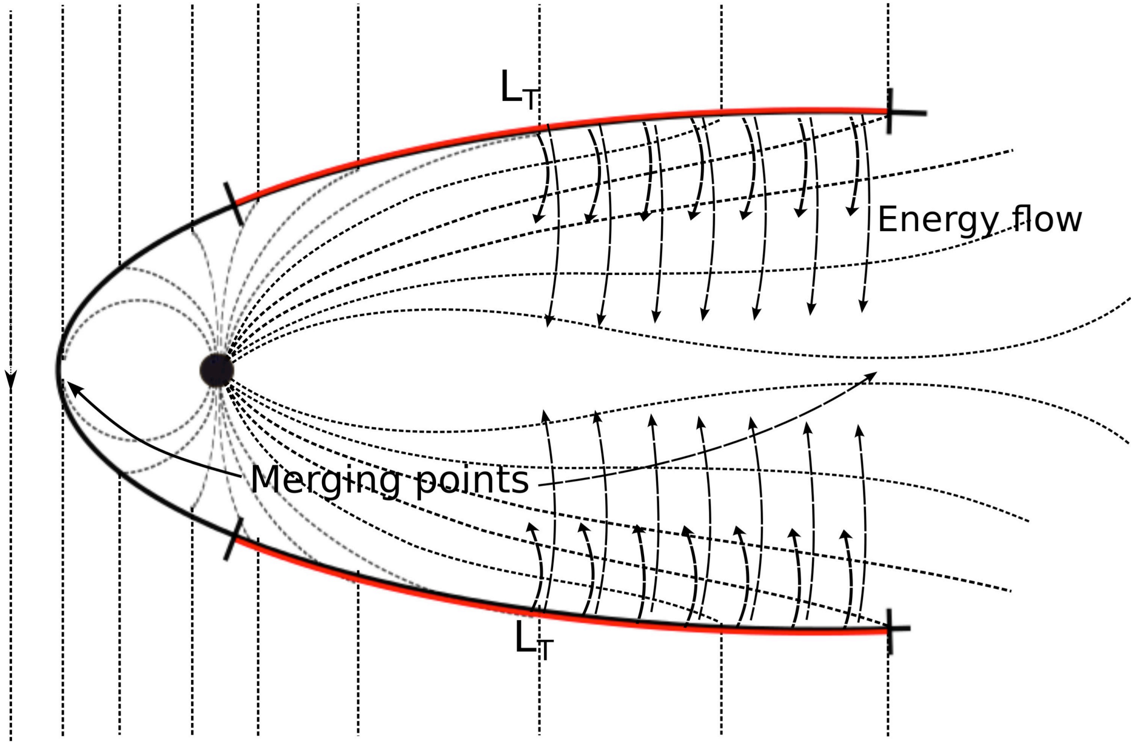
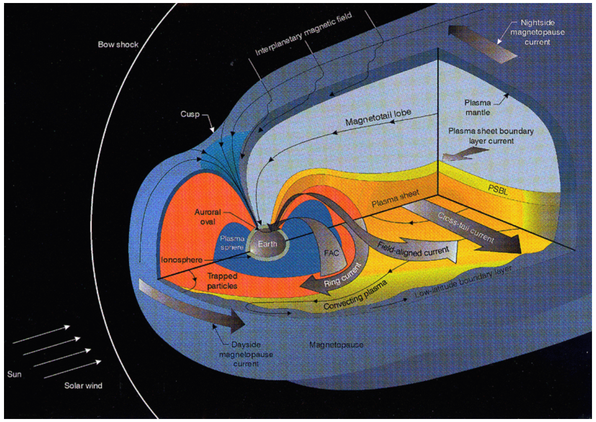
Dungey Cycle – reconnection, day and night



Solar wind dynamo – magnetic flux





On dayside: plasma on field lines is accelerated:

magnetic to kinetic energy

On nightside – tail: Plasma on field lines is de-accelerated

kinetic to magnetic energy – and stretched tail

induces a tail current

Reconnection : magnetic and kinetic energy into the closed system

Current on magnetopause

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Out of the plane

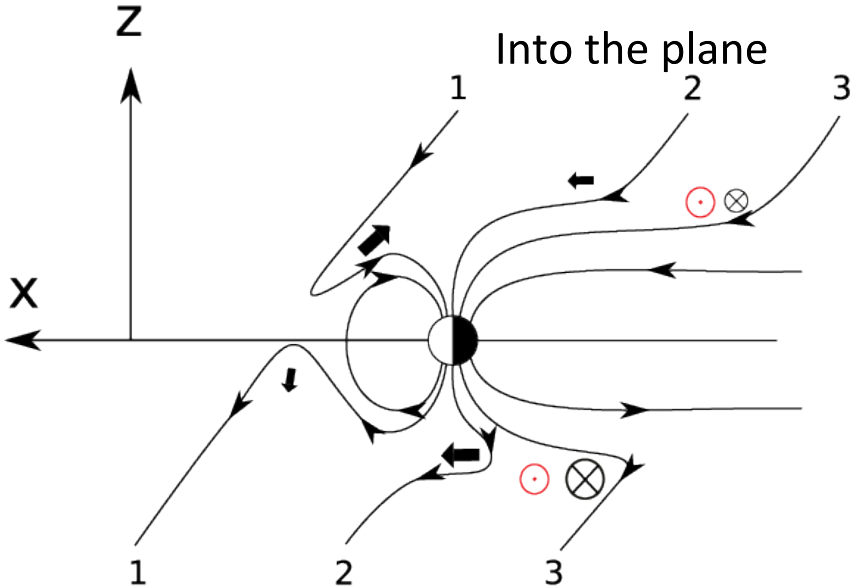
IMF $B_x > 0$

IMF $B_z < 0$

$\odot = \mathbf{E} = -\mathbf{v} \times \mathbf{B}$

$\otimes = \delta \mathbf{j}_\perp = \frac{\rho \mathbf{B} \times \frac{d\mathbf{v}}{dt}}{B^2}$

Into the plane



$$\rho \frac{\mathrm{dv}}{\mathrm{dt}} = \mathrm{J} \times \mathrm{B} \qquad \times B$$

Only perpendicular component

$$J = \frac{B \times \rho \dfrac{dv}{dt}}{B^2}$$

$E \bullet J < 0$ *Also dynamo*

Current and dynamo

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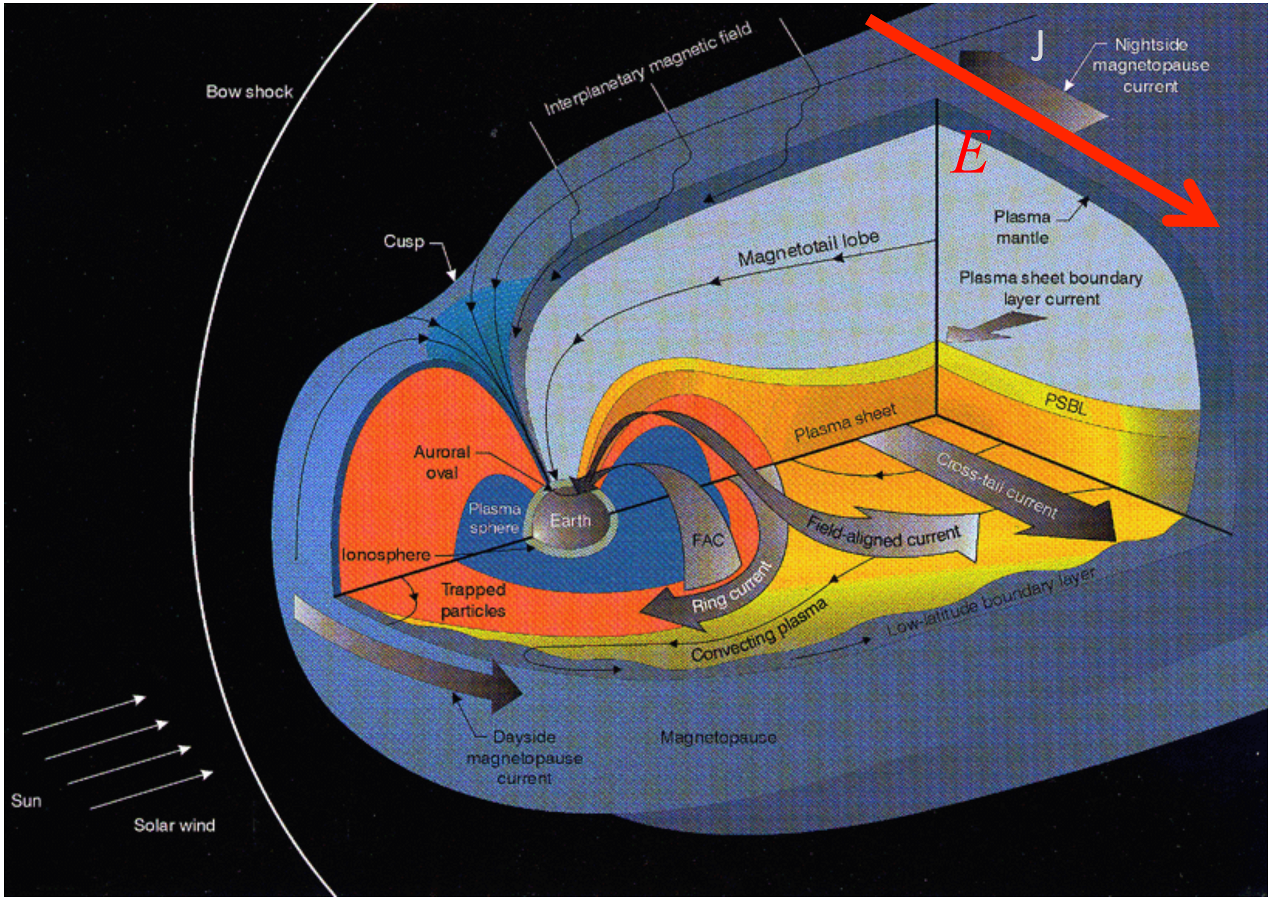

