Joule Heating and the Atmospheric Dynamo

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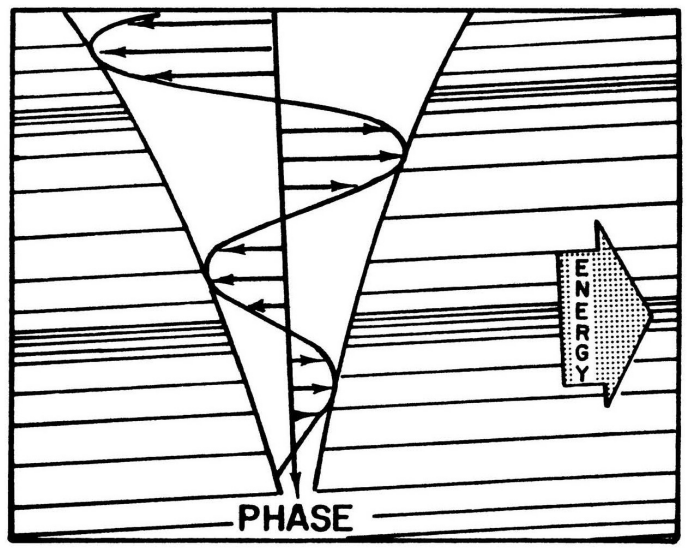
$14\#^{th}$ 2021-11-29, Kiruna

November 29, 2021



from C. O. Hines, The Upper Atmosphere in Motion, p. 1027, 1974

Back to basics

- Einstein (1905), Zur Elektrodynamik bewegter Körper:
- the electric field depends on the reference frame;
- $\vec{E}_\perp{}' = \gamma\left(\vec{E}_\perp + \vec{v} \times \vec{B}\right)$, Joules-Bernoulli equation; Jackson (1975), Classical Electrodynamics
- $\gamma = 1/\sqrt{1 - v^2/c^2} \approx 1$
- relative $\vec{v}$ between reference frames, i.e. a constant vector

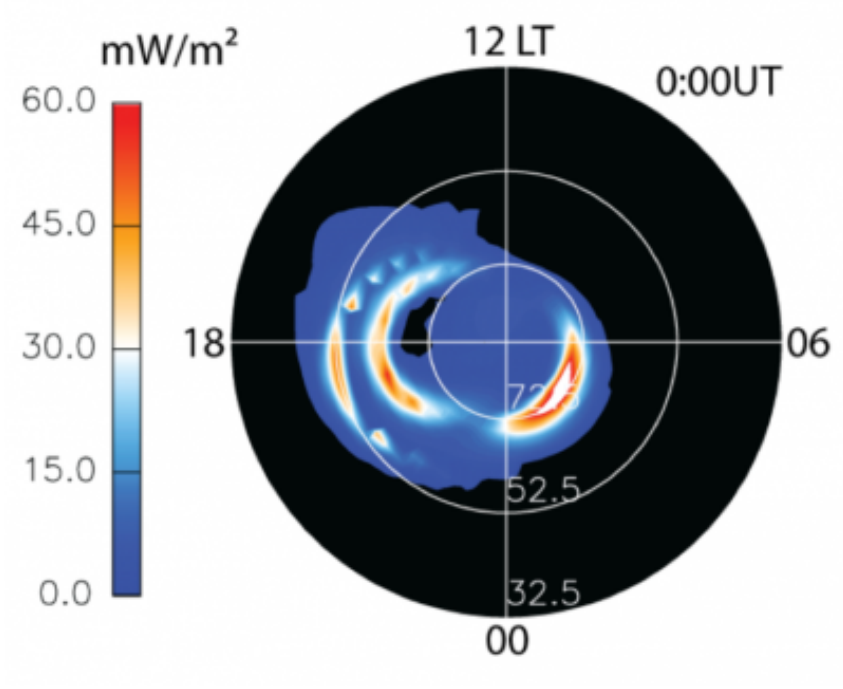
Joule heating

- Ohm's law in the ionosphere:

$$\vec{j}_\perp = \sigma_P \left(\vec{E}_\perp + \vec{u} \times \vec{B} \right) - \sigma_H \left(\vec{E}_\perp + \vec{u} \times \vec{B} \right) \times \vec{B}/B$$

- the field in the reference frame of the neutral gas, $\vec{E}_\perp + \vec{u} \times \vec{B}$, determines currents;
- which field determines Joule heating?
- also $\vec{j} \cdot \left(\vec{E}_\perp + \vec{u} \times \vec{B} \right)$ must be used
- and gives the dissipated heat, Vasyliūnas and Song (2005);
- (some publications say that $\vec{j} \cdot \left(\vec{u} \times \vec{B} \right)$ is an "acceleration term", which is incorrect)
- forces are $\vec{j} \times \vec{B}$ or, equivalently, ion drag.

