Ionospheric electrodynamics and its coupling to the magnetosphere

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Outline

(1) Fluid description (**B**,**V**) for partially ionized system

- Plasma Equation of motions
- Generalized Ohm's law

(2) M-I coupling via shear Alfven wave

- magnetospheric dynamo
- wave generation and propagation and their relation to velocity shear
- atmospheric dynamo
- 3D current closure inside ionosphere

Fundamental evolution equations of physical quantities Q_k

$$\frac{\partial}{\partial t} Q_k = F_k\left(Q_1, Q_2, Q_3, \ldots\right)$$

$$Q_k = \mathbf{B}, \mathbf{E}, \mathbf{J}, \mathbf{V}, \mathbf{V}_n$$

What's drive What in the weakly ionized system?

evolution of B-field $$\frac{\partial}{\partial t}\mathbf{B} = -(\nabla \times \mathbf{E})$$

evolution of E-field $$\frac{\partial}{\partial t}\mathbf{E} = \frac{(\nabla \times \mathbf{B}) - \mu_0 \mathbf{j}}{\varepsilon_0 \mu_0}$$

evolution of current density $$\frac{\partial}{\partial t}\mathbf{j} = ?$$

evolution of plasma velocity $$\frac{\partial}{\partial t}\mathbf{V} = ?$$

evolution of neutral velocity $$\frac{\partial}{\partial t}\mathbf{V}_n = ?$$

momentum equations in the collisional system

for ion fluid

$$m_i n_i \frac{\partial}{\partial t}\mathbf{v}_i = e n_i\left(\mathbf{E}+\mathbf{v}_i\times\mathbf{B}\right)-\nabla\cdot p_i - m_i \nu_{in} n_i\left(\mathbf{v}_i-\mathbf{v}_n\right)-m_e \nu_{ei} n_i\left(\mathbf{v}_i-\mathbf{v}_e\right) \quad (1)$$

Lorentz force

kinetic tensor

momentum exchange between plasma and neutral

momentum exchange between electron and ion

for electron fluid

$$m_e n_e \frac{\partial}{\partial t}\mathbf{v}_e = -e n_e\left(\mathbf{E}+\mathbf{v}_e\times\mathbf{B}\right)-\nabla\cdot p_e - m_e \nu_{en} n_e\left(\mathbf{v}_e-\mathbf{v}_n\right)+m_e \nu_{ei} n_i\left(\mathbf{v}_i-\mathbf{v}_e\right) \quad (2)$$

for neutral fluid

momentum exchange Between ion and neutral

momentum exchange Between electron and neutral

$$\rho_n\left[\frac{\partial \mathbf{v}_n}{\partial t}+(\mathbf{v}_n.\nabla)\mathbf{v}_n\right]=-\nabla p_n-\rho_n \nu_{ni}(\mathbf{v}_n-\mathbf{V}_i)-\rho_n \nu_{ne}(\mathbf{v}_n-\mathbf{V}_e)+\mathbf{F}_n \quad (3)$$

One fluid–description for global phenomena (Hall MHD approximation)

plasma density

$$n = n_i = n_e$$

pressure gradient

$$P = P_i + P_e$$

current density

$$\mathbf{j} = en\left(\mathbf{v}_i - \mathbf{v}_e\right)$$

$+ \ll -$

barycentric velocity

$$\mathbf{V} = \frac{m_i \mathbf{v}_i + m_e \mathbf{v}_e}{m_i + m_e}$$

$+ \gg -$

mass density

$$\rho = \left(m_i + m_e\right) n$$

$+ \gg -$

$$m_i \gg m_e$$

ion velocity

$$\mathbf{v}_i = \mathbf{V} + \left(\frac{m_e}{\rho e}\right)\mathbf{j}$$

electron velocity

$$\mathbf{v}_e = \mathbf{V} - \left(\frac{m_i}{\rho e}\right)\mathbf{j}$$

One-fluid description of ion and electron (motion and current)

