Lecture #13 Radiation Belts, Ionosphere, Ionospheric Sounding, and Magnetic Reconnection

I. Van Allen Radiation Belts

A. 1. Van Allen first measured using a Geiger counter on the Explorer I in 1958 — Developed at University of Iowa.

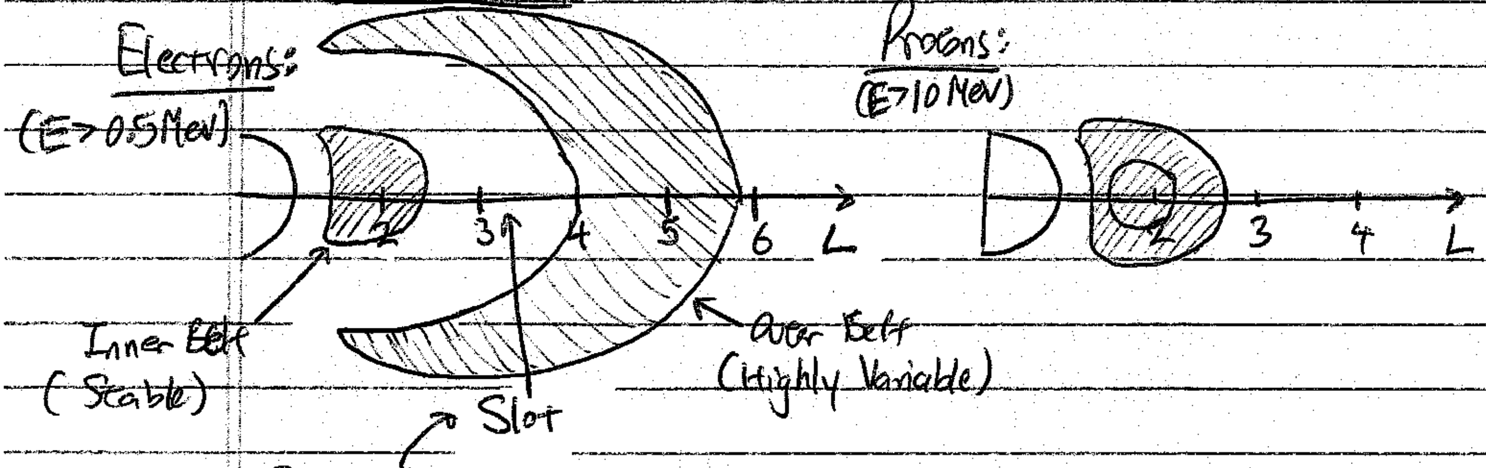
2. Trapped in the Earth's Dipole field, ring current particles and radiation belt particles are part of the same spectrum of particles

a. Ring Current dominated by a moderate density of 10-100 keV particles.

b. Much higher energy particles, electrons at >1 MeV and protons at >10 MeV, have much lower density, so contribute little to ring current

c. BUT, these high energy particles represent penetrating radiation, which can damage spacecraft instrumentation and be lethal for humans.

3. Distribution:



Caused by loss due to wave-particle interactions with global MHD wave modes

II. Ionosphere

A. General Comments:

1. Above ~60 km altitude, the partial ionization of the upper atmosphere creates the ionosphere.

Lecture #13 Continued

II A (Continued)

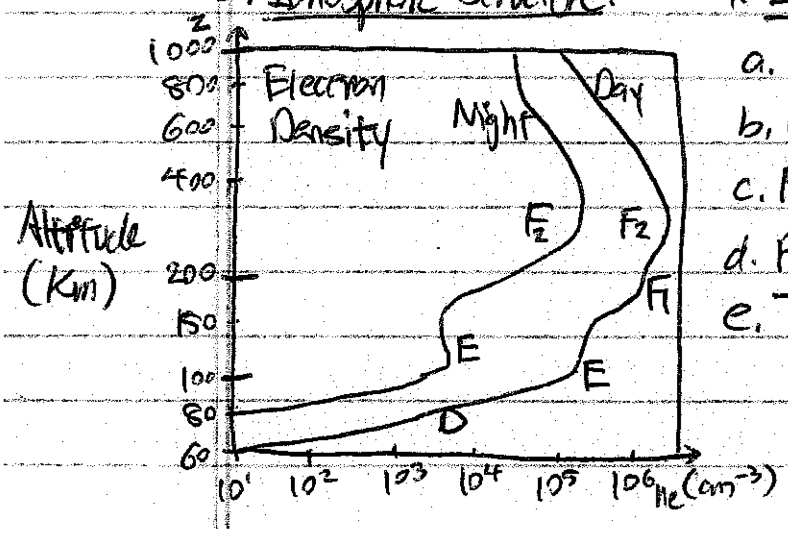
2. The properties of the ionosphere are determined by a balance of <u>ion production</u> and <u>ion loss</u> mechanisms.