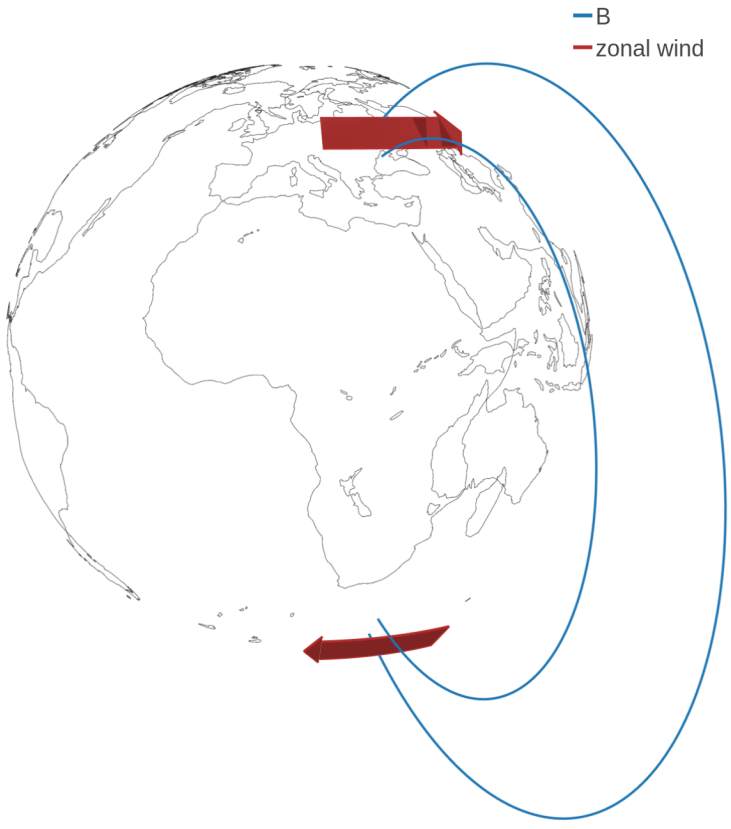
Joule heating driven by ionosphere-magnetosphere coupling

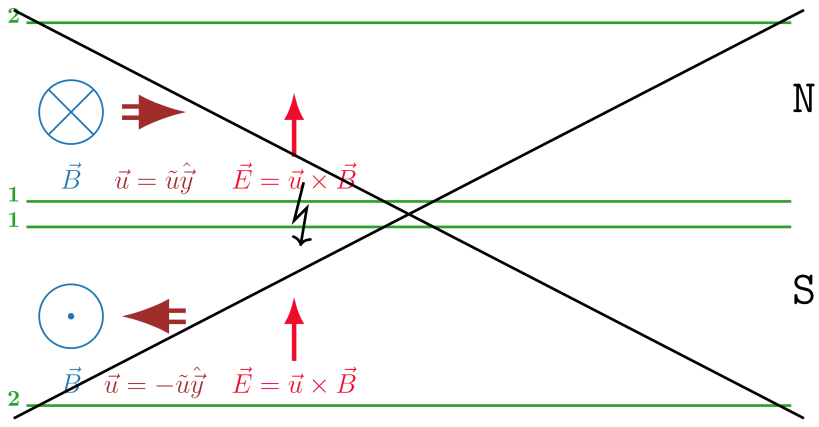


Joule heating of the ionosphere simulated by the NCAR TIE-GCM

- is being intensely studied.