○ dominant part

↕ cancellation part

equation of motion (mass weighted form of velocity evolution)

for ion

$$m_i n \frac{d}{dt}\left[\mathbf{V}+\left(\frac{m_e}{\rho e}\right)\mathbf{j}\right]=en(\mathbf{E}+\mathbf{V}\times\mathrm{B})+\left(\frac{m_e}{m_i+m_e}\right)\mathbf{j}\times\mathbf{B}-m_i n\nu_{in}\left[\mathbf{V}-\mathbf{v}_n-\left(\frac{m_e}{\rho e}\right)\mathbf{j}\right]-\left(\frac{m_i\nu_{ie}}{e}\right)\mathbf{j}-\nabla p_i$$

for electron

$$m_e n \frac{d}{dt}\left[\mathbf{V}-\left(\frac{m_i}{\rho e}\right)\mathbf{j}\right]=-en(\mathbf{E}+\mathbf{V}\times\mathrm{B})+\left(\frac{m_i}{m_i+m_e}\right)\mathbf{j}\times\mathbf{B}-m_e n\nu_{en}\left[\mathbf{V}-\mathbf{v}_n+\left(\frac{m_i}{\rho e}\right)\mathbf{j}\right]-\left(\frac{m_e\nu_{ei}}{e}\right)\mathbf{j}-\nabla p_e$$

inertial part | Lorentz force | Ampere force | momentum exchange to neutrals | momentum exchange between ion and electrons

current density (charge weighted form of velocity evolution)

ionic current

$$en\frac{d}{dt}\left[\mathbf{V}+\left(\frac{m_e}{\rho e}\right)\mathbf{j}\right]=\left(\frac{e^2 n}{m_i}\right)(\mathbf{E}+\mathbf{V}\times\mathrm{B})+e\left(\frac{m_e}{m_i}\right)\frac{\mathbf{j}\times\mathbf{B}}{m_i+m_e}-en\nu_{in}\left[\mathbf{V}-\mathbf{v}_n-\left(\frac{m_e}{\rho e}\right)\mathbf{j}\right]-\nu_{ie}\mathbf{j}-\frac{e\nabla p_i}{m_i}$$

electron current

$$-en\frac{d}{dt}\left[\mathbf{V}-\left(\frac{m_i}{\rho e}\right)\mathbf{j}\right]=\left(\frac{e^2 n}{m_e}\right)(\mathbf{E}+\mathbf{V}\times\mathrm{B})-e\left(\frac{m_i}{m_e}\right)\frac{\mathbf{j}\times\mathbf{B}}{m_i+m_e}+en\nu_{en}\left[\mathbf{V}-\mathbf{v}_n+\left(\frac{m_i}{\rho e}\right)\mathbf{j}\right]+\nu_{ei}\mathbf{j}+\frac{e\nabla p_e}{m_e}$$

ion : main portion of plasma dynamics **electron : main portion of current carier**

Generalized Equation of motion for one-fluid plasma

inertial — pressure gradient — friction force along j

$$\rho \frac{\partial}{\partial t}\mathbf{V} = \mathbf{j}\times\mathbf{B} - \nabla P - n\left(m_i \nu_{in} + m_e \nu_{en}\right)\left(\mathbf{V} - \mathbf{V}_n\right) - m_e\left(\nu_{in} - \nu_{en}\right)\frac{\mathbf{j}}{e}$$

Ampere force — momentum exchange between neutral and charged particles

Generalized Ohm's law

electromotive e-field

$$\frac{\partial}{\partial t}\mathbf{j} = \varepsilon_0 \omega_{pe}^2 \left(\mathbf{E} + \overrightarrow{emf} - \overleftrightarrow{R}\cdot\mathbf{j}\right)$$

reactive-field

convection electric field — am-bipolar field

$$\overrightarrow{emf} = \mathbf{V}\times\mathbf{B} + \frac{B\left(\nu_{in} - \nu_{en}\right)}{\Omega_e}\left(\mathbf{V} - \mathbf{v}_n\right) - \frac{\nabla p_e}{ne}$$

electric field induced by momentum exchange effect

$$\overleftrightarrow{R}\cdot\mathbf{j} = \left(\frac{B}{ne}\right)\left[\left(\frac{\nu_{en} + \nu_{ei}}{\Omega_e}\right)\mathbf{j} + \left(\mathbf{j}\times\hat{\mathbf{b}}\right)\right]$$