3. <u>Ion Production</u>:
   a. <u>Photoionization</u> by EUV (17–175 nm) and X-rays (0.1–17 nm) from the sun
   b. <u>Impact Ionization</u> by cosmic rays or energetic particles from the sun or magnetosphere
   c. Ionization of primary atmospheric constituents: N_2, O_2, & O

4. <u>Ion Loss</u>:
   a. Radiative Recombination: $e + X^+ \rightarrow X + h\nu$ (airglow)
   b. Dissociative Recombination: $e + XY^+ \rightarrow X + Y$
   c. <u>NOTE</u>: <u>Auroral emission</u> is typically due to excitation of atomic and molecular electrons caused by Coulomb collisions with energetic particles precipitating from magnetosphere.

5. Note that in the lower <u>ionosphere</u>, chemistry can play an important role in the equilibrium ionospheric conditions.

B. <u>Ionospheric Structure</u>:

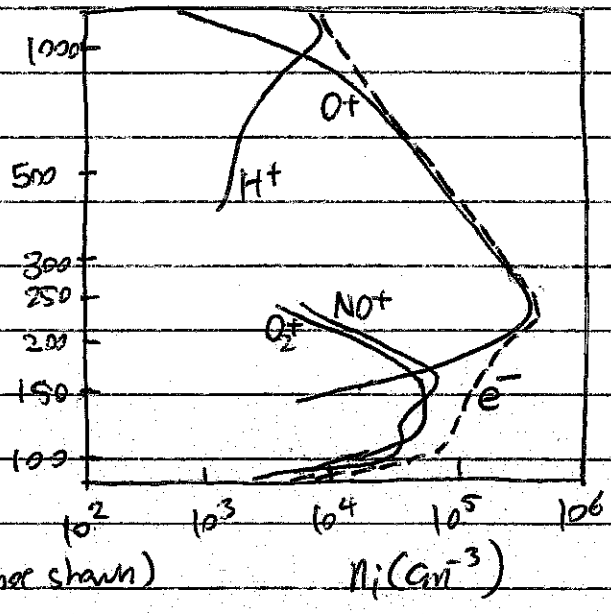


1. <u>Ionospheric Regions</u>:
   a. D region ($60\text{ km} \lesssim z \lesssim 90\text{ km}$) ← Disappear at night
   b. E region ($90\text{ km} \lesssim z \lesssim 140\text{ km}$)
   c. F_1 region ($140\text{ km} \lesssim z \lesssim 200\text{ km}$)
   d. F_2 region ($200\text{ km} \lesssim z \lesssim 500\text{ km}$)
   e. Topside Ionosphere ($z \gtrsim 500\text{ km}$)

II. B. (Continued)

2. Ionospheric Composition:

Dayside Ion Composition



a. Low altitudes: O_2^+ & NO^+

b. F_2 region (200km) to 1000km: O^+

c. Topside Ionosphere above 1000 km: H^+

d. Minor species: He^+, N^+, N_2^+ (not shown)

3. Partially Ionized Plasma: Below 500km, fractional ionization is $\leq 1\%$, so neutral dynamics (winds) and collisions with neutrals are important to ionospheric plasma physics.

4. Polar Winds: a. High latitude ionosphere has magnetic field lines that are "open" — they do not connect to the opposite pole.

b. In these regions, where the magnetic field is nearly vertical, light ions (H^+ and He^+) are accelerated upward, leading to steady polar wind outflow.