E and J opposite on the nightside magnetopause

Solar wind energy transfer function

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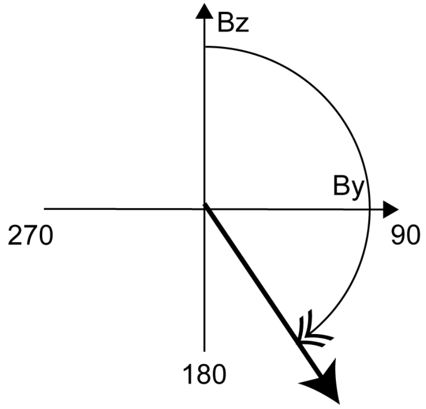
EPSILON-parameter, Perrault and Akasofu 1978, derived from Poynting Flux:

Poynting flux $$S = \frac{1}{\mu_0} ExB$$

$$\varepsilon = \int S dA = vB^2 F(\theta) l_0^2$$

Clock angle $[\theta_c]$



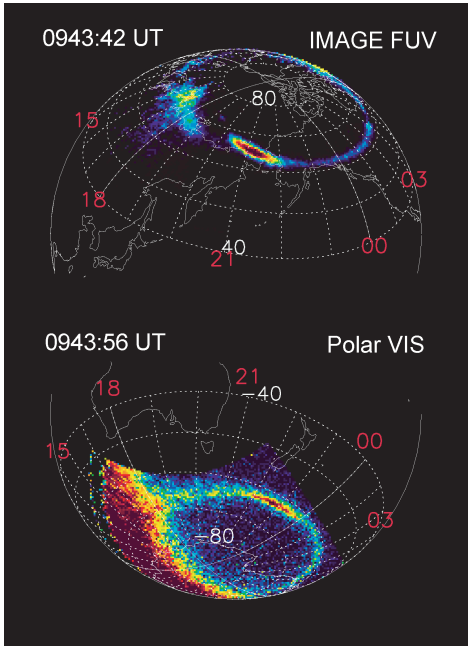
$$\theta = a\tan\left({B_y}/{B_z} \right)$$

$$\varepsilon = 10^7 vB^2 \sin^4\left(\frac{\theta_c}{2}\right) l_0^2$$

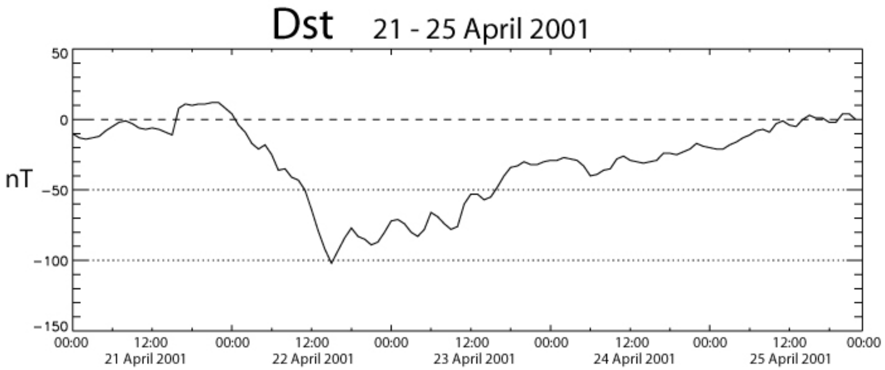
l_0 (=7Re) and F(θ) is determined empirically
Needs to be improved

Two main system processes to deposit stored energy

Substorms – aurora and increase of Aurolar Electrojet index – typical hour(s)



Geomagnetic storm – increase of ring current and Dst index Typical days



The three main energy sinks

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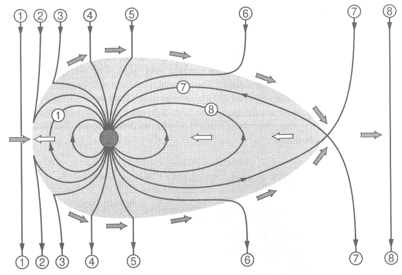
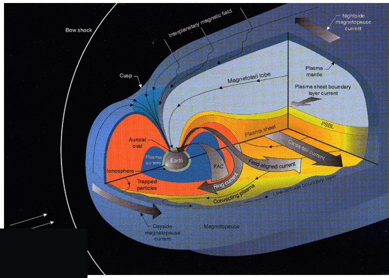
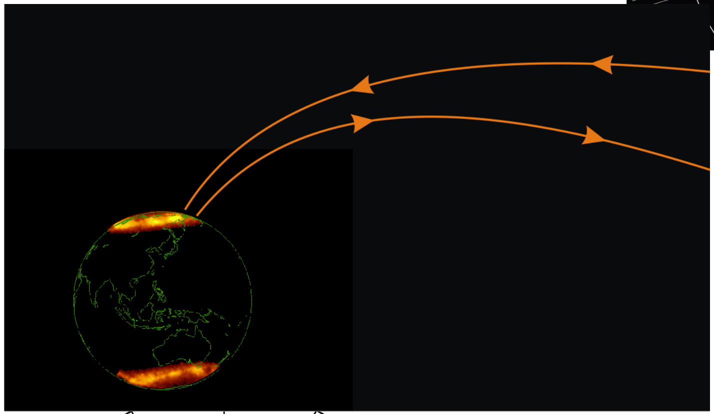
1. Injection and increase of RING CURRENTS



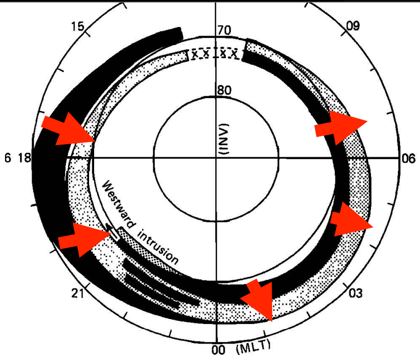
$$v_d = \frac{K}{qB^3} B \times \nabla B$$



2. PRECIPITATING particles into the upper atmosphere



3. JOULE HEATING – Pedersen currents (along E-field, a load)



$$E \bullet J > 0$$

Outline

BIRKELAND CENTRE FOR SPACE SCIENCE

Plasma regions in the magnetosphere

- Overview of the plasma regions in the Earth's magnetosphere
- Magnetopause – magnetic shielding and pressure balance
- Plasma sheet and magnetotail

Currents in the magnetosphere and ionosphere

- Magnetopause currents
- Ring current
- Tail currents
- Ionospheric currents: Pedersen and Hall
- Field aligned currents, Birkeland region 1 and 2

The Energy flow the Earth's magnetosphere/ionosphere,

- Available energy in the solar wind
- Reconnection, the solar wind dynamo and the epsilon parameter

The energy sinks in the system

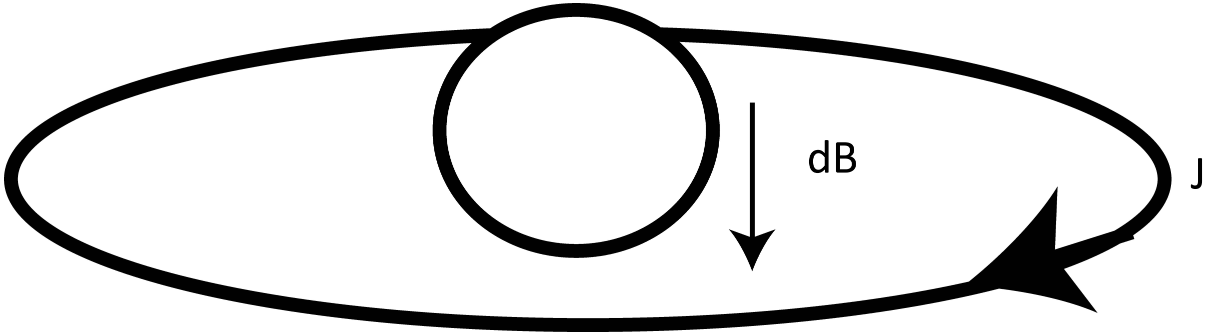
- Ring current increase (UR) – Dst index
- Joule heating of the ionosphere (UJ) – AE index
- Particle precipitation (UA) – AL index