resistive e-field — Hall e-field

Distribution of collision frequency

controls the momentum exchange between neutral and charged particles

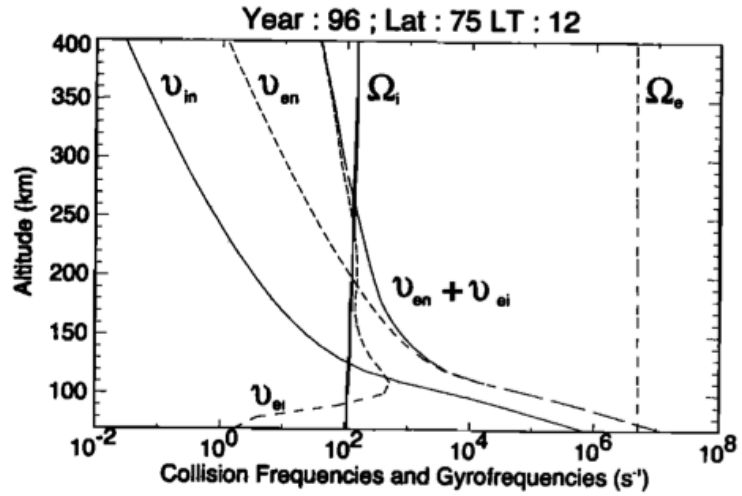
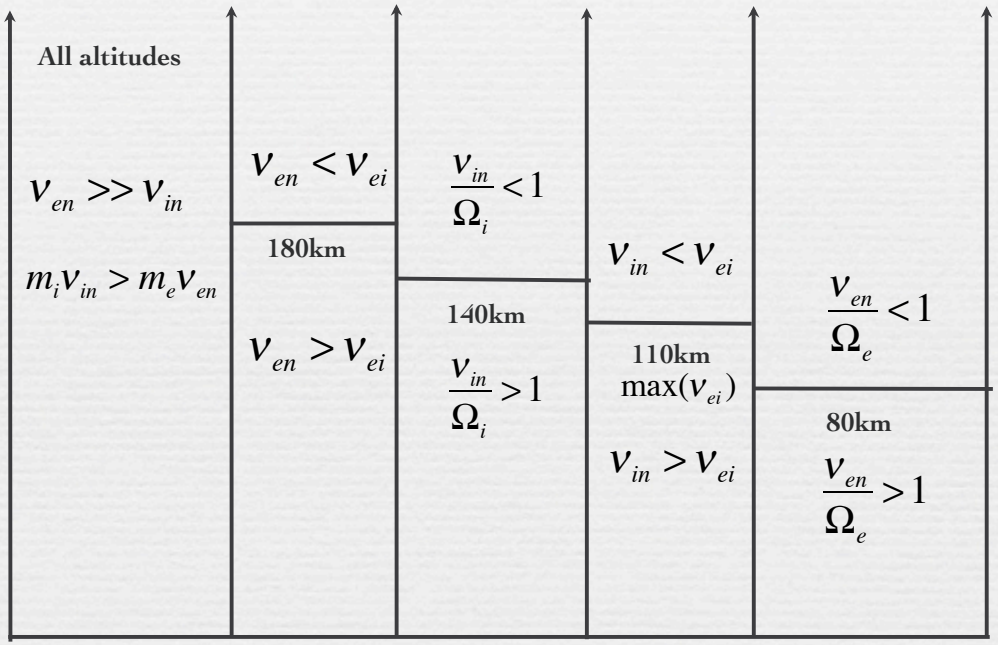
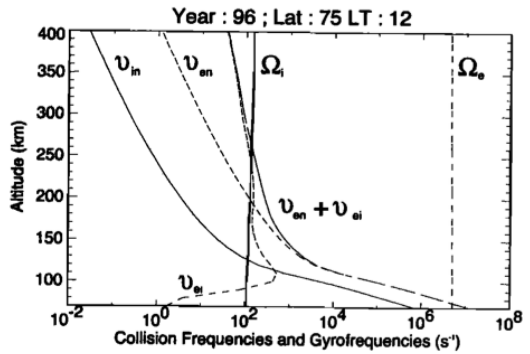


Figure 1. Collision frequencies and gyrofrequencies as functions of altitude at local noon at 75° latitude. They are determined based on the observations/laboratory experiments and the formula of *Kelley* [1989]. The anisotropy in the collision frequencies become unimportant above 80 km. More detailed discussion on the relationships among these quantities and anisotropies is given by *Richmond* [1995].



From Song, et al., [2001]

Equation for motion of plasma (dominant)



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$$m_i \nu_{in} >> m_e \nu_{en} \qquad \nu_{in} << \nu_{en}$$

inertial — momentum exchange between ion and neutrals — Ampere force — friction force along j — pressure gradient force

$$\frac{\partial}{\partial t}\mathbf{V} = -\nu_{in}\left(\mathbf{V}-\mathbf{V}_n\right) + \frac{\mathbf{j}\times\mathbf{B}}{\rho} + \frac{B}{\rho}\left(\frac{\nu_{en}}{\Omega_e}\right)\mathbf{j} - \frac{\nabla P}{\rho}$$