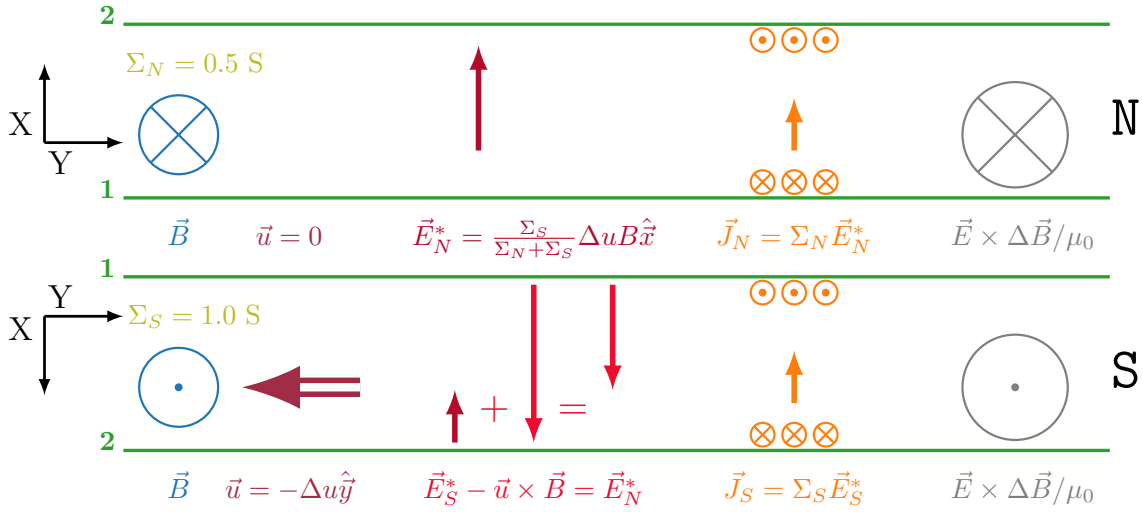
Electric fields and JH at mid-latitudes



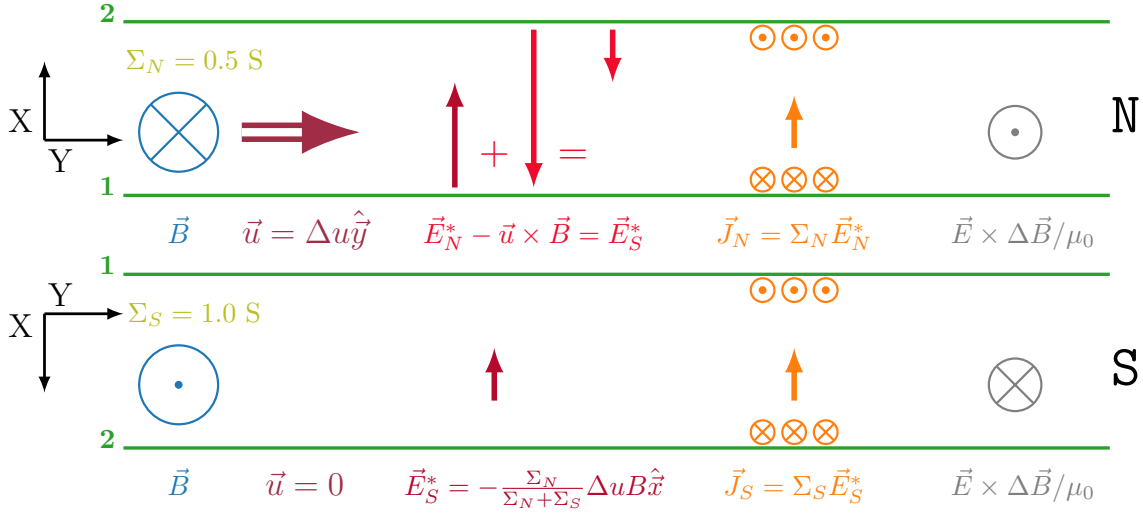


- because of high conductivity $\sigma_{\parallel}$
- $\vec{E}_{\perp} + \vec{u} \times \vec{B} \neq 0$, the field in the neutral gas frame cannot be 0 in both hemispheres;
- different zonal winds in both hemisphere cause currents and JH!

Instead, in the northern reference frame



and in the southern reference frame



Equations

E_N^* and E_S^* are fields transformed into the northern and southern reference frames, respectively

1. $\vec{E}^* - \Delta\vec{u} \times \vec{B}$ otherwise there would be a non-zero $E_{\|}$:

$$E_N^* = E_S^* + \Delta u B \tag{1}$$

   Δu is positive for $u_{y,N} > u_{y,S}$.