Energy budget

- Short intervals
- For12 years
- New energy coupling function

1. Energy sink: Ring Current and Dst

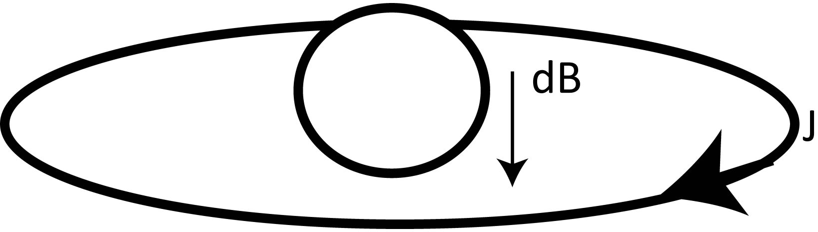
BIRKELAND CENTRE FOR SPACE SCIENCE

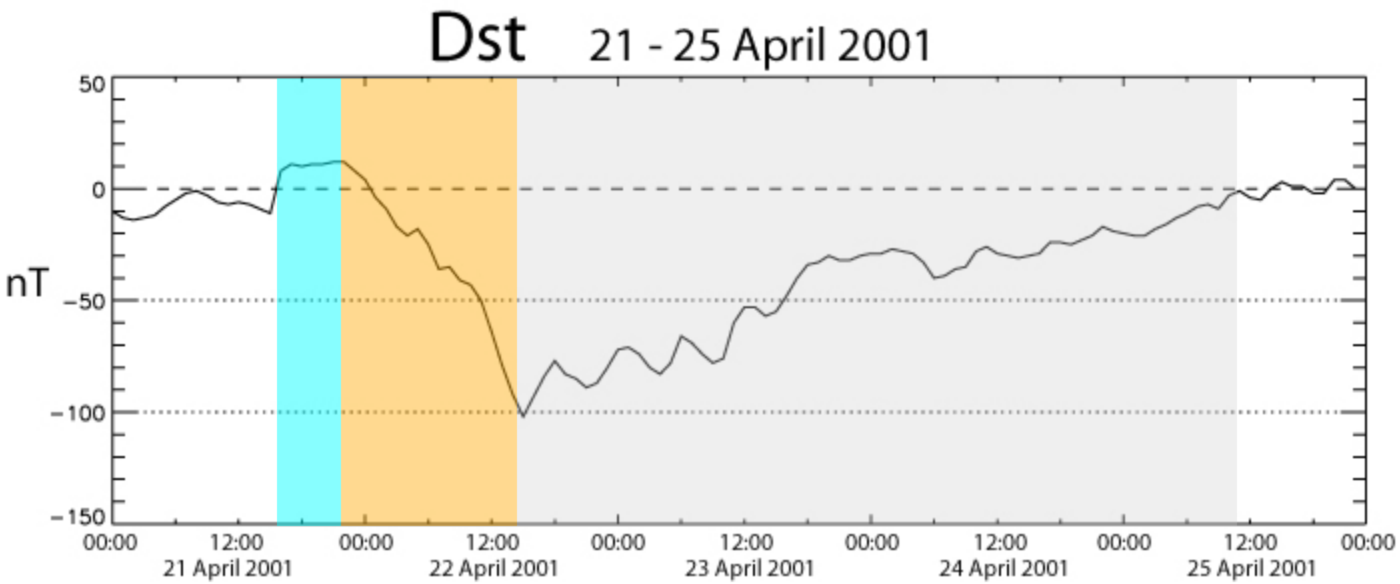


Dst is the average of magnetic dB
at 4 stations located close to magnetic equator

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}(\vec{r}-\vec{r}\,')\times(\vec{r}-\vec{r}\,')}{(\vec{r}-\vec{r}\,')^3} d^3 r'$$

Magnetic index: Dst, magnetic storm



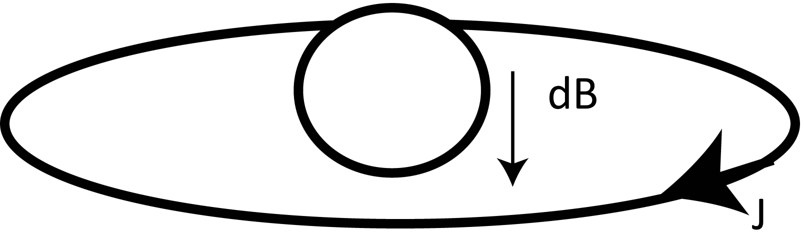


Magnetopause current

Loss of ring current, recovery

Injection to ring current

Ring Current energy increase estimates



$$J = \frac{1}{\mu_0} \nabla x B$$

Dst is the average of magnetic dB
at 4 stations located close to magnetic equator

First Energy sink:
RING CURRENT energy increase

$$U_R = 4 \times 10^4 \left(\frac{dDst^*}{dt} + \frac{Dst^*}{\tau} \right)$$

Pressure corrected

$$Dst^* = Dst - \Delta H(p)$$

Ring Current energy increase estimates

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$$\frac{dK}{dt} = U_R - \frac{K}{\tau}$$

