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Electron Vortices in Earth's Magnetotail

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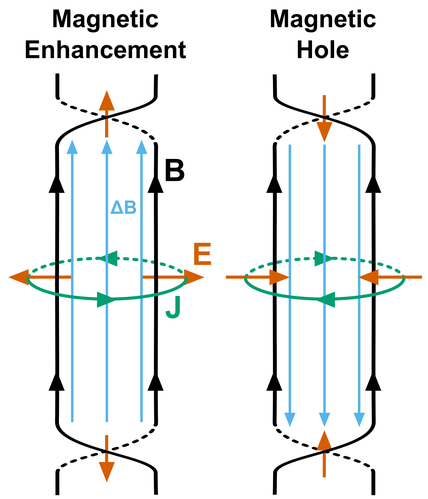
What Are Electron Vortices?

Electron vortices are often associated with kinetic-scale magnetic holes

Azimuthal current carried by frozen-in electrons is supported by a radial $\boldsymbol{E}$

Current can lead to a depletion or enhancement of the field depending on orientation (inward/outward) of $\boldsymbol{E}$

Linked with both turbulence and reconnection and may play a role in wave excitation and $\boldsymbol{j} \cdot \boldsymbol{E}$



Force Balance

Electron vortices can be understood through the balance between the Hall term and the ion and/or electron pressure forces

Ion Momentum Equation

$$\boldsymbol{E}_{ion} = \boldsymbol{E}_{plas} + \delta\boldsymbol{u}_i \times \boldsymbol{B} = \frac{1}{en}\nabla \cdot \boldsymbol{p}_i + \frac{m_i}{en}\left[\nabla \cdot (n\boldsymbol{u}_i\boldsymbol{u}_i) + \frac{\partial n\boldsymbol{u}_i}{\partial t}\right]$$

Electron Momentum Equation

$$\boldsymbol{E}_{ion} = \boldsymbol{E}_{plas} + \delta\boldsymbol{u}_i \times \boldsymbol{B} = \frac{1}{en}\boldsymbol{j} \times \boldsymbol{B} - \frac{1}{en}\nabla \cdot \boldsymbol{p}_e + \frac{m_e}{en}\left[\nabla \cdot (n\boldsymbol{u}_e\boldsymbol{u}_e) + \frac{\partial n\boldsymbol{u}_e}{\partial t}\right]$$

Ion-balanced vortex

$$\boldsymbol{j}_\perp = -en\frac{\boldsymbol{E}_{plas} \times \boldsymbol{B}}{B^2} = -\frac{(\nabla \cdot \boldsymbol{p}_i) \times \boldsymbol{B}}{B^2}$$

$$\Delta\left(\frac{B^2}{2\mu_0}\right) = \Delta p_{i,\perp}$$

Electron-balanced vortex

$$\boldsymbol{j}_\perp = -\frac{(\nabla \cdot \boldsymbol{p}_e) \times \boldsymbol{B}}{B^2}$$

$$\Delta\left(\frac{B^2}{2\mu_0}\right) = \Delta p_{e,\perp}$$

$$\boldsymbol{j}_\perp = -en\frac{\boldsymbol{E}_{plas} \times \boldsymbol{B}}{B^2} - \frac{(\nabla \cdot \boldsymbol{p}_e) \times \boldsymbol{B}}{B^2} = -\frac{[\nabla \cdot (\boldsymbol{p}_i + \boldsymbol{p}_e)] \times \boldsymbol{B}}{B^2}$$

