Skobeltsyn Institute of Nuclear Physics

Joule heating in the corona and chromosphere

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HANNES ALFVEN

Electric Currents in Cosmic Plasmas

REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 15, NO. 3 , AUGUST 1977

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- Since the beginning of the century, physics has been dualistic in the sense that some phenomena are described by a **field concept** and others by a **particle concept**. This dualism is essential also in the physics of cosmic plasmas: some phenomena should be described by a magnetic field formalism, and others by an electric current formalism. During the first period of evolution of cosmic plasma physics the magnetic field aspect has dominated, and a fairly exhaustive description has been given of those phenomena, like the propagation of waves, which can be described in this way. We have now entered **a second period, which is dominated by a systematic exploration of the particle (or current) aspect**. A survey is given of a number of phenomena which can be understood only from the particle aspect. These include the formation of electric double layers, the origin of 'explosive' events like magnetic substorms and solar flares, and further, the transfer of energy from one region to another. A useful method of exploring many of these phenomena is to draw the electric circuit in which the current flows and to study its properties. A number of simple circuits are analyzed in this way.
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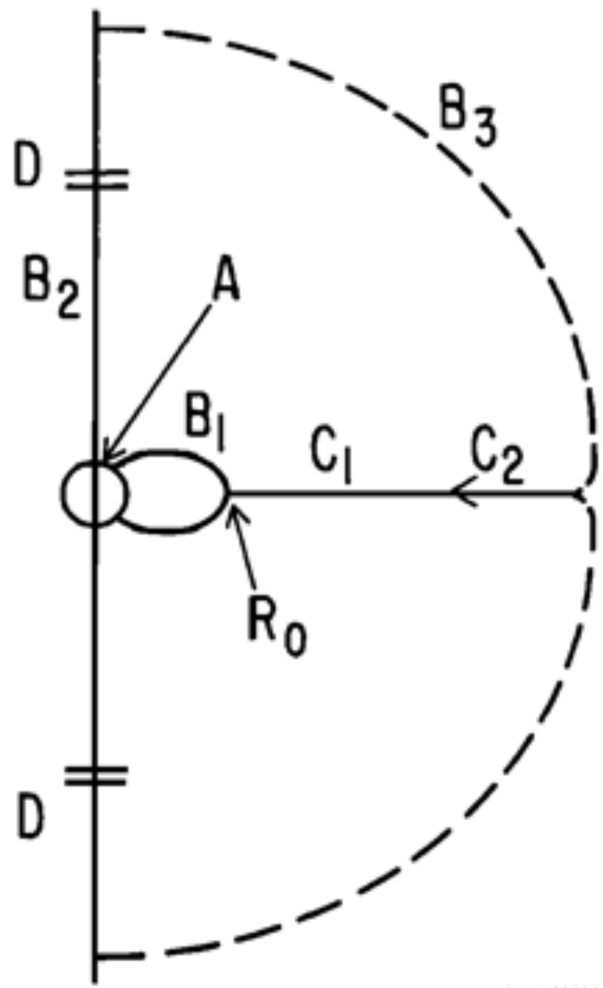
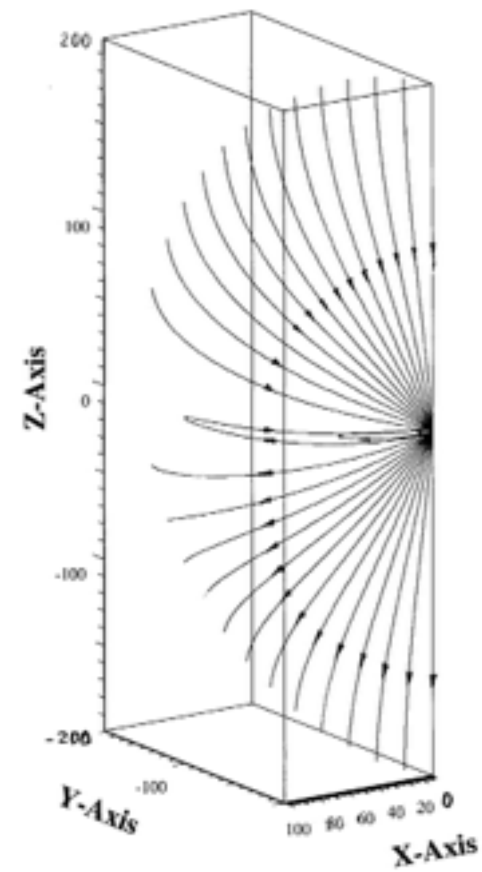
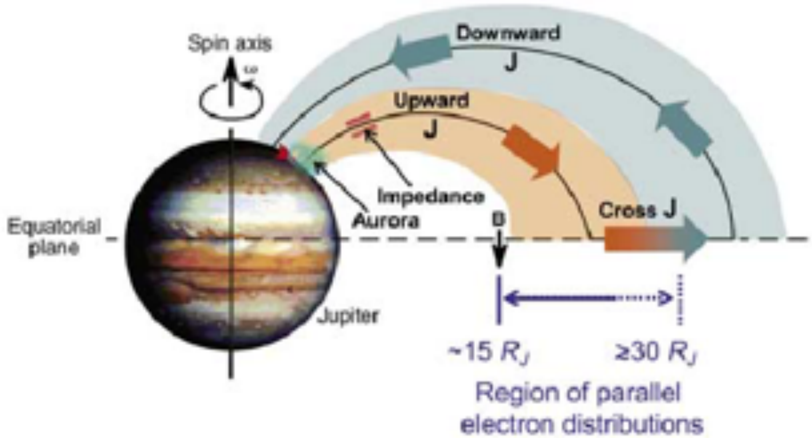
Alfvenic Current System in the Heliosphere





