Kelvin-Helmholtz (KH) Vortex-generated Field-Aligned Currents

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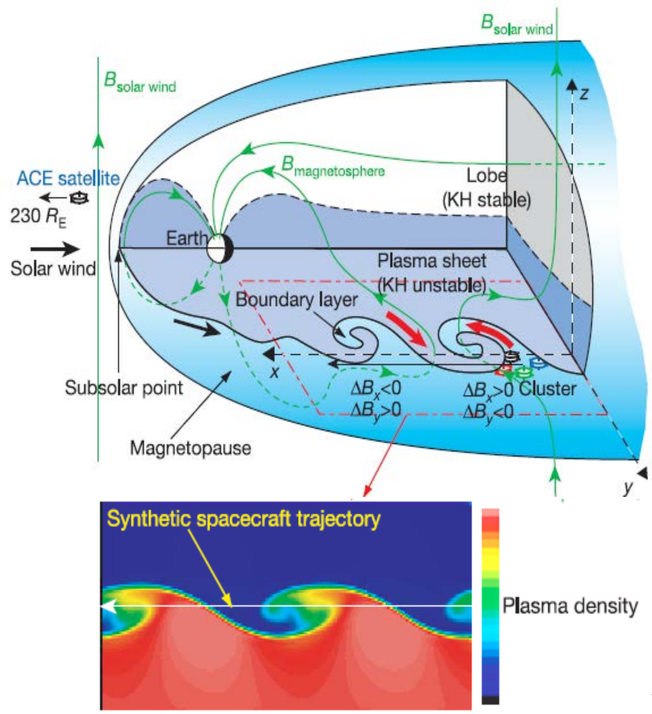
This study was partially supported by NSF AGS-1305374

Acknowledgements: MMS FPI, FGM, EDP teams, Cluster FGM, CIS, PEACE, EFW teams, FAST teams, and THEMIS GMAG/ASI teams

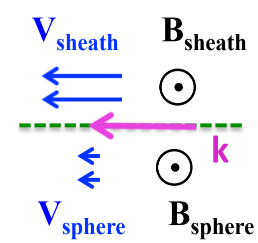
Kelvin-Helmholtz Waves/Vortices (KHW/KHV)



[*Hasegawa et al.*, 2004]

- KH instability (KHI): (Magneto-) Hydro-Dynamic instability that grows in a velocity shear layer (between the fast anti-sunward magnetosheath and the stagnant magnetosphere)
- KHI is one of mechanisms by which the shocked solar wind enters into the Earth's magnetosphere at the Earth's magnetopause/LLBL (low-latitude boundary layer)
- Kelvin-Helmholtz instability condition [*Chandrasekhar*, 1961; *Hasegawa*, 1975]:

$$\left