2. the current loop between N and S closes, $\nabla \cdot \vec{j} = 0$:

$$J_N = \Sigma_N E_N^*, \; J_S = \Sigma_S E_S^*; \tag{2}$$

$$J_N + J_S = \Sigma_N E_N^* + \Sigma_S E_S^* = 0 \tag{3}$$

Solutions

$$E_N^* = \frac{\Sigma_S}{\Sigma_N + \Sigma_S} \Delta u B = -\frac{\Sigma_S}{\Sigma_N} E_S^* \tag{4}$$

and

$$E_S^* = -\frac{\Sigma_N}{\Sigma_N + \Sigma_S} \Delta u B = -\frac{\Sigma_N}{\Sigma_S} E_N^* \tag{5}$$

Pedersen current in N and S:

$$J = \frac{\Sigma_N \Sigma_S}{\Sigma_N + \Sigma_S} \Delta u B \tag{6}$$

Joule heating rates

$$Q_N = \Sigma_N \left(\frac{\Sigma_S}{\Sigma_N + \Sigma_S} \Delta u B \right)^2 = \frac{\Sigma_S}{\Sigma_N} Q_S \tag{7}$$

and

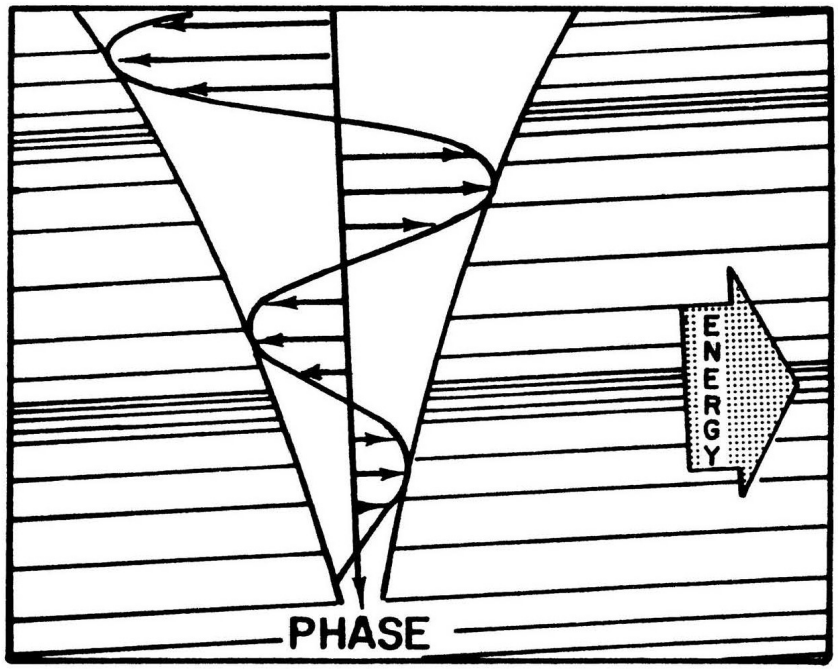
$$Q_S = \Sigma_S \left(\frac{\Sigma_N}{\Sigma_N + \Sigma_S} \Delta u B \right)^2 = \frac{\Sigma_N}{\Sigma_S} Q_N \tag{8}$$

$$Q = Q_N + Q_S = \frac{\Sigma_N \Sigma_S}{\Sigma_N + \Sigma_S} (\Delta u B)^2 \tag{9}$$

- this basically explains the Sq (solar quiet) magnetic variations (known since ~ 400 years);
- the driver is wind *differences* between N and S, ΔuB ($\Delta w = u_N B_N - u_S B_S$ for also asymmetric $\vec{B}$)
- "entangled" dynamos:
- to see the load, go into the references frame of the northern (southern) neutral gas;
- in this frame the other is hemisphere is the corresponding dynamo, i.e. $\vec{j} \cdot \vec{E} < 0$
- Lorentz/drag forces try to achieve magnetically symmetric wind patterns.