Change of energy in ring current

$$v = \frac{K}{qB^3} B x \nabla B$$

Drift for one particle

$$I = qvN \propto K_{Total}$$

$$\Delta B = D_{st} \propto I \propto K_{Total}$$

$$\frac{dDst}{dt} = Const \cdot (U_R - \frac{Dst}{\tau})$$

$$U_R = 4 \times 10^4 \left(\frac{dDst^*}{dt} + \frac{Dst^*}{\tau} \right)$$

Pressure corrected

$$Dst^* = Dst - \Delta H(p)$$

Loss of ring current

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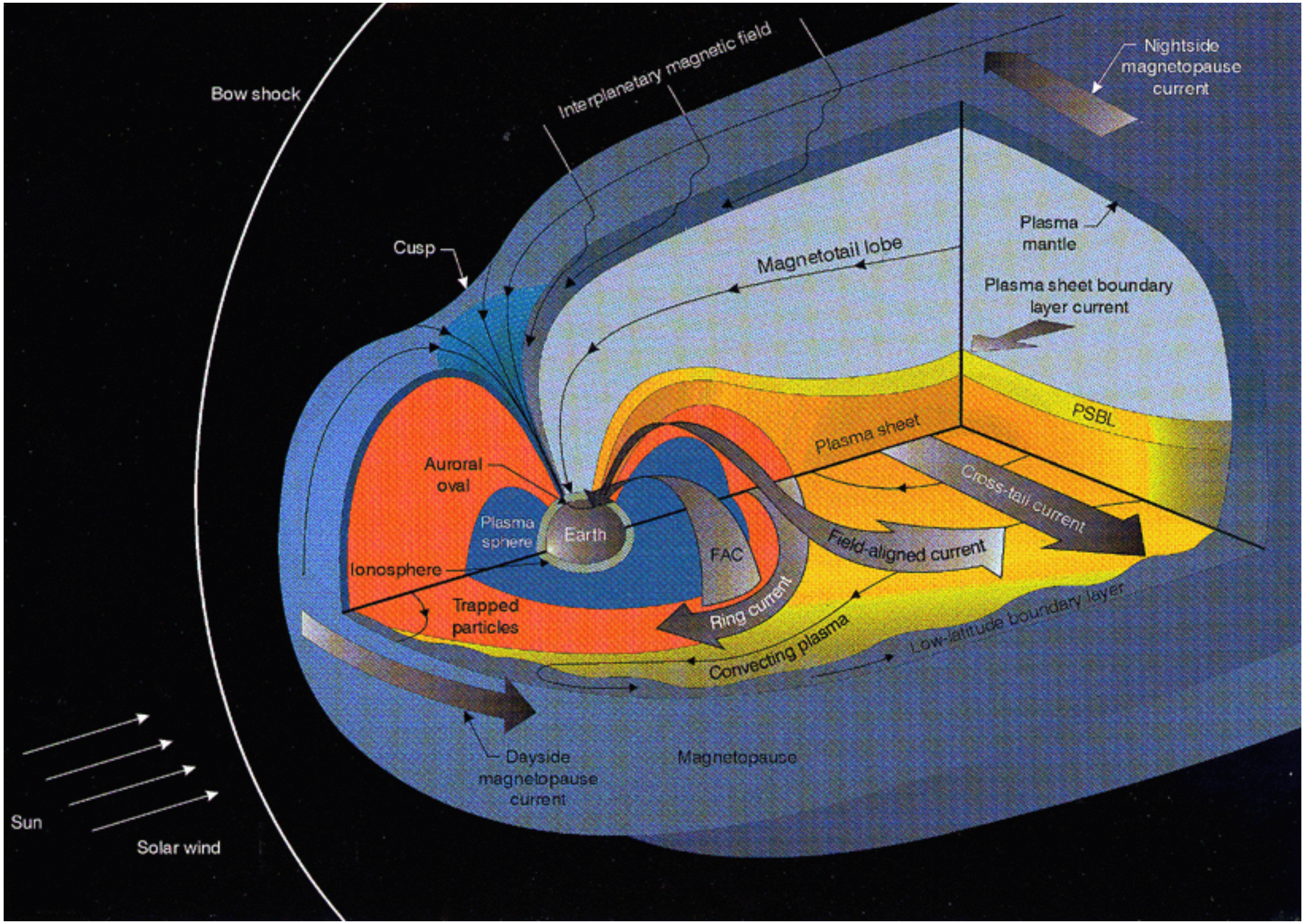
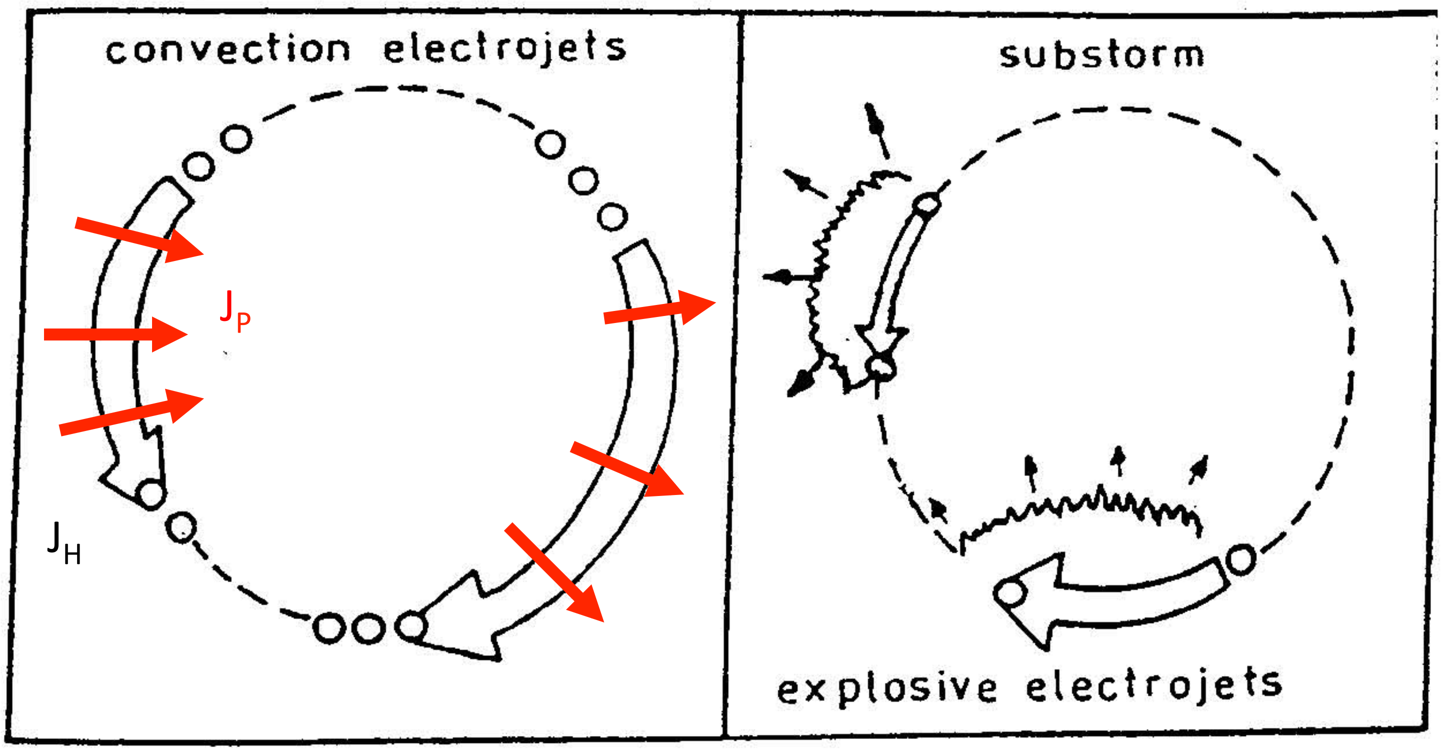


1. Convection
2. Charge exchange
3. Wave-particle interaction

2. Energy sink: Joule heating



Pedersen currents – north- south, above 130 km in same direction as electric field

$$Uj = J \cdot E$$

Auroral Electrojet (AE) index

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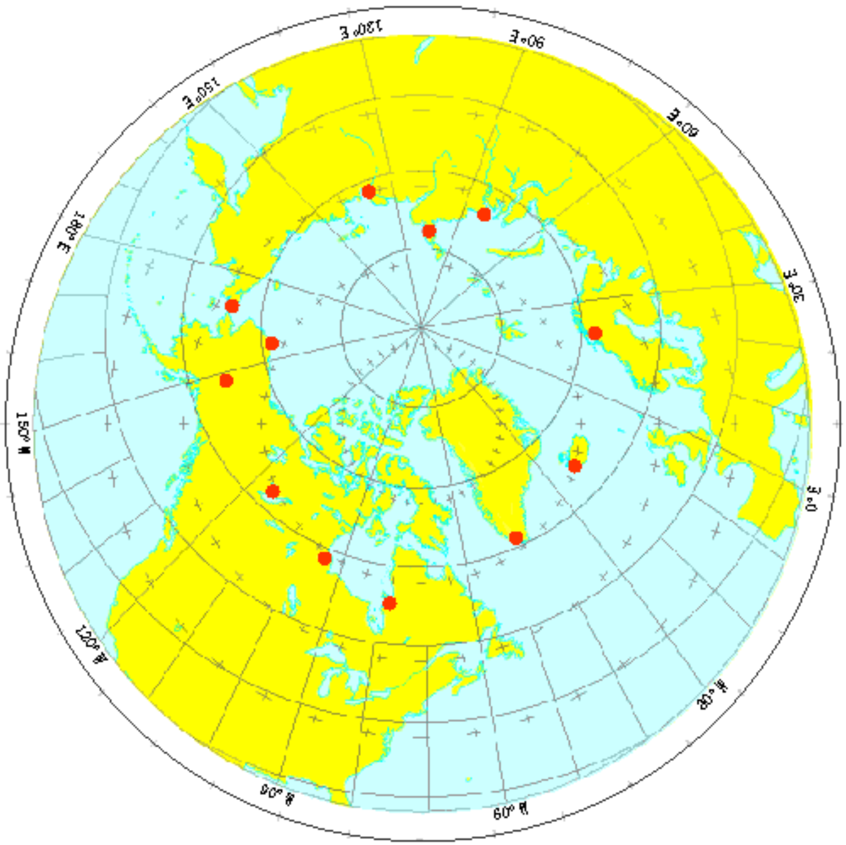
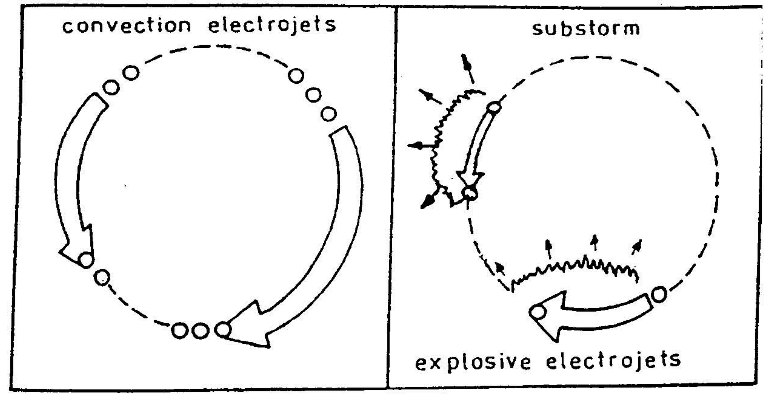
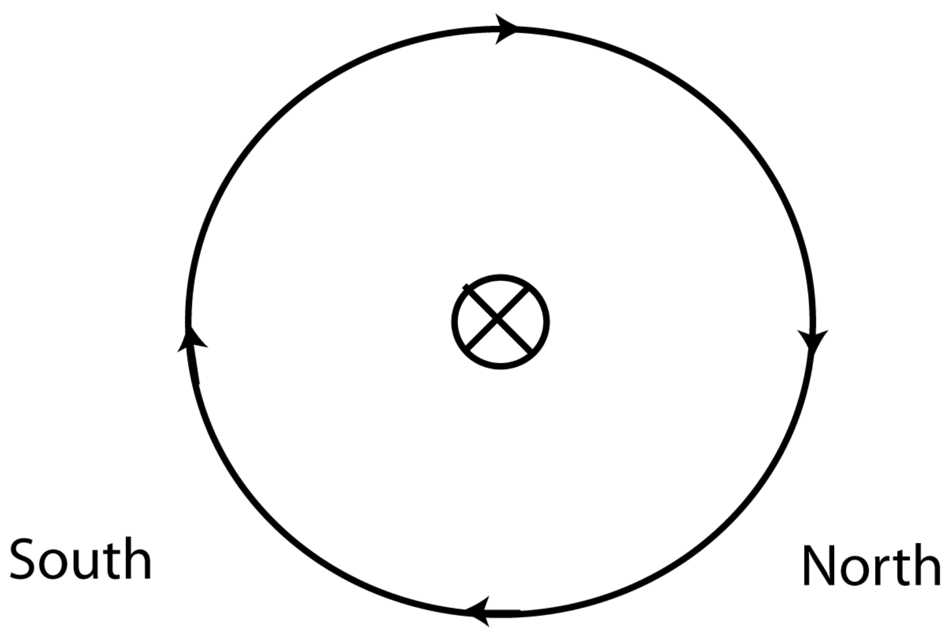
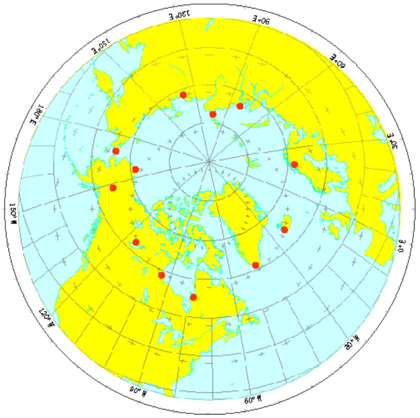