C. Ionospheric Conductivities and Currents:

1. Pederson and Hall Conductivities:

a. In a partially ionized plasma, collisions with neutrals play an important role in determining the plasma conductivity

b. Ohm's Law (see Lect #5 I.B.6.) can be written

$\underset{\sim}{j} = \sigma_0 (\underset{\sim}{E} + \underset{\sim}{U} \times \underset{\sim}{B})$ where Define: Plasma Conductivity $\boxed{\sigma_0 \equiv \frac{n e^2}{m_e \nu_c} = \frac{1}{\eta}}$

I. Col. (Continued)

c. This can be written, for a partially ionized plasma, as

$$\underset{\sim}{j} = \underset{\approx}{\sigma} \cdot \underset{\sim}{E}$$

Define: Plasma Conductivity Tensor $\underset{\approx}{\sigma} = \begin{pmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix}$

where

Pedersen Conductivity: $\sigma_P = \dfrac{\nu_{en}^2}{\nu_{en}^2 + \Omega_e^2}\sigma_0$

Hall Conductivity: $\sigma_H = -\dfrac{\Omega_e \nu_{en}}{\nu_{en}^2 + \Omega_e^2}\sigma_0$

Parallel Conductivity: $\sigma_\parallel = \sigma_0$

d. NOTE: Above, we have simplified by assuming stationary neutrals and ions and that electron collisions are dominated by ν_{en}.

e.

$$\underset{\sim}{j} = \underbrace{\sigma_\parallel \underset{\sim}{E}_\parallel}_{\substack{\text{Parallel (Field-} \\ \text{Aligned) Current}}} + \underbrace{\sigma_P \underset{\sim}{E}_\perp}_{\substack{\text{Pedersen Current,} \\ \text{(in direction of} \\ \underset{\sim}{E}_\perp)}} - \underbrace{\sigma_H(\underset{\sim}{E}_\perp \times \hat{\underset{\sim}{b}})}_{\substack{\text{Hall Current} \\ \text{(in direction } \perp \\ \text{to } \underset{\sim}{E}_\perp)}}$$

f. Limits: i. Highly Collisional Plasma; $\nu_{en} \gg \Omega_e$

$\Rightarrow \sigma_P = \sigma_\parallel = \sigma_0$ & $\sigma_H = 0 \Rightarrow$ Isotropic (scalar) conductivity

ii. Collisionless, Magnetized Plasma: $\nu_{en} \ll \Omega_e$

$\Rightarrow \sigma_P \simeq \sigma_H \simeq 0$ & $\sigma_\parallel = \sigma_0 \Rightarrow$ Only field-aligned current.

iii. Moderate Collisionality; $\nu_{en} \sim \Omega_e$

(a) $\Omega_e < \nu_{en} \rightarrow$ Pedersen conductivity dominates

(b) $\Omega_e > \nu_{en} \rightarrow$ Hall conductivity dominates

2. Pedersen & Hall Conductivity enables ionospheric currents to flow perpendicular to Earth's magnetic field

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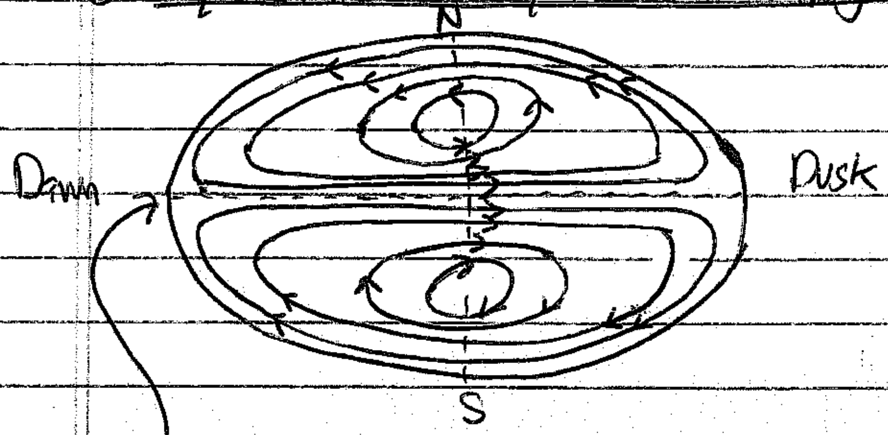
II C. Continued)

3. Sq Current and Equatorial Electrojet:



a. Solar quiet (Sq) Current is driven by tides of the atmosphere driven by diurnal heating

b. Equatorial Electrojet is an enhanced current along the equator toward dusk (eastward). Causes a disturbance of equatorial field of 50-100 nT.