Unipolar jovian generator



Mauk et al., 2002

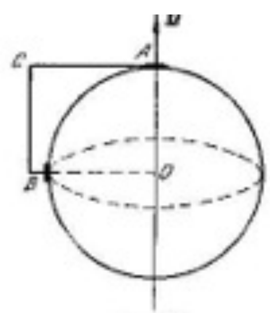
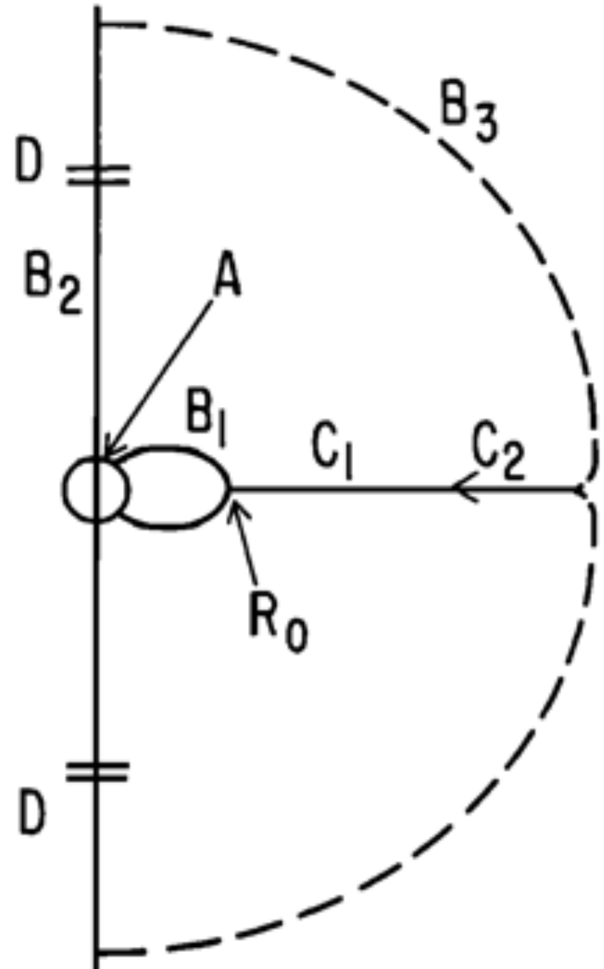