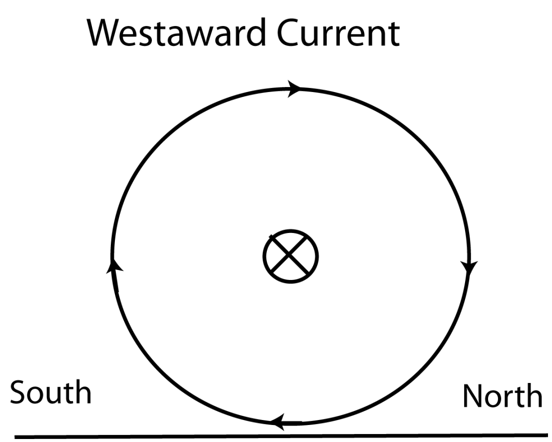


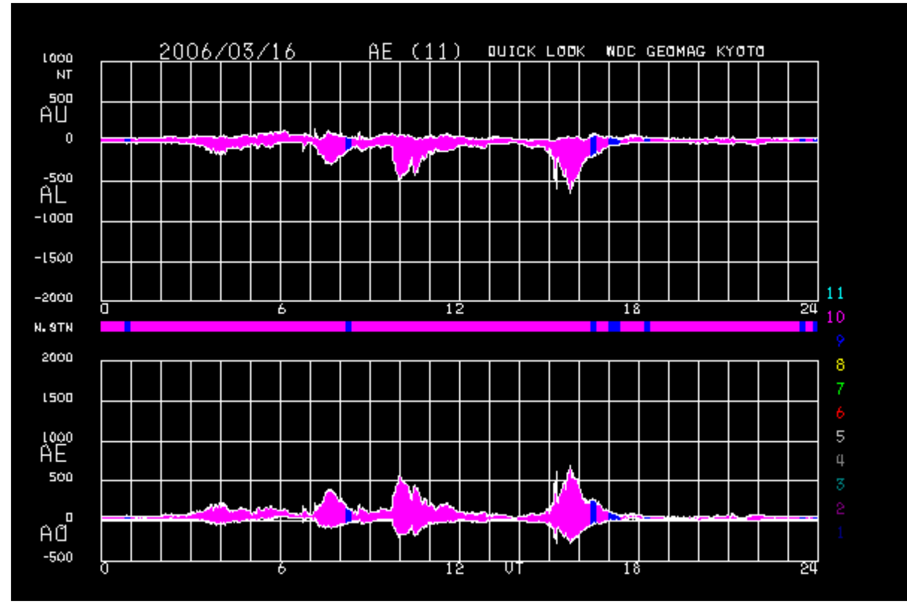
Westaward Current



2. energy sink: Joule heating (Uj) using AE index







AE is an index for westward and eastward currents in the auroral oval.
Many studies have established relations between Uj and AE.

JOULE HEATING rate

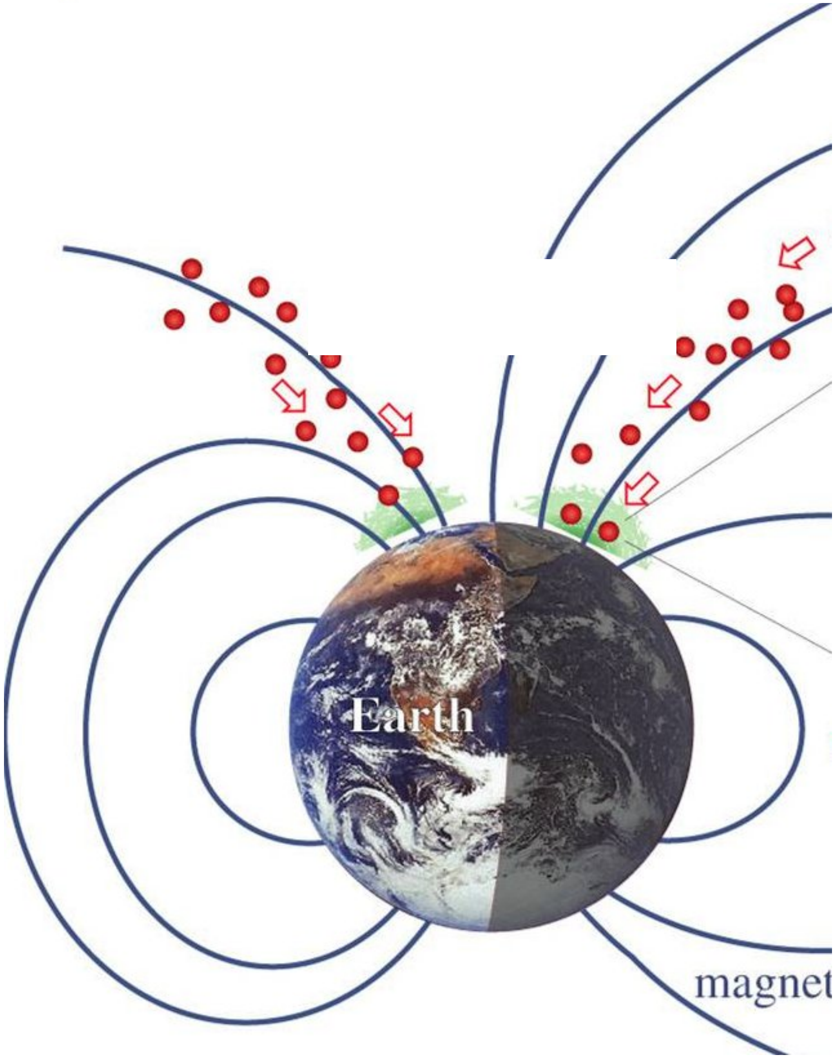
$$Uj = J \cdot E$$

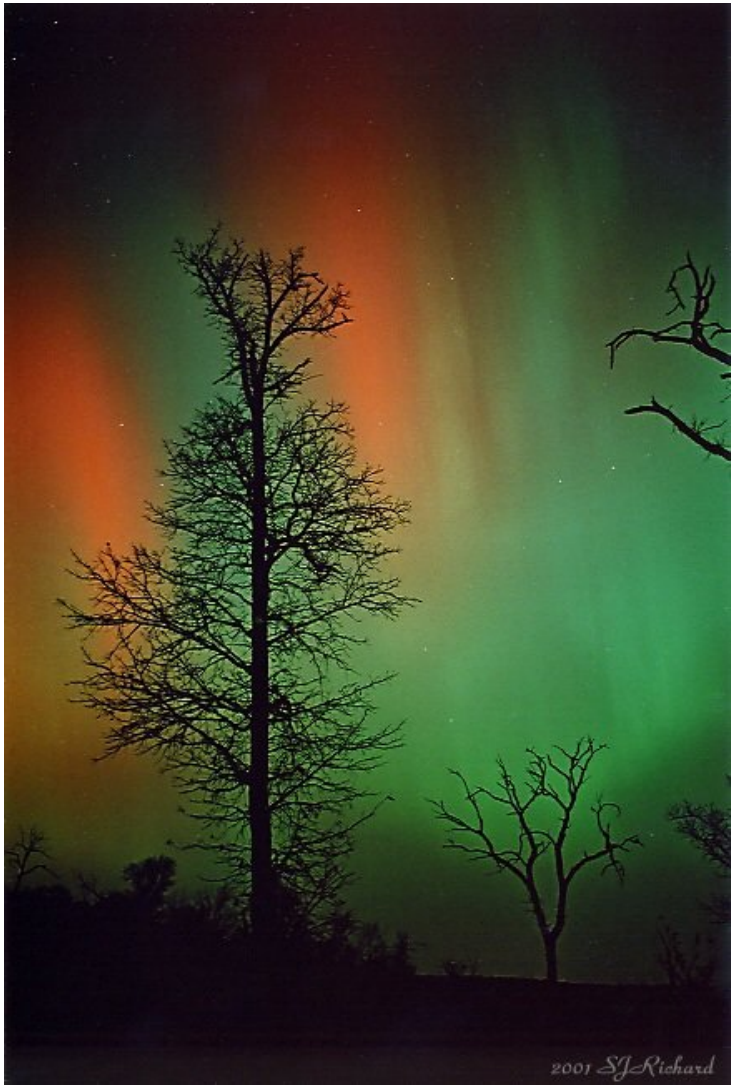
Both hemispheres – solstice:

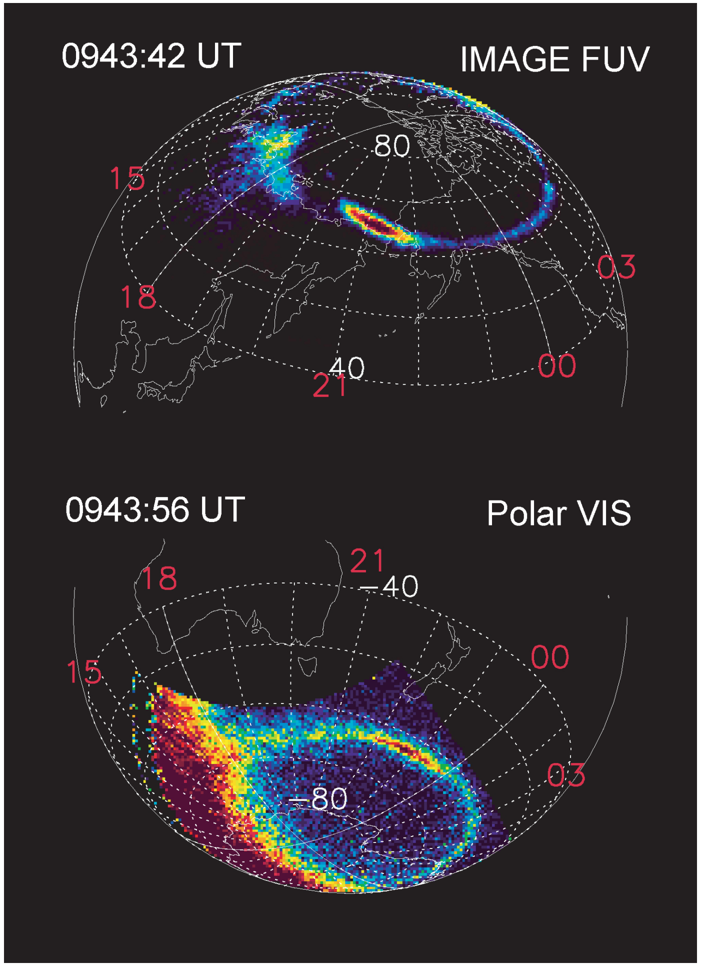
$$U_J = 0.54AE + 1.8$$

3. energy sink: Particle precipitation

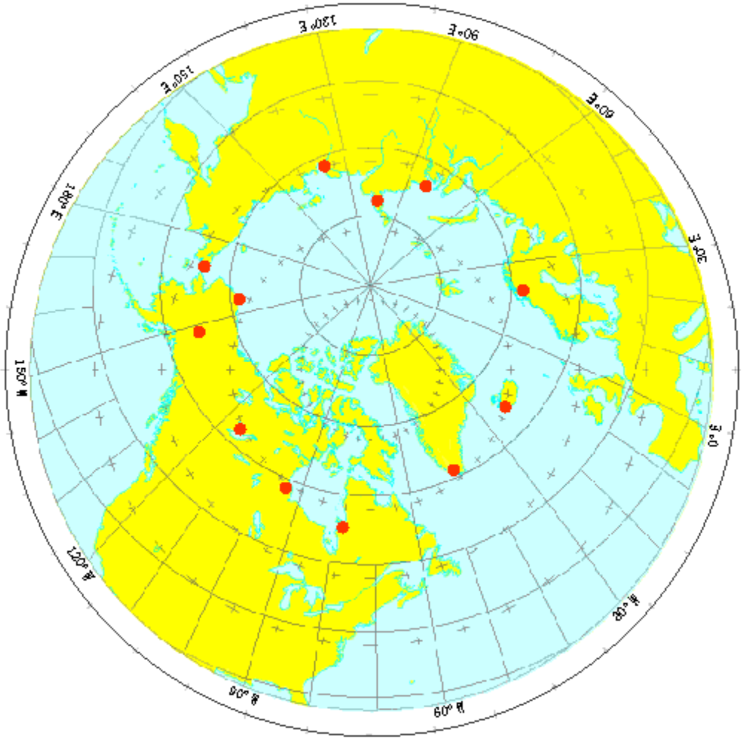
BIRKELAND CENTRE FOR SPACE SCIENCE







Stations for AE, AU, AL



$$U_A = 4.4\sqrt{AL} - 7.6$$

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The energy transfer rates - summarize

BIRKELAND CENTRE FOR SPACE SCIENCE

Solar wind - magnetosphere - ionosphere system:

1) Available SOLAR WIND kinetic energy

$$U_{SW} = {}^{1}\!/_{2}\, \rho \cdot v^{3} A$$

2) The energy transfer function (ε-parameter) :

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

The three main energy sinks:

3) RING CURRENT energy increase

$$U_R = 4 \times 10^{4}\left(\frac{dDst^{*}}{dt} + \frac{Dst^{*}}{\tau}\right)$$

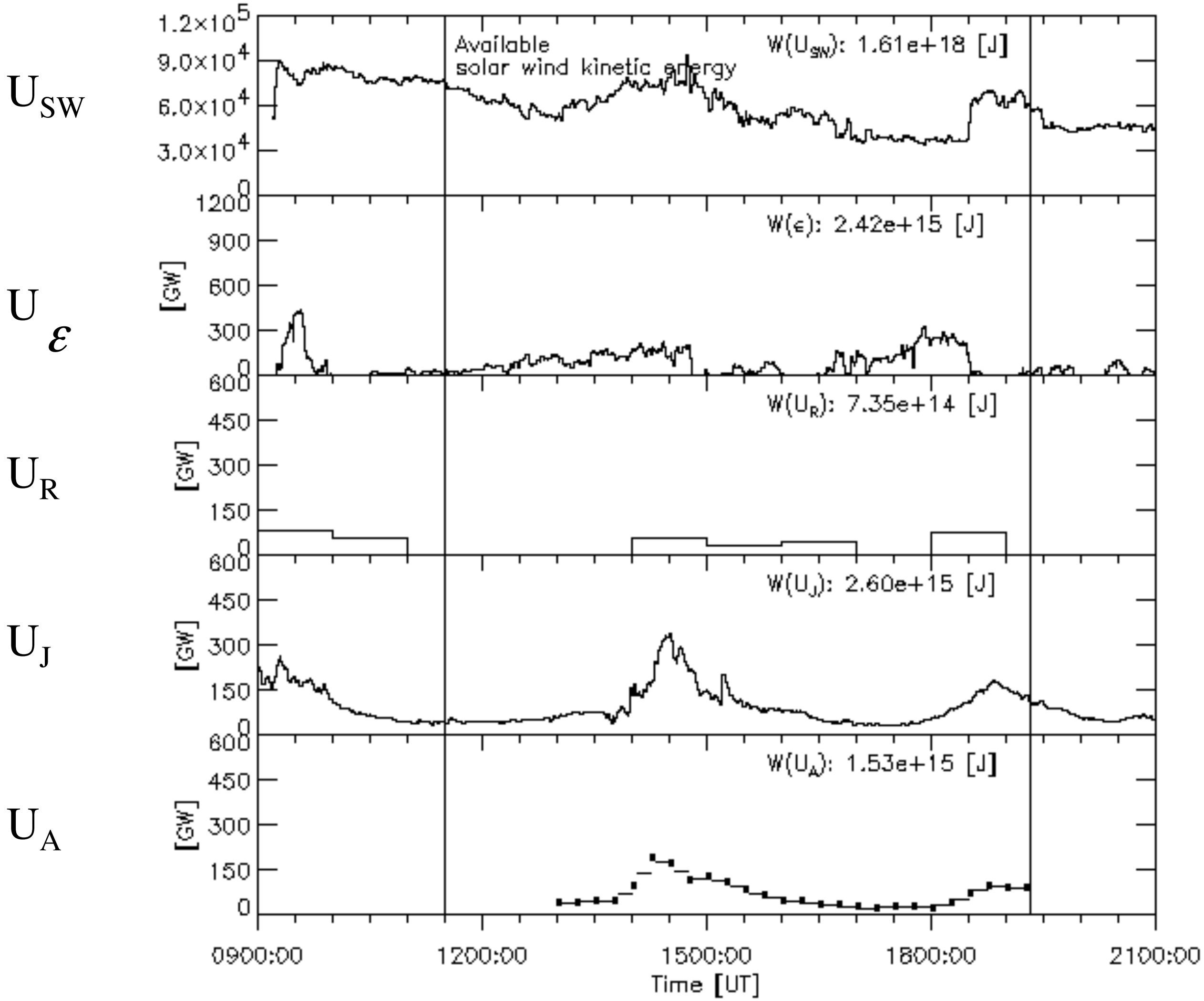
4) Global AURORAL PRECIPITATION (both hemispheres)

$$U_A = 4.4\sqrt{AL} - 7.6$$

5) JOULE HEATING rate (both hemispheres at solstice)

$$U_J = 0.54 AE + 1.8$$

Energy input/output for July 24, 1997



Energy sinks - distribution

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Substorms and geomagnetic storms