Important near plasma sheet

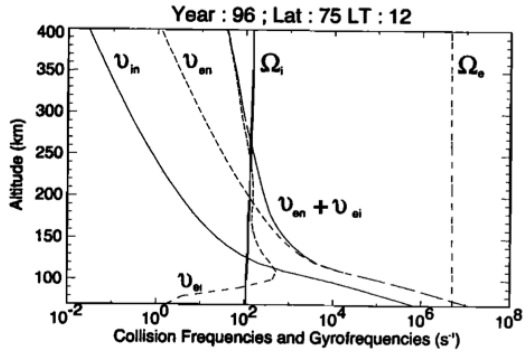
important $\omega >\sim \nu_{in}$

dominant in the ionosphere

everywhere important

important below 80km

Force balance Equation below E-layer



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$$m_i \nu_{in} >> m_e \nu_{en} \qquad \nu_{in} << \nu_{en}$$

$$\omega << \nu_{in}$$

With cold plasma plasma approximation

inertial | momentum exchange between ion and neutrals | Ampere force | friction force along j

$$0 \simeq -\nu_{in}\left(\mathbf{V}-\mathbf{V}_n\right) + \frac{\mathbf{j}\times\mathbf{B}}{\rho} + \frac{B}{\rho}\left(\frac{\nu_{en}}{\Omega_e}\right)\mathbf{j}$$

dominant in the ionosphere | everywhere important | important below 80km

Ionospheric current is a force balance current

$$\mathbf{j}\times\mathbf{B} = en\left\{\left(\frac{k_{en}^2}{1+k_{en}^2}\right)k_{in}^{-1}\left(\mathbf{V}-\mathbf{V}_n\right)+\left(\frac{k_{en}}{1+k_{en}^2}\right)k_{in}^{-1}\left(\mathbf{V}-\mathbf{V}_n\right)\times\mathbf{B}\right\}$$

$$k_{in} \equiv \left(\frac{\nu_{in}}{\Omega_i}\right) \qquad k_{en} \equiv \left(\frac{\nu_{en}}{\Omega_e}\right)$$

For 90km~140km

$$\mathbf{j}\times\mathbf{B} \simeq k_{in}^{-1}en\left(\mathbf{V}-\mathbf{V}_n\right)$$

Atmospheric dynamo through collision via ion
(dynamo region-> 90~140km)

Important only for 80km

Atmospheric dynamo through collision via electron
(dynamo region-> 70~90km)

plasma – neutral interaction

$$\mathbf{j}\times\mathbf{B} \cong \rho\nu_{in}\left(\mathbf{V}-\mathbf{u}_n\right)$$

Equivalence of electromagnetic load and mechanical load

In the neutral frame

$$\left(\mathbf{j}\times\mathbf{B}\right)\cdot\mathbf{V}'' \cong \rho\nu_{in}\left|\mathbf{V}''\right|^2 \qquad \mathbf{V}' \cong \mathbf{V}-\mathbf{u}_n$$

Work done by Ampere force = heating by plasma

In the rest (plasma) frame

Work done by Ampere force = work done by momentum exchange by collision

$$\left(\mathbf{j}\times\mathbf{B}\right)\cdot\mathbf{v} \cong \rho\nu_{in}\left(\mathbf{V}-\mathbf{u}_n\right)\cdot\mathbf{v} = \mathbf{j}\cdot\mathbf{E}$$

$$\mathbf{j}\cdot\mathbf{E} > 0 \quad for \quad \mathbf{v} > \mathbf{u}_n$$

Atmospheric load

Electromagnetic energy is converted into mechanical energy

$$\mathbf{j}\cdot\mathbf{E} < 0 \quad for \quad \mathbf{v} < \mathbf{u}_n$$

Atmospheric dynamo

Electromagnetic energy is generated from mechanical energy

Atmospheric dynamo

To the magnetosphere

↑ *Alfven wave generation*

Plasma flow out side dynamo region

↑ *Ampre froce (magnetic tension acting plasma)*

Magnetic perturbation, current

↑ *Non-zero curl E (different E within and outside dynamo region along* $\boldsymbol{B}_0$*)*

Electric field (within the dynamo region)

↑ *Generalized Ohm"s law*

Plasma flow (within the dynamo region)

↑ *Momentum exchange by Ion-neutral collision*

neutral wind

Atomospheric dynamo

$$(\mathbf{j}\times\mathbf{B})\cdot\mathbf{V} \simeq k_{in}^{-1}en(\mathbf{V}-\mathbf{V}_n)\cdot\mathbf{V}$$

Work done by Ampere force acting on ion

Work done by momentum exchange between ion and neutral on ion

Case (A) if

$$(\mathbf{j}\times\mathbf{B})\cdot\mathbf{V} \simeq k_{in}^{-1}en(\mathbf{V}-\mathbf{V}_n)\cdot\mathbf{V} > 0$$