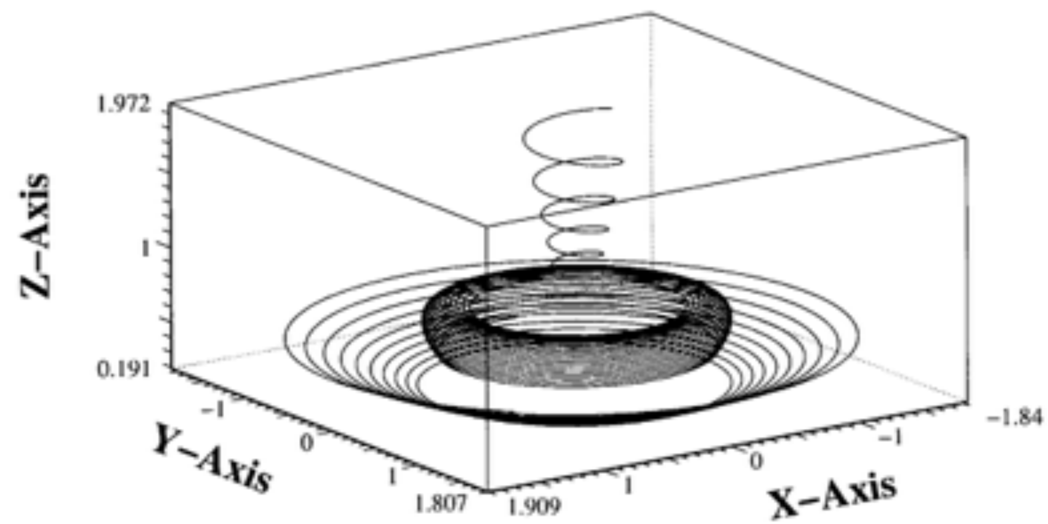
Рис. 27.

Landay and Lifshitz, 1959

Schematic of the relationship between observed equatorial electron field-aligned enhancements reported by Toma´s et al. [2004a, 2004b] and the circuit of electric currents that connects Jupiter's middle magnetosphere to the auroral ionosphere. The auroral circuit figure is based on concepts of Hill [1979] and Vasyliunas [1983] as replotted by Mauk et al. [2002]. It is understood that the shape of the field lines in the actual Jovian system are substantially stretched away from the dipolar configuration.

Currents in the Heliosphere





Maxwell' equations

$$\nabla\times\vec{B}=\mu_0\vec{J}\qquad \nabla\times\vec{E}=\nabla\cdot\vec{B}=0\qquad \nabla\cdot\vec{E}=\frac{\rho}{\varepsilon_0}$$

$$\vec{E}+\left[\vec{V}\times\vec{B}\right]=\frac{\vec{J}}{\sigma}$$

if $\partial/\partial\varphi\equiv 0$, then

$$\begin{cases}\dfrac{\partial\left(RB_\varphi\right)}{\partial R}-\dfrac{R_m}{R_s}\cdot RB_\varphi-\mu_0\sigma\dfrac{\partial\Phi}{\partial\theta}=0\\[2ex]\dfrac{1}{R\sin\theta}\dfrac{\partial}{\partial\theta}\left(\sin\theta\cdot B_\varphi\right)+\mu_0\sigma\dfrac{\partial\Phi}{\partial R}=0\end{cases}\quad\text{and}\quad\begin{cases}\dfrac{\partial\left(RB_\theta\right)}{\partial R}-\dfrac{\partial B_R}{\partial\theta}-\dfrac{R_m}{R_s}\cdot RB_\theta=0\\[2ex]\dfrac{1}{R}\dfrac{\partial\left(R^2B_R\right)}{\partial R}+\dfrac{1}{\sin\theta}\dfrac{\partial}{\partial\theta}\left(\sin\theta\cdot B_\theta\right)=0\end{cases}$$