D. Ionospheric Sounding:

1. Ionospheric electron density (on Earth, or other planets) can be mapped using ionospheric sounding

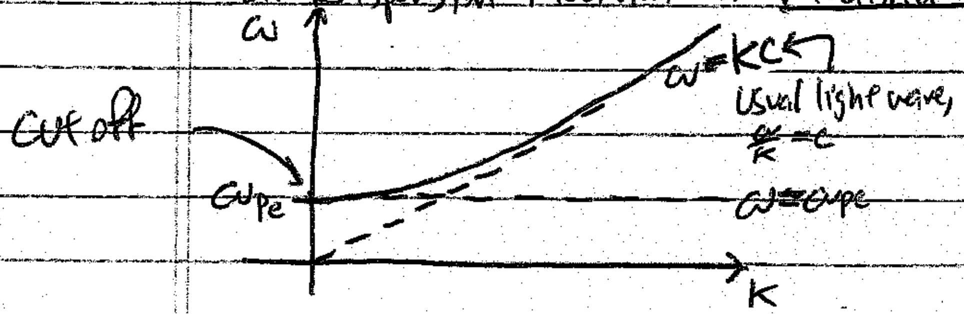
2. Propagation of Electromagnetic (light/radio) waves through plasma:

a. Take the Cold Plasma Approximation, $v_{te} \ll \frac{\omega}{k} \leftarrow$ wave phase velocity
This gives a closure $T_i = T_e = 0$.

b. The Moment Equations (Lec#4 IV C.) are then closed using Continuity Equation, Momentum Equation, and Maxwell's Equations (including Displacement Current)

c. For simplicity, we assume ions are a stationary, neutralizing background ($\mathbf{u}_i = 0$)

d. Dispersion Relation for Modified Light Waves:



$$\boxed{\omega^2 = \omega_{pe}^2 + k^2c^2}$$

for cold, unmagnetized plasma

Lecture #13 (Continued)

II D. (Continued)

3. What happens when wave frequency $\omega < \omega_{pe}$?

a. Solving for k: $k = \pm \frac{i}{c}\sqrt{\omega_{pe}^2 - \omega^2}$

b. Thus

$$e^{i(\underset{\sim}{k}\cdot\underset{\sim}{x}-\omega t)} = e^{-i\omega t}\underbrace{e^{-\frac{z}{c}\sqrt{\omega_p^2-\omega^2}}}_{\text{Wave becomes evanescent} \rightarrow \text{non-propagating.}} \quad \text{for } \underset{\sim}{k} = k\hat{\underset{\sim}{z}}$$

c. $\boxed{\text{Waves don't propagate at } \omega < \omega_{pe} \text{ in a cold, unmagnetized plasma}}$

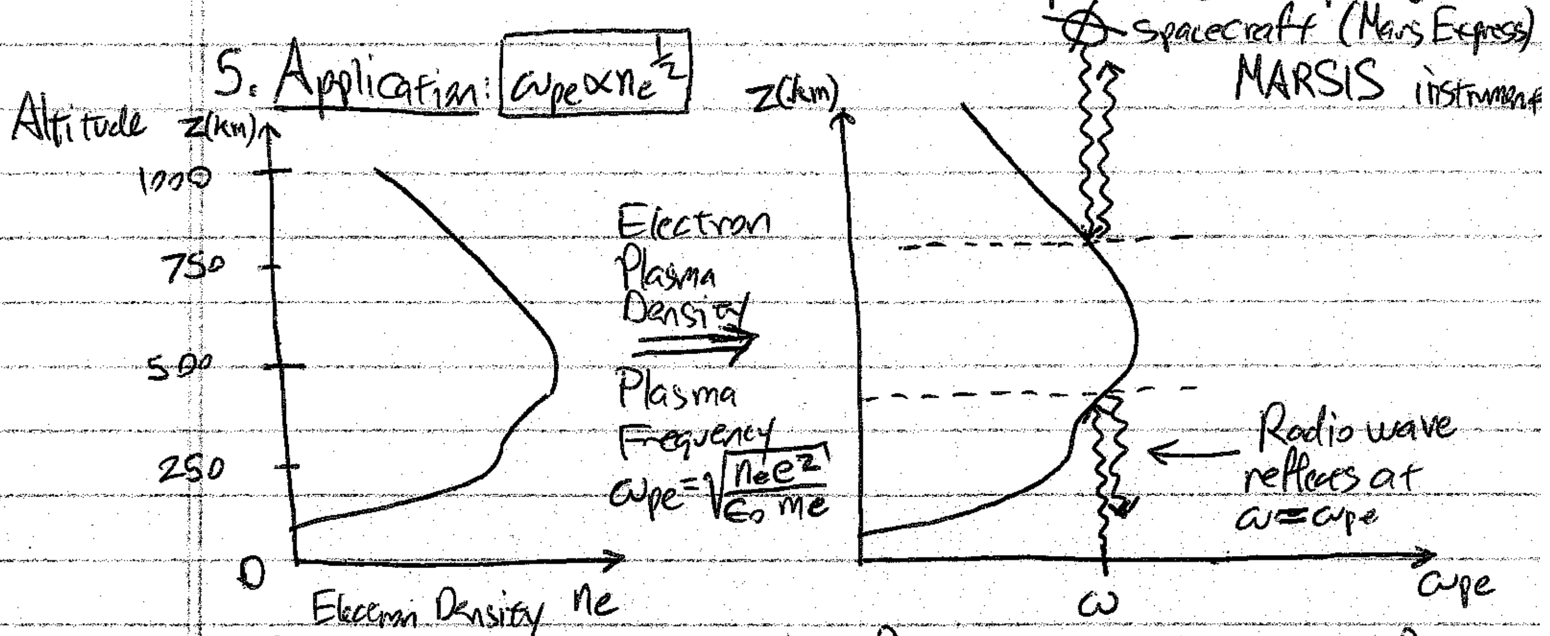
4. What causes the cutoff at ω_{pe}?

a. Ampere-Maxwell Law: $\nabla \times \underset{\sim}{B} = \underbrace{\mu_0 \underset{\sim}{j}}_{\text{Conduction Current}} + \underbrace{\mu_0 \epsilon_0 \frac{\partial E}{\partial t}}_{\text{Displacement Current}}$

b. In free space ($j = 0$), light waves are supported by displacement current.

c. In a plasma, the conduction current can oppose, and effectively short out, the displacement current, preventing wave propagation.

5. Application: $\boxed{\omega_{pe} \propto n_e^{\frac{1}{2}}}$



a. Radio waves reflect when their frequency equals local plasma frequency.

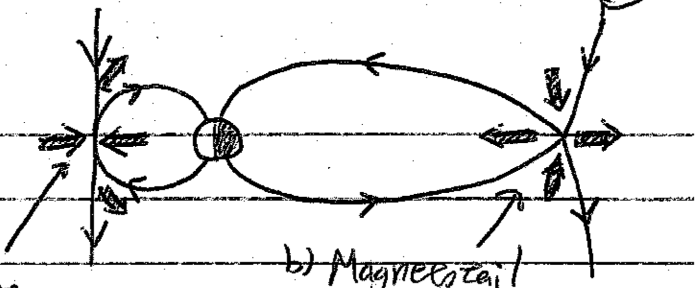
b. Time of flight is used to determine altitude with $\omega_{pe} \propto n_e^{\frac{1}{2}}$

c. Sweeping radio wave frequency enables mapping of $n_e(z)$.

III. Magnetic Reconnection:

A. Magnetospheric Reconnection

1. Dungey Model:



2. Resistive Induction Equation (Lec #5, I.D.4.)

a. $$\frac{\partial \underset{\sim}{B}}{\partial t} = \nabla\times(\underset{\sim}{U}\times\underset{\sim}{B}) + \frac{\eta}{\mu_0}\nabla^2\underset{\sim}{B}$$

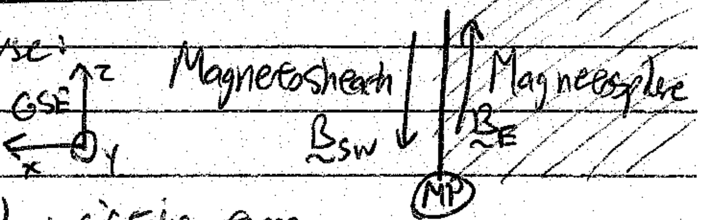
b. Magnetic Reynolds Number in Magnetosphere $R_{eM} = \frac{\mu_0 L V_0}{\eta} \sim 10^{11}$

c. Thus, Magnetic flux is frozen to plasma to high accuracy

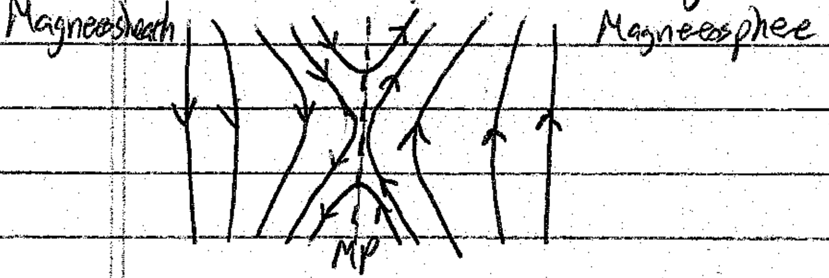
d. Frozen-in flux condition breaks down only at very thin boundaries

$\Rightarrow$ $\boxed{\text{Thin boundaries separate plasmas from different regions}}$

For example, at magnetopause:



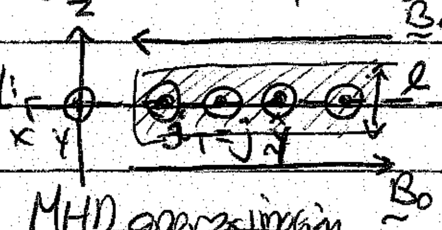
3. When $R_{eM}\sim 1$ (L very small), resistive term becomes important and magnetic reconnection can occur:



a) Plasma from different regions can mix when reconnection occurs

$\Rightarrow$ magnetic topology changes

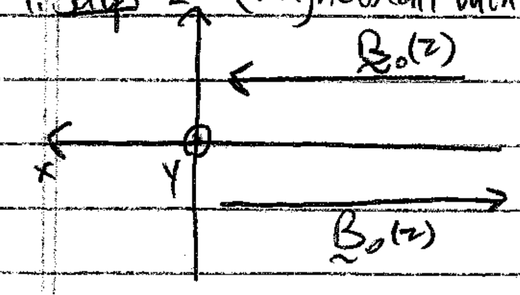
4. a. Current Sheet occurs at boundary: Tail:

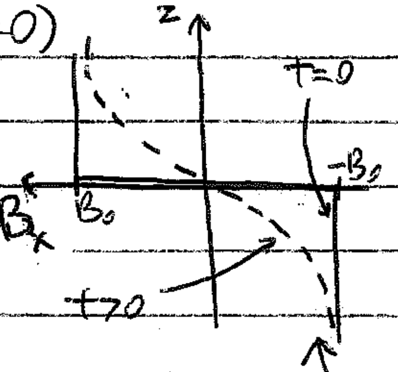


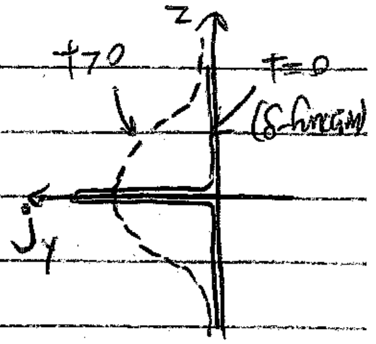
b. Boundary layer width $\ell < \rho_i$ breaks down MHD approximation.

III B. Quantitative Treatment of Reconnection

1. Setup: (Magnetotail with $\underset{\sim}{U}=0$)







2. a. $\frac{\partial \underset{\sim}{B}}{\partial t} = \nabla\times(\underset{\sim}{U}\times\underset{\sim}{B}) + \frac{\eta}{\mu_0}\nabla^2\underset{\sim}{B}$

Evolution of $\underset{\sim}{B} = B_x(z,t)\hat{x}$

b. Take $\underset{\sim}{B} = B_x(z,t)\,\hat{x}$ and $\underset{\sim}{U} = 0$

c. Thus $\boxed{\frac{\partial B_x}{\partial t} = \frac{\eta}{\mu_0}\frac{\partial^2 B_x}{\partial z^2}}$

d. Solution: $\boxed{B_x(z,t) = B_0 \,\mathrm{erf}\left[\left(\frac{\mu_0}{2\eta t}\right)^{\frac{1}{2}} z\right]}$

where $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x dx'\, e^{-x'^2}$ is the error function.

e. Current: $\underset{\sim}{j} = \frac{1}{\mu_0}\nabla\times\underset{\sim}{B} = \frac{1}{\mu_0}\frac{\partial B_x}{\partial z}\hat{y} = j_y\hat{y}$

3. a. Magnetic energy is lost, converted into heat via Joule heating,

$$\frac{\partial}{\partial t}\left(\frac{B^2}{2\mu_0}\right) = -\underset{\sim}{E}\cdot\underset{\sim}{j}$$

b. To achieve a steady state, we must transport magnetic flux (and its frozen-in plasma) toward the current sheet.

c. Inflow rate of energy is then set to match the rate of magnetic energy dissipation.