Ampere force can accelerate neutrals through collision (atmospheric load)

Case (B) if

$$(\mathbf{j}\times\mathbf{B})\cdot\mathbf{V} \simeq k_{in}^{-1}en(\mathbf{V}-\mathbf{V}_n)\cdot\mathbf{V} < 0$$

Neutral particle can produces Ampere force through Collision (electromagnetic energy is produced by kinetic energy of Neutral particles) (atmospheric dynamo)

Generalized Ohm's law (dominant)

Current evolution equation

$$\frac{\partial}{\partial t}\mathbf{j} = \varepsilon_0 \omega_{pe}^2 \left(\mathbf{E} + \overrightarrow{emf} - \overleftrightarrow{R} \cdot \mathbf{j} \right)$$

e-field

Electromotive e.m.f. e-field

$$\overrightarrow{emf} = \mathbf{V} \times \mathbf{B} - B\left(\frac{\nu_{en}}{\Omega_e}\right)\left(\mathbf{V} - \mathbf{v}_n\right)$$

convection e- field

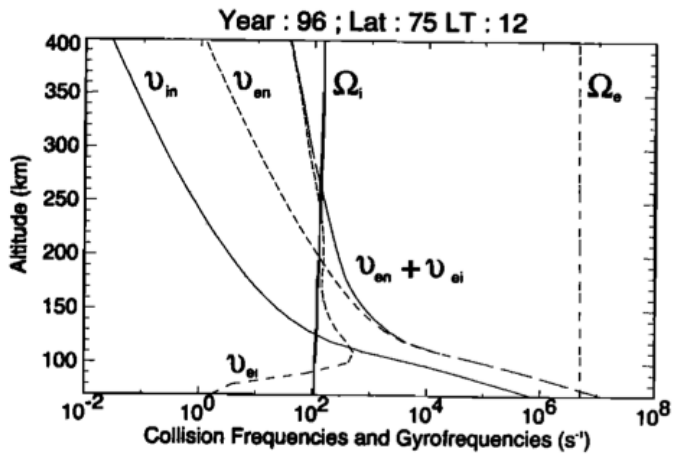
e-field induced by momentum exchange between electron and neutral

reactive-field

$$\overleftrightarrow{R} \cdot \mathbf{j} = \left(\frac{B}{ne}\right)\left[\left(\frac{\nu_{en}}{\Omega_e}\right)\mathbf{j}_\perp + \left(\mathbf{j} \times \hat{\mathbf{b}}\right)\right]$$

resistive e-field

Hall e-field



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Electromagnetic wave Radiation

evolution of B-field

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

evolution of E-field

$$\frac{\partial}{\partial t}\mathbf{E} = \frac{(\nabla \times \mathbf{B}) - \mu_0 \mathbf{j}}{\varepsilon_0 \mu_0}$$

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{E} + \nabla \times (\nabla \times \mathbf{E}) = -\mu_0 \frac{\partial}{\partial t}\mathbf{j}$$

evolution eq of **J**?

no!! electromagnetic field radiations eq by changing of current
(like a dipole antenna)

we need to know how **J** is produced by electro-dynamics (not -magnetics)

$$\frac{\partial}{\partial t}\mathbf{j} = \varepsilon_0 \omega_{pe}^2 \left(\mathbf{E} - \overrightarrow{emf} - \overleftrightarrow{R}\mathbf{j}\right)$$

$$\overleftrightarrow{R}\mathbf{j} = \left[\frac{B}{ne}\right]\left[\left(\frac{\nu_{en} + \nu_{ei}}{\Omega_e}\right)\mathbf{j} + \mathbf{j} \times \hat{\mathbf{b}}\right]$$

After radiation of plasma waves

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{E}+\nabla\times(\nabla\times\mathbf{E})=-\mu_0\frac{\partial}{\partial t}\mathbf{j}$$

$$\frac{\partial}{\partial t}\mathbf{j}=\varepsilon_0\omega_{pe}^2\left\{\mathbf{E}+\overrightarrow{emf}-\left[\frac{B}{ne}\right]\left[\left(\frac{\nu_{en}+\nu_{ei}}{\Omega_e}\right)\mathbf{j}+\mathbf{j}\times\hat{\mathbf{b}}\right]\right\}$$

$$\mathbf{j}=\frac{(\nabla\times\mathbf{B})}{\mu_0}-\varepsilon_0\frac{\partial}{\partial t}\mathbf{E}$$