Plasma flow

- Inside sphere with $R=R_S$ R_S is the Sun radius

$$\vec{V} = \{0,\ 0,\ \Omega \cdot R\sin\theta\}$$

- Outside sphere with $R=R_S$

$$\vec{V} = \{V_0,\ 0,\ 0\}$$

- Conductivity σ is homogenous

Solutions

$$B_\varphi(t,\theta) = \sum_{n=1}^{\infty} c_n F_n(t) P_n^1(\cos\theta), \qquad \Phi = t_0 \sum_{n=1}^{\infty} c_n Q_n(t) P_n(\cos\theta),$$

$$F_n(t) = \frac{e^{t/2}}{\sqrt{\pi t}} K_{n+1/2}\left(\frac{t}{2}\right), \quad Q_n(t) = nF_n(t) + \frac{t}{2}\left(F_{n-1}(t) + F_n(t)\right), \quad t_0 = \frac{c}{4\pi\sigma}, \quad t = R_m \frac{R}{R_S}$$

$$B_R(t,\theta) = \frac{1}{t} \sum_{n=1}^{\infty} n\cdot(n+1) d_n F_n(t) P_n(\cos\theta), \qquad B_\theta(t,\theta) = \Phi = t_0 \sum_{n=1}^{\infty} d_n P_n^1(\cos\theta) \frac{d}{dt}\left(tF_n(t)\right),$$

Magnetic Reinolds number

$$R_m = \mu_0 \sigma L_S V$$

Comparison transport and diffusion

- $\partial \mathbf{B}/\partial t = \mathbf{circl}\ \mathbf{V}\times\mathbf{B}+\nabla^2\ \mathbf{B}/\mu_0\ \sigma_0$

- $B/\tau = VB/L_B + B/\tau_B$ $\qquad\qquad \tau_B = \mu_0\ \sigma_0\ L_B{}^2$

- $B\ (\tau_B\ /\tau) = R_m\ B + B.$
- $R_m = \mu_0 \sigma_0 L_B V \qquad 3 \cdot 10^{15}$

Inside sphere $R \leq R_S$

$$\Phi_0 = \Phi_0 \left(\left(\frac{R}{R_S} \right)^2 \sin^2\theta - \frac{2}{3} \right) \quad E_R = -\frac{2\Phi_0 R}{R_S^2} \sin^2\theta$$

$$E_\theta = -\frac{\Phi_0 R}{R_S^2} \sin 2\theta \qquad E_\varphi = 0 \qquad B_R = B_0 \cos\theta$$

$$B_\theta = -B_0 \sin\theta \qquad B_\varphi = 0 \qquad \rho = \frac{\Phi_0}{\pi R_S^2} \quad \vec{J} = 0$$

Outside of the sphere $R \geq R_S$

$$\Phi_0 = -\frac{\Phi_\infty}{2} Q_2(t)\left(\cos 2\theta + \frac{1}{3}\right)$$

$$E_R = -3\frac{\Phi_\infty R_m}{R_S^2} F_2(t)\left(\cos 2\theta + \frac{1}{3}\right) \qquad E_\theta = -\frac{\Phi_\infty R_m}{R_S^2} Q_2(t)\sin 2\theta$$

$$E_\varphi = 0 \qquad B_R = B_0 \frac{R_m^3}{t^3}\frac{t+2}{R_m+2}\cos\theta$$

$$B_\theta = B_0 \frac{R_m^3}{t^3}\frac{\sin\theta}{R_m+2} \qquad B_\varphi = -B_0 \frac{R_m \xi F_2(t)}{2Q_2(R_m)}\sin 2\theta$$

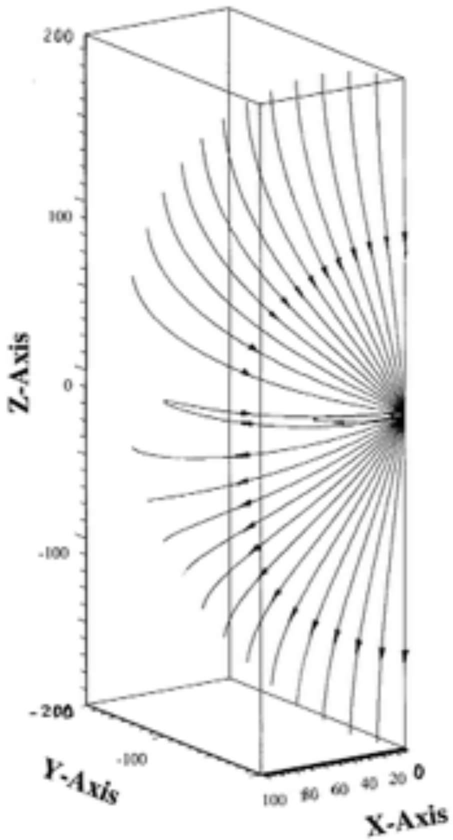
$$J_\varphi = \sigma V B_\theta \qquad \rho = -\frac{3\Phi_\infty R_m}{4\pi R_S^2 t} F_2(t)\left(\cos 2\theta + \frac{1}{3}\right)$$