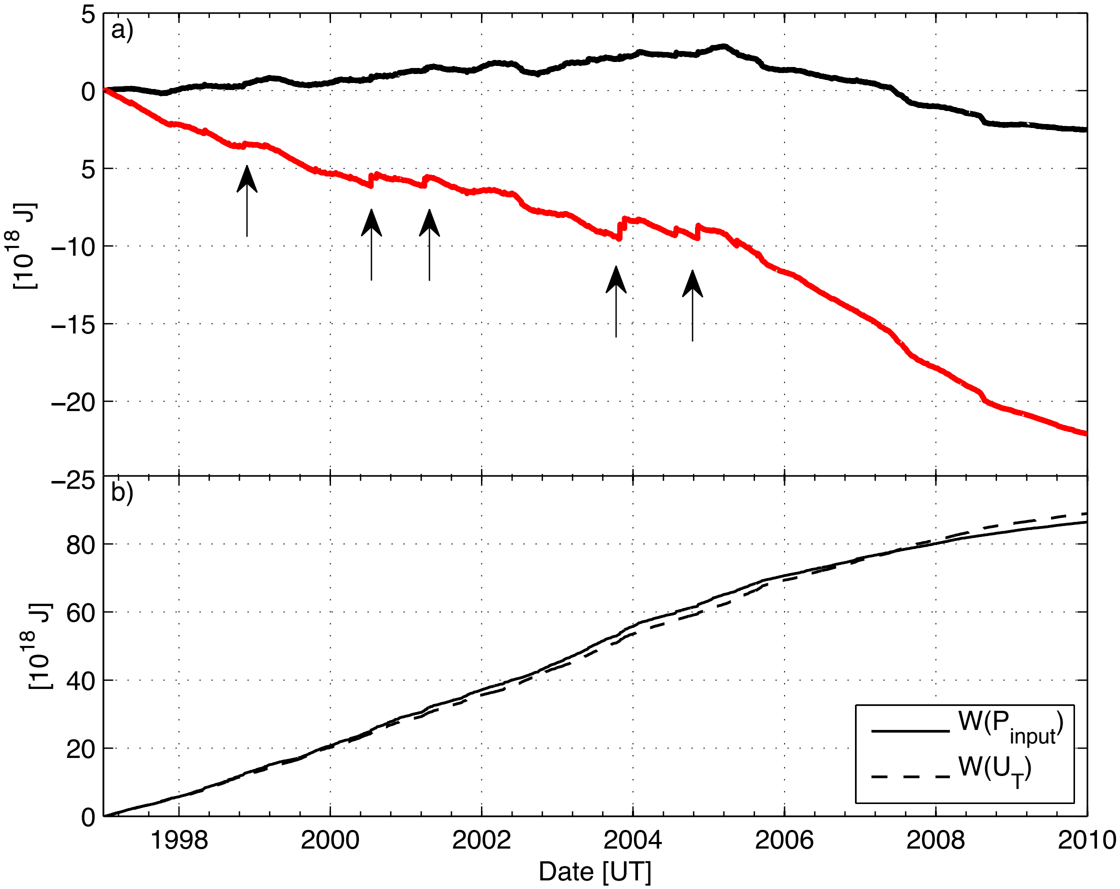
- Typically - The **ionospheric energy sinks dominate**:

  U_J: 55%
  U_A: 30%
  U_R: 15%

- The coupling efficiency: 0.3-0.9% of the total available solar wind kinetic energy is deposited to the MI system

$$Eff = \frac{U_{RC} + U_J + U_A}{U_{SW}}$$

Energy coupling function



$$W(t) = \int_{t_1}^{t} [\varepsilon(t) - U_T(t)]dt$$

$$\varepsilon = 10^7 vB^2 \sin^4\left(\frac{\theta_c}{2}\right) l_0^2$$

12 year of data, red is epsilon

Improved energy coupling function

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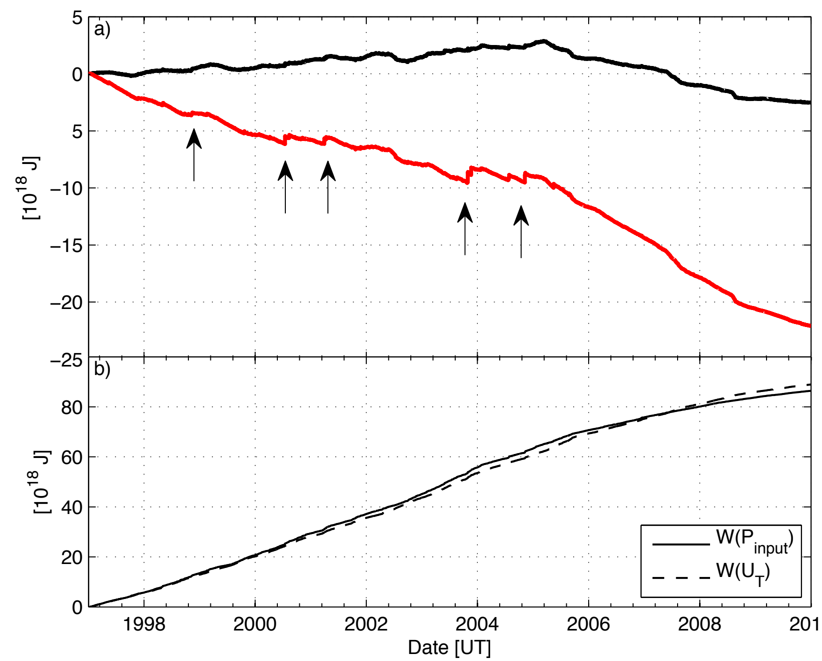

$$\varepsilon = 10^{7}\, vB^{2} \sin^{4}\left(\frac{\theta_c}{2}\right) l_0^{2}$$

$$P = \frac{vB^{2}}{\mu_0} M_A \sin^{4}\left(\frac{\theta_c}{2}\right) \frac{167}{5\times 10^{22}\left|B_z\right|^{3} + 1} R_E^{2}$$

Tenfjord and Østgaard, 2013 - JGR

Summary

BIRKELAND CENTRE FOR SPACE SCIENCE

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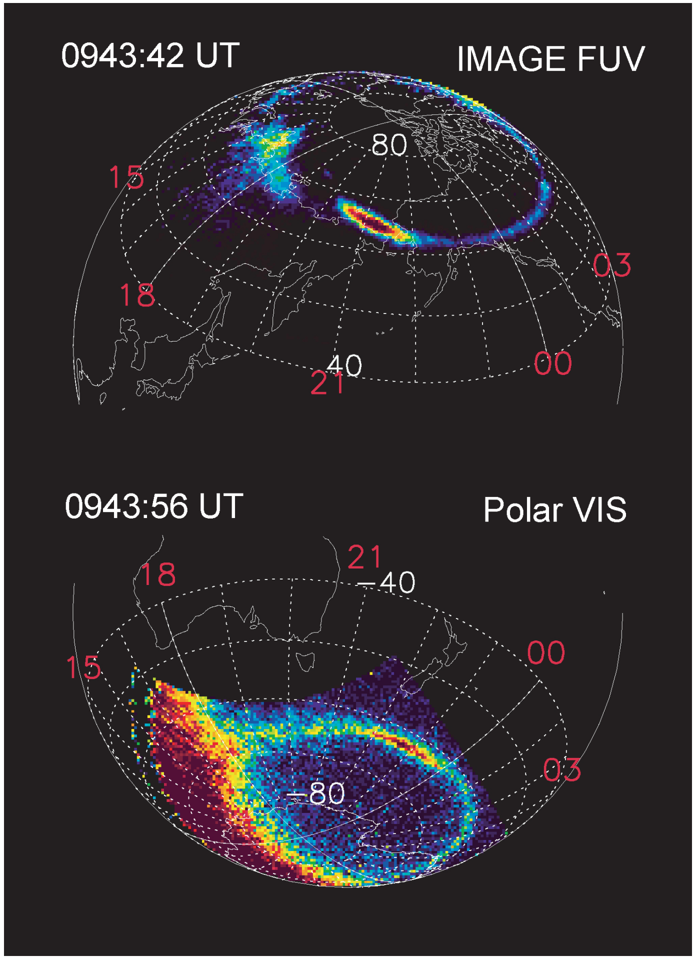
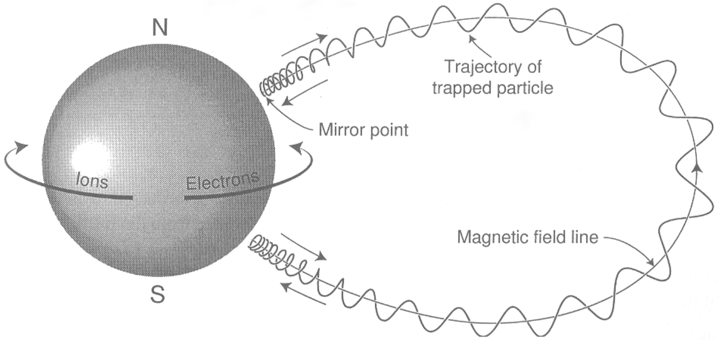
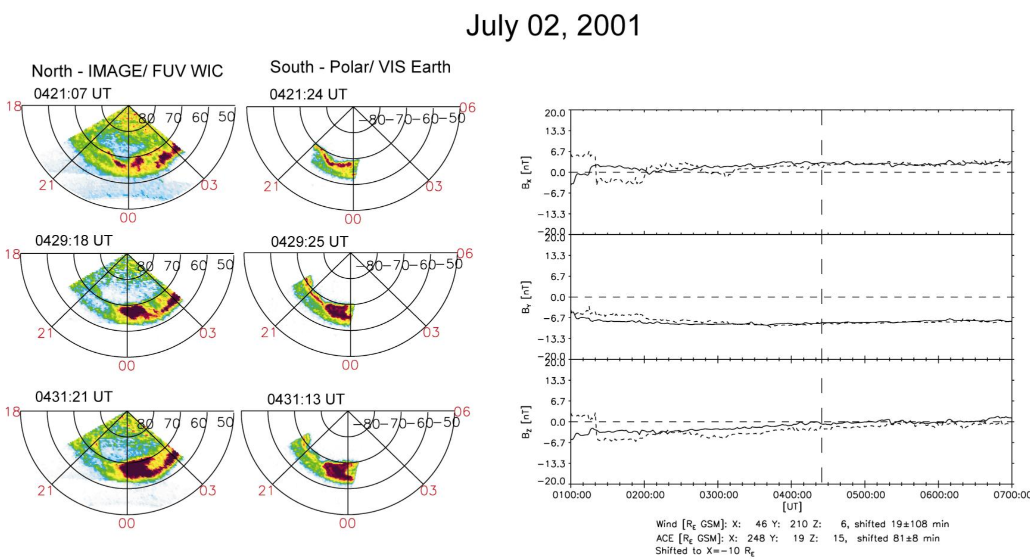
Asymmetries between hemispheres