Neutral wind variations within the ionosphere

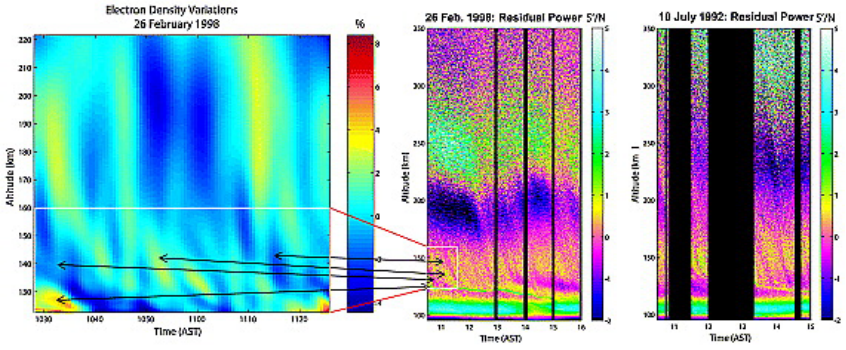
- gravity waves from below:



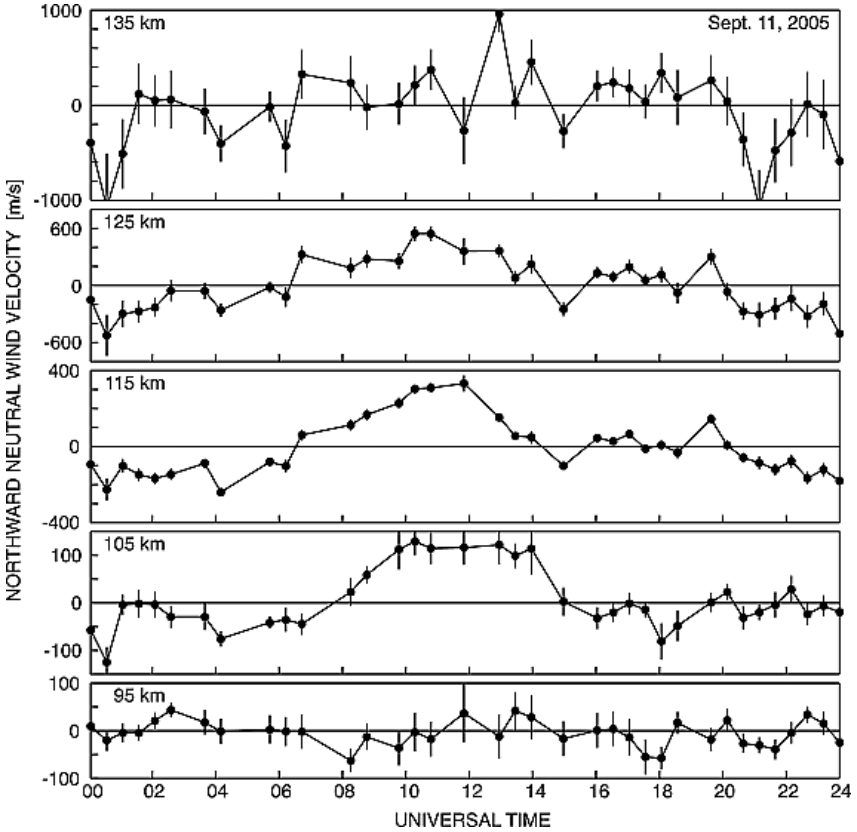
from C. O. Hines, The Upper Atmosphere in Motion, p. 1027, 1974

- do similarly have a dynamo effect, drive currents and cause JH;
- currents close within the ionosphere, top side $j_{\parallel} = 0$;
- the top side $\vec{E}$ in an Earth fixed frame might be zero;
- $\rightarrow$ magnetic effect not observable at the ground or by satellites in LEOs
- is JH by the atmospheric dynamo part of the missing energy in the lower thermosphere?
- ("fudge factor", ≈ 1.8, in TIE CGM)

Height resolved neutral wind estimated with EISCAT



from Duth et al. (2004), A continuum of gravity waves in the Arecibo thermosphere?



from Nygren et al., JGR, 2011

- in the future with E3D:
- Stamm et al., AG, 2021
- my present project: clarify the physical implications
  - Joule heating of the thermosphere
  - damps upward propagating gravity waves (more than viscosity?)