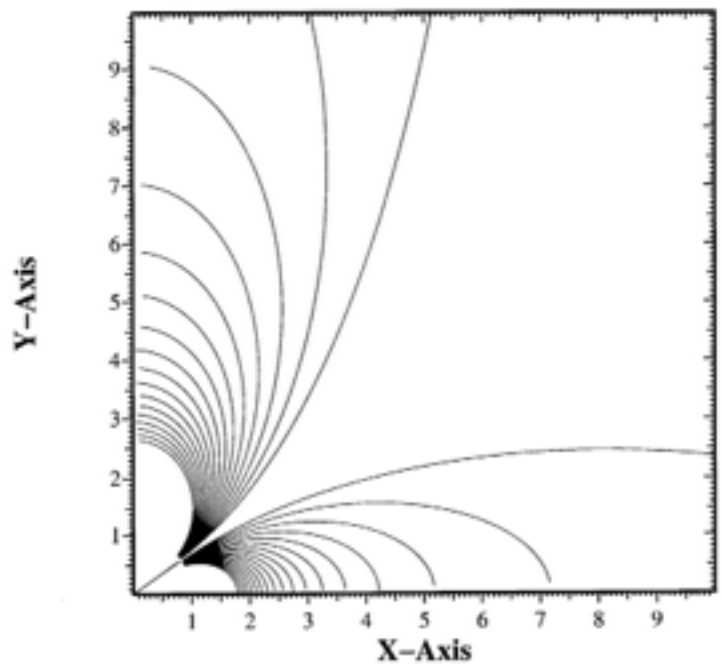
$$J_R = \sigma E_R \qquad J_\theta = -\frac{\sigma \Phi_\infty R_m}{R_S^2 t^3}\left(1 + \frac{4}{t}\right)\sin 2\theta$$

$$Q_2(1/t) = 1 + 6t + 18t^2 + 24t^3 \qquad F_2(1/t) = t \cdot \left(1 + 6t + 12t^2\right)$$

$$t = R_m \frac{R}{R_S} \qquad R_m = \mu_0 \sigma V_0 R_S$$

Heliospheric magnetic and electric fields





Saha equation

- $n_e n_+ / N = A(g_+/g_n) T^{3/2} \exp(-I/kT)$
- $A = 2(m_e k_B/\hbar)^{3/2} = 4{,}85\ 10^{15}\ \mathrm{sm}^{-3}\mathrm{K}^{-3/2}$
- For He, Xn $g_+ = 6$ and $g_n = 1$,
- but for Na, K $g_+ = 1$ and $g_n = 2$
- Coulomb electron cross-section is
- $\sigma_C \cong 2{,}3 \cdot 10^{-17}\ \mathrm{m}^2$ for $T_e = 1$ eV
- $\sigma_n \cong 1 \cdot 10^{-20}\ \mathrm{m}^2$ for neutrals

- $\sigma_P=(\nu_{en}/(\nu_{en}{}^2+\omega_e{}^2)+m_e\nu_{in}/m_i(\nu_{in}{}^2+\omega_i{}^2))n_e e^2/m_e$