$$\underbrace{-\lambda_e^2\nabla\times(\nabla\times\mathbf{E})}_{\sim\frac{\lambda_e^2}{L^2}\mathbf{E}}-\underbrace{\omega_{pe}^{-2}\frac{\partial^2}{\partial t^2}\mathbf{E}}_{\sim(\omega_{pe}T)^{-2}\mathbf{E}}+\underbrace{\left(\frac{\Omega_e}{\omega_{pe}^2}\right)\frac{\partial}{\partial t}(\mathbf{E}\times\hat{e}_B)}_{\sim(\omega_{pe}T)^{-1}\left(\frac{\Omega_e}{\omega_{pe}}\right)\mathbf{E}}+\underbrace{\left(\frac{\nu_{en}-\nu_{ei}}{\omega_{pe}^2}\right)\frac{\partial}{\partial t}\mathbf{E}}_{(\omega_{pe}T)^{-1}\left(\frac{\nu_{en}-\nu_{ei}}{\omega_{pe}}\right)\mathbf{E}}=\mathbf{E}-\overrightarrow{emf}-\mu_0^{-1}\overleftrightarrow{R}\cdot(\nabla\times\mathbf{B})$$

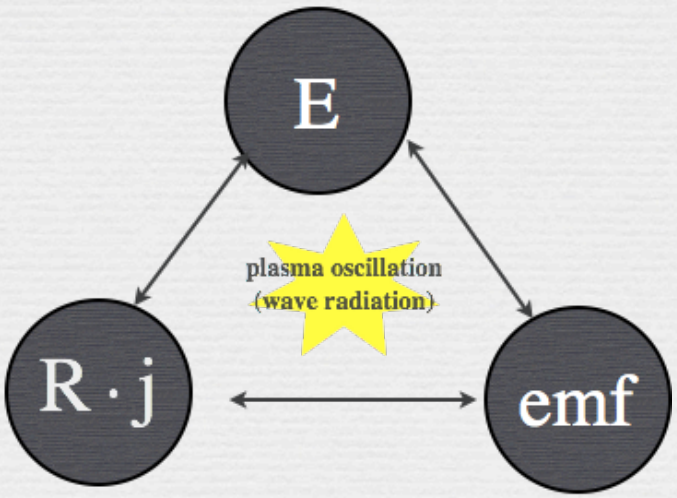
$L>>\lambda_e$

much larger than electron inertial length

$T>>\omega_{pe}^{-1}$

much slower than plasma oscillation

$$\mathbf{E}=\overrightarrow{emf}+\mu_0^{-1}\overleftrightarrow{R}\cdot(\nabla\times\mathbf{B})$$



after electromagnetic wave radiation

balance equation among E, emf and reactive fields : (Steady Ohm's law) in (B,V) scheme is established

Ohm's law in ion-collisional system

Eq of motion (force balance)

$$\mathbf{j}\times\mathbf{B} \simeq k_{in}^{-1} en\left(\mathbf{V}-\mathbf{V}_n\right)$$

Generalized Ohm's law

$$\mathbf{E} = \overrightarrow{emf} + \overleftrightarrow{R}\cdot\mathbf{j}$$

$$\overrightarrow{emf} \simeq -\mathbf{V}\times\mathbf{B}$$ Convection e-field

$$\overleftrightarrow{R}\cdot\mathbf{j} \simeq \left(\frac{B}{ne}\right)\left(\mathbf{j}\times\hat{\mathbf{b}}\right)$$ Hall e-field

$$= k_{in}^{-1} B\left(\mathbf{v}_i - \mathbf{v}_n\right)$$ Ion-collisional resistive e-field

$$\mathbf{E} = \overrightarrow{emf} + \overleftrightarrow{R}\cdot\mathbf{j}$$

$$\boxed{\mathbf{E} = -\mathbf{V}\times\mathbf{B} + k_{in}^{-1} B\left(\mathbf{V}-\mathbf{v}_n\right)}$$ Ohm's law in the rest frame

$$\mathbf{E} + \mathbf{v}_n\times\mathbf{B} = -\left(\mathbf{V}-\mathbf{v}_n\right)\times\mathbf{B} + k_{in}^{-1} B\left(\mathbf{V}-\mathbf{v}_n\right)$$

$$\mathbf{E}^* = \mathbf{E} + \mathbf{v}_n\times\mathbf{B}$$
$$\mathbf{V}^* = \mathbf{V} - \mathbf{v}_n$$

$$\boxed{\mathbf{E}^* = -\mathbf{V}^*\times\mathbf{B} + k_{in}^{-1} B\mathbf{V}^*}$$ Ohm's law in the neutral frame