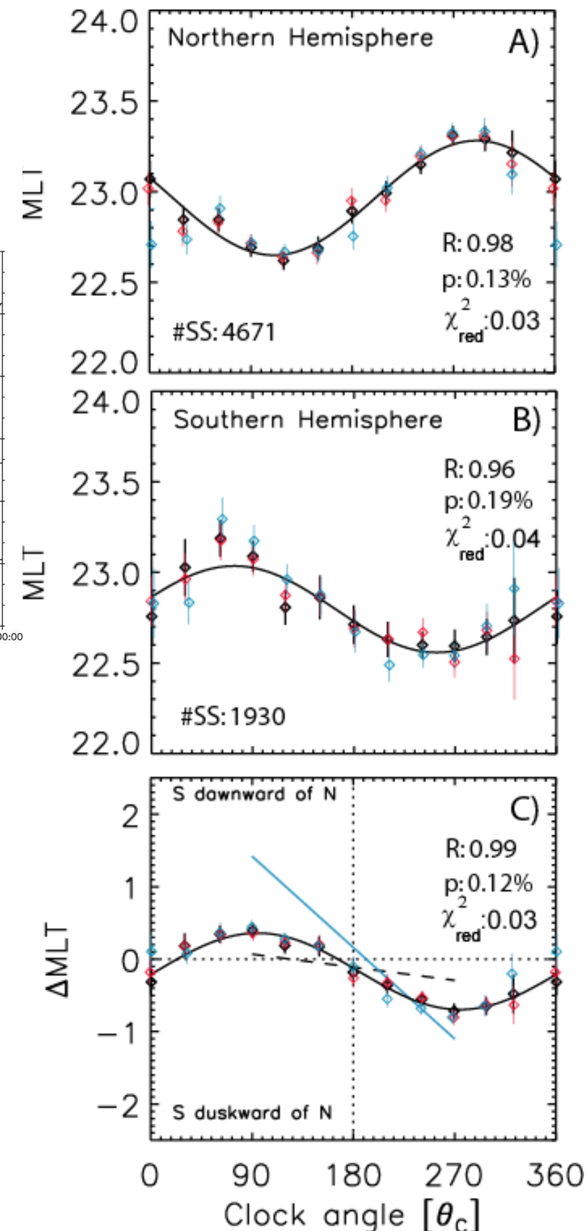


Substorm onsets have asymmetric location

Asymmetries substorm location



IMF
Penetrate
The closed
magnetosphere



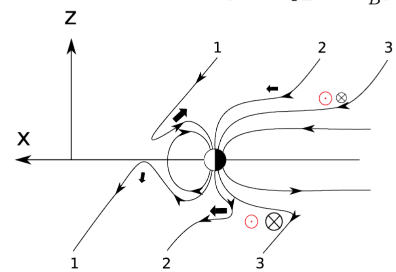
Complete asymmetric aurora

Three candidates for asymmetric Aurora/currents

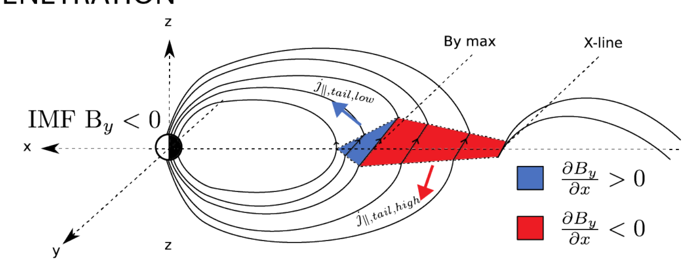
SOLAR WIND DYNAMO

IMF $B_x > 0$ — $\odot = \mathbf{E} = -\mathbf{v} \times \mathbf{B}$

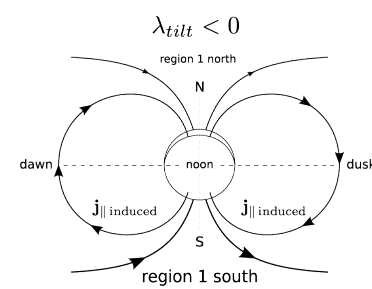
IMF $B_z < 0$ — $\otimes = \delta \mathbf{j}_\perp = \frac{\rho \mathbf{B} \times \frac{d\mathbf{v}}{dt}}{B^2}$



IMF By PENETRATION



CONDUCTIVITY



Transient Luminous Events - TLE

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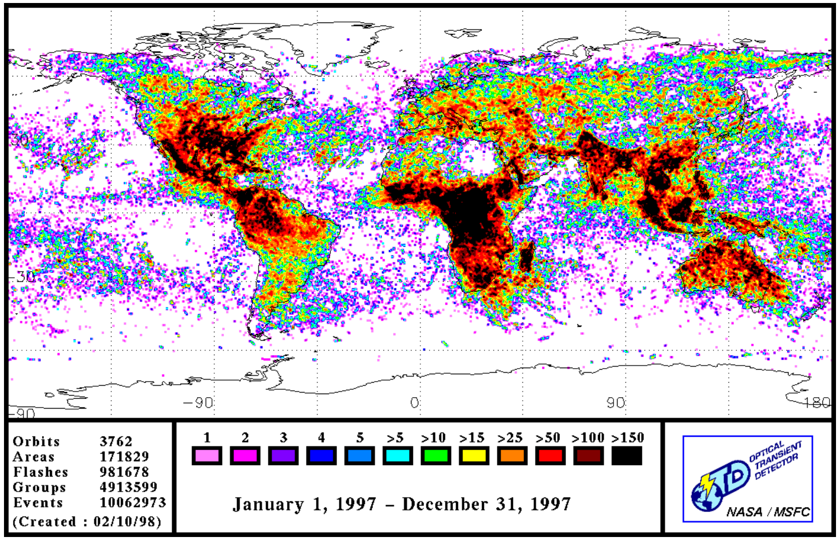

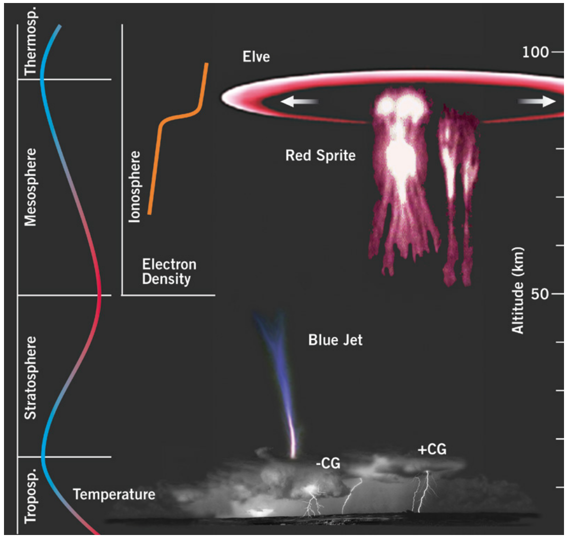

- Occurence rate of lightening: 45 per sec

- Red sprites
- Blue Jets
- Elves

FORMOSAT:7.6 TLEs pr dag

ASIM: 8 TLE pr dag

Terrestrial Gamma Flashes - TGF

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FOR SPACE SCIENCE