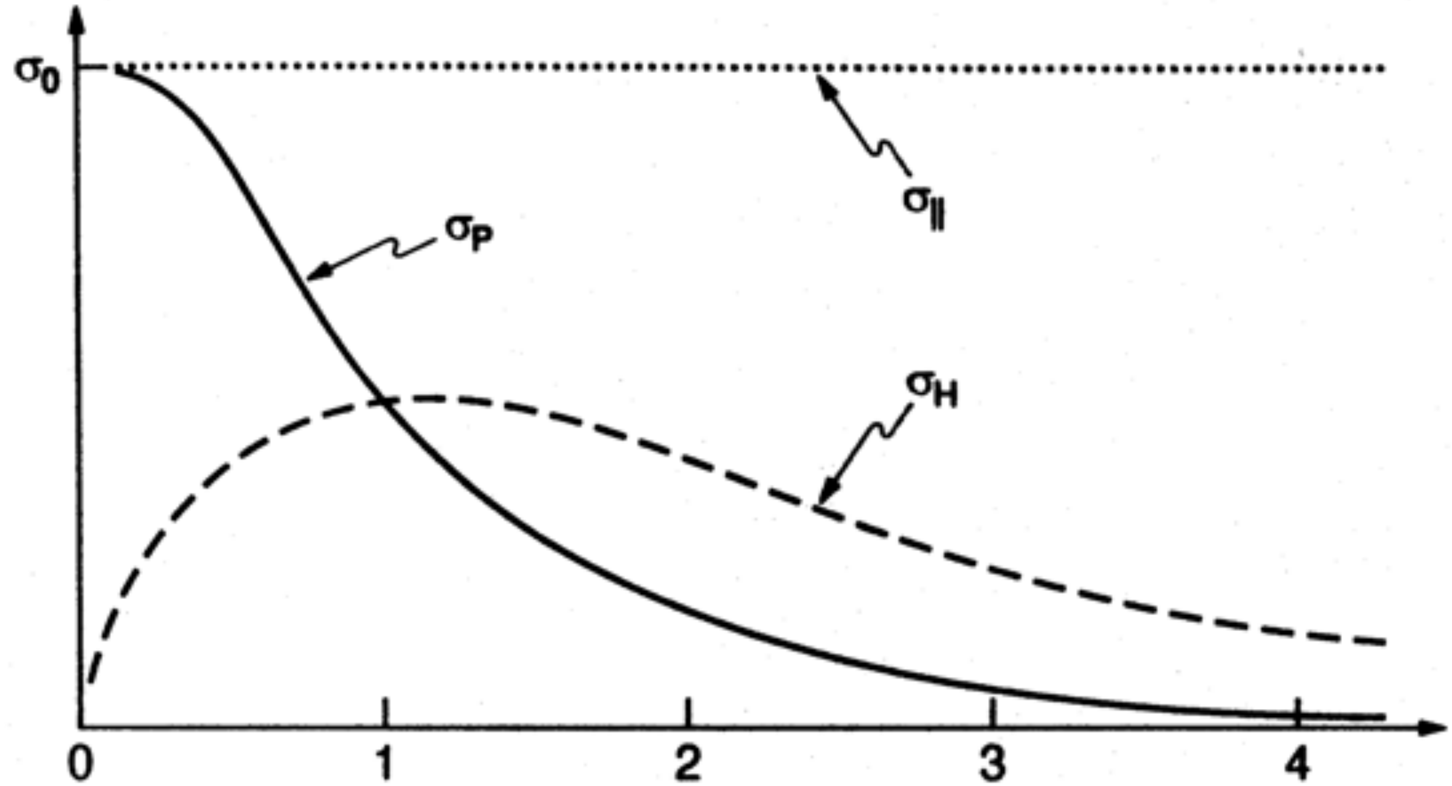
- $\sigma_H=(\omega_e/(\nu_{en}{}^2+\omega_e{}^2)+m_e\omega_i/m_i(\nu_{in}{}^2+\omega_i{}^2))n_e e^2/m_e$

- $\sigma_0=(1/\nu_{en}+m_e/m_i\nu_{in})n_e e^2/m_e$

- $\nu_m = n_e\, \sigma_C v_e + N_n\, \sigma_n v_e$

- $\sigma_0 = e/m_e\nu_m = 9(k_B T)^2 / (4\pi e^2\, m_e v_e\, \ln\Lambda)$

  $\cong 1{,}9 \bullet 10^4\, (\mathrm{T[эВ]})^{3/2} / \ln\Lambda\ \mathrm{Ohm}^{-1}\ \mathrm{m}^{-1}$