In the ionosphere electric field is induced not only in–VxB (convection electric field) direction but also

in the direction of plasma flow !!(very different from magnetosphere)

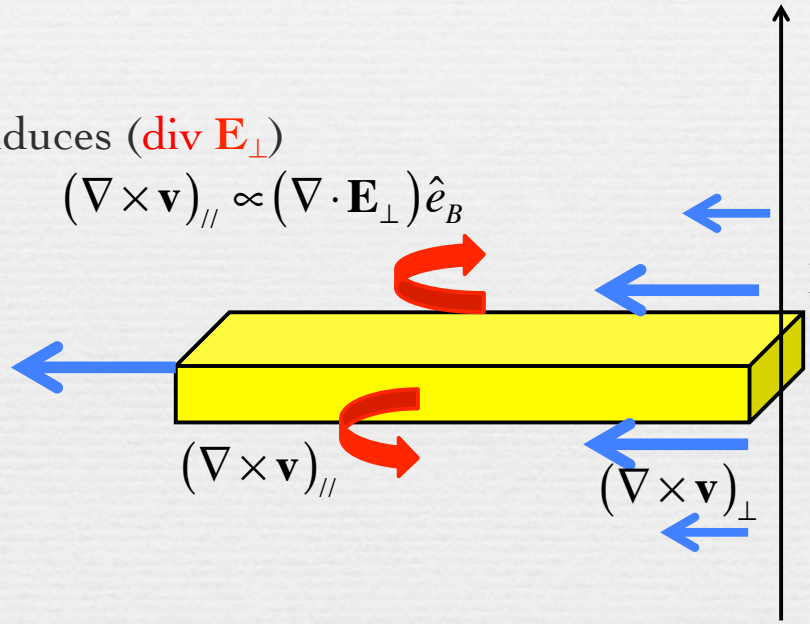
Magnetospheric Generator

"Generator" region can be defined as a region enable to production of **velocity shear (vorticity)** both parallel and perpendicular direction to $\mathbf{B}_0$ by the mechanical balance.

Parallel shear induces (div $\mathbf{E}_\perp$)

$$(\nabla\times\mathbf{v})_{//} \propto (\nabla\cdot\mathbf{E}_\perp)\hat{e}_B$$

$$\mathbf{v}_\perp = \frac{\mathbf{E}\times\hat{e}_B}{B_0}$$



perpendicular shear produces (rot $\mathbf{E}_\perp$)

$$\frac{\partial}{\partial s}\mathbf{v}_\perp \propto (\nabla\times\mathbf{v})_\perp \propto (\nabla\times\mathbf{E}_\perp)_\perp$$

Always inductive!!

Note: $\nabla\cdot(\nabla\times\mathbf{v})=0 \longleftrightarrow \nabla_{//}\cdot(\nabla\times\mathbf{v})_{//} = -\nabla_\perp\cdot(\nabla\times\mathbf{v})_\perp$

Vorticity conservation as like a current

$$\nabla\cdot\mathbf{j}=0 \longleftrightarrow \nabla_{//}\cdot\mathbf{j}_{//} = -\nabla_\perp\cdot\mathbf{j}_\perp$$

Shear Alfven wave

$$\mathbf{j}_\perp = B_0\Sigma_A(\nabla\times\mathbf{v})_\perp$$

$$\nabla\cdot\mathbf{j}_\perp = 0 \longleftrightarrow \nabla\cdot(\nabla\times\mathbf{v})=0$$