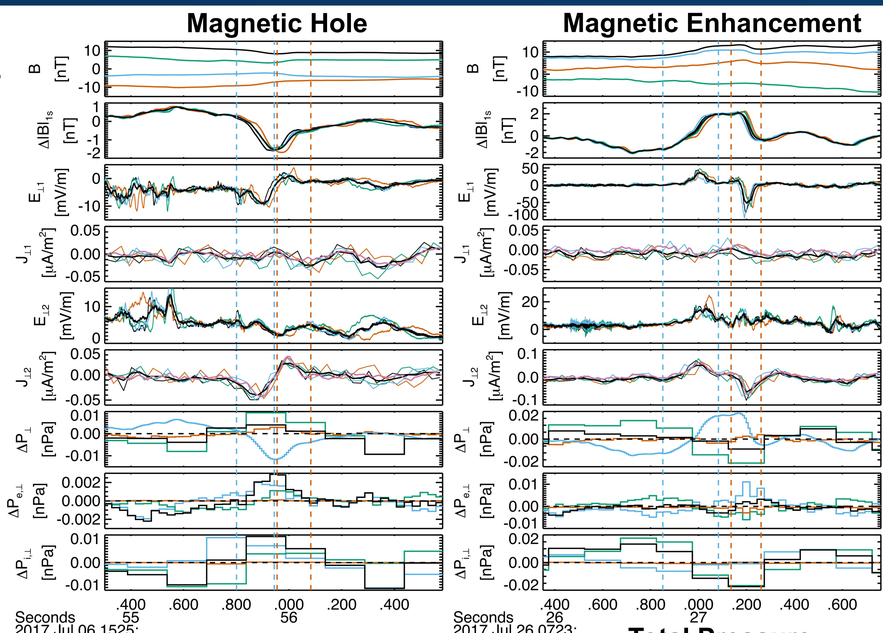
$$\Delta\left(\frac{B^2}{2\mu_0}\right) = \Delta\left(p_{i,\perp} + p_{e,\perp}\right)$$

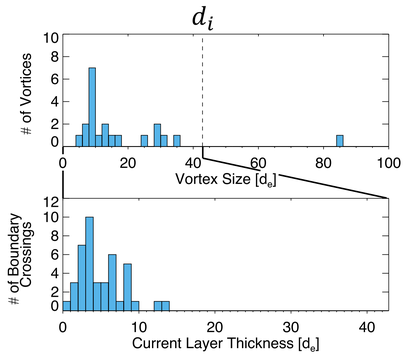
Observations

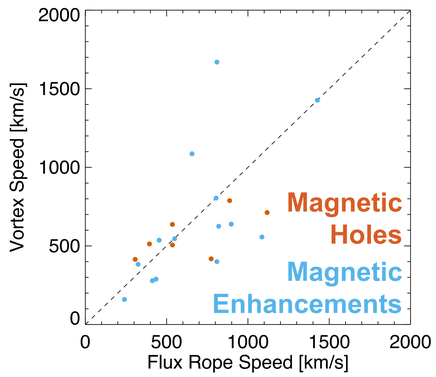
Motivated by Stawarz+ [2018, *GRL*], which reported a small-scale electron vortex inside of a flux rope associated with magnetotail reconnection

Examined 108 flux ropes observed during 2017 tail season for evidence of electron vortices
→ isolated magnetic enhancements or depletions with bipolar $\boldsymbol{j}_\perp$ and $\boldsymbol{E}_\perp$

Identified 21 electron vortices
(14 magnetic enhancements; 7 magnetic holes)







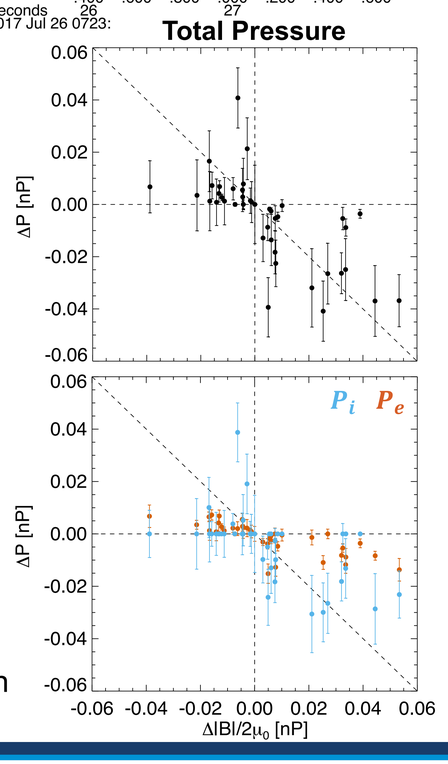
(Left) Based on timing analysis:
→ Vortices tend to be sub-proton scale both in terms of current layer thickness and overall size

→ Speed of the vortices tends to match motion of flux rope they are embedded within, indicating they are moving with surrounding plasma

(Right) Vortices roughly in pressure balance, as expected

Despite being sub-ion-scale structures, ion dynamics are needed to account for the magnetic perturbation

Role of ions may be partially understood through quasi-neutrality and significant contribution of $T_0\Delta n$ to pressure perturbation



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