ω_B / ν_c

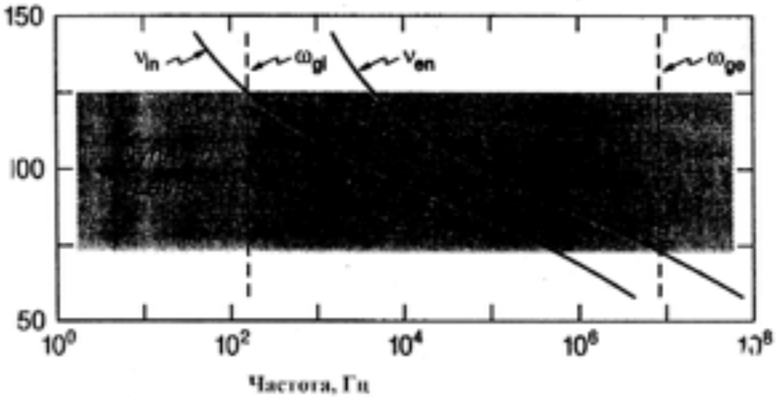
$\omega_B = qB/m << \nu_c$

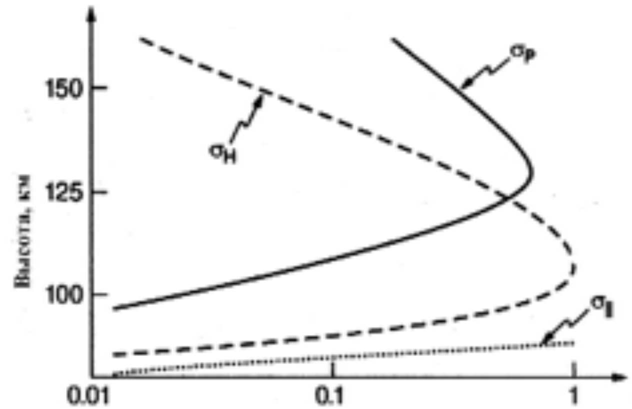
To a good approximation, the velocity can be obtained by balancing the Lorentz force and the frictional force caused by collisions with neutrals [e.g., Richmond, 1995]. The resultant conductivity expressions are

$$\sigma_P = \sum_i \sum_n \frac{N_i e}{B} \left(\frac{\nu_{en\perp} \Omega_e}{\nu_{en\perp}^2 + \Omega_e^2} + \frac{\nu_{in} \Omega_i}{\nu_{in}^2 + \Omega_i^2} \right)$$

$$\sigma_H = \sum_i \sum_n \frac{N_i e}{B} \left(\frac{\Omega_e^2}{\nu_{en\perp}^2 + \Omega_e^2} - \frac{\Omega_i^2}{\nu_{in}^2 + \Omega_i^2} \right),$$

Dynamo layer





$\mathbf{j} = \sigma_0 \mathbf{E}_0 + \sigma_P\, \mathbf{E}_\perp - \sigma_H [\mathbf{E} \mathrm{x} \mathbf{B}]/B$

Numerical estimation

$$e.m.f. \quad \Phi_0 = \frac{\Omega_0 B_0 R_S^2}{2} \quad \Omega_0 = 2.7 \cdot 10^{-6}\, s^{-1} \quad B_0 = 10\ G \quad R_S = 0.7 \cdot 10^9\, m$$

$$I = 2.65\,\mathrm{GA} \quad \Phi_0 = 0.66\ GV$$

$$W_J = 2 \cdot I \cdot \Phi_0 = 3.5 \cdot 10^{18}\, W$$

$$W_S = 3.84 \cdot 10^{26}\, W$$

$$W_B = V_0 B_0^2 R_S^2 = 4.0 \cdot 10^{22}\, W$$

$$L_B = 10^{-2}\, R_s \qquad L_J = 10^{-2}\, L_B$$

Conclusions

- The analitic (kinematic) solution of the problem solar wind expansion into heliosphere give us possibility to check the numerical solution.

- Joule heating in the dynamo region of the solar atmosphere can be essential if the latitudial size of closure current region is about several degrees .

Thank you !!!