$$\mathbf{j}_{//} = B_0\Sigma_A(\nabla\times\mathbf{v})_{//}$$

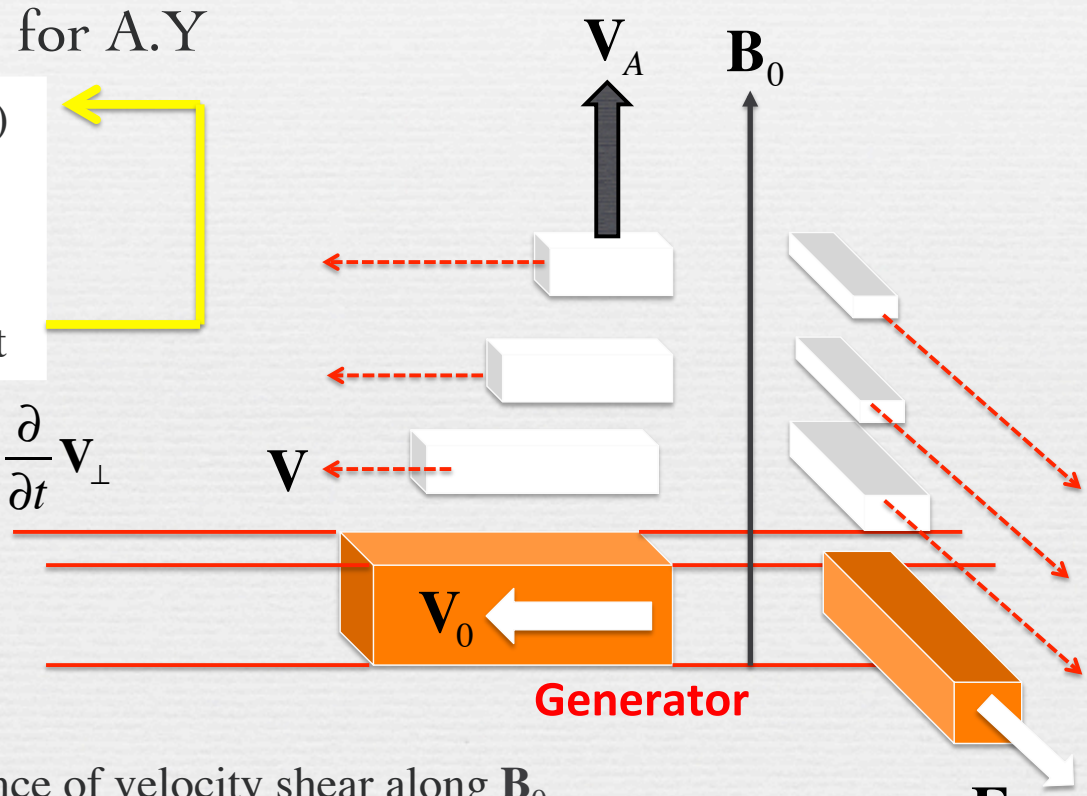
Induction process: generation and propagation shear Alfven wave

(1) Generator : drives enhanced convection velocity by balance of acceleration by pressure gradient force and deceleration by the magnetic tension force

Alfven Induction loop responsible for A.Y

(2) velocity shear along corresponds to rot(E)
→ development of magnetic field
→ development of tension force
→ acceleration of plasma flow at wave front

$$\frac{\partial}{\partial s}\mathbf{V}_\perp \propto (\nabla\times\mathbf{E})_\perp \propto \frac{\partial}{\partial t}\mathbf{b}_\perp \rightarrow \mathbf{j}\times\mathbf{B}_0 \rightarrow \rho\frac{\partial}{\partial t}\mathbf{V}_\perp$$



- role of shear Alfven wave → disappearance of velocity shear along $\mathbf{B}_0$
- Generator acts until difference of convection velocity along $\mathbf{B}_0$ is disappeared

$$\nabla_{//}\cdot\mathbf{S}_{//} > 0$$

$$(\mathbf{j}\times\mathbf{B}_0)\cdot\mathbf{v}_0 > 0 \qquad -\nabla p\cdot\mathbf{v}_0 < 0$$

Magnetospheric dynamo

Enhanced convection velocity (plasma flow within the dynamo region)

↓ *Generalized Ohm"s law*

Electric field (within the dynamo region)

↓ *Non-zero curl E (different E within and outside dynamo region along* $\boldsymbol{B}_0$*)*

Magnetic perturbation, current

↓ *Ampre froce (magnetic tension force acting plasma)*

Plasma flow out side dynamo region

velocity shear along corresponds to rot(E)
→ development of magnetic field
→ development of tension force
→ acceleration of
plasma flow at wave front

Alfven induction loop

↓

To the ionosphere

Propagation of electromagnetic field inside the ionosphere and production of reflection field

Ion collision
Alfven-induction loop

From the magnetosphere

↓

velocity shear along B0 corresponds to rot(E)$_\perp$
→ development of magnetic field
→ development of tension force
→ acceleration of ion flow
→ **braking of ion flow by collision**
→ **no braking of electron flow**

↓

attenuation of vi

No attenuation of v_e

↓

Motion of ion induces two types electric field
(1) Convection electric field
(2) Hall electric field

Process (1)

(1) reflection
Alfven-induction loop

To the magnetosphere

↑

Plasma flow out side dynamo region

↑ *Ampere force*

Magnetic perturbation, current

↑

Shear (rot) of e-field
along B-field

↑

Equivalent to generation of oppositely
directed e-field

↑ *Generalized Ohm's law*

Attenuation of vi through collision
Corresponds to attenuation of type (1) e-field

Propagation of electromagnetic field inside the ionosphere and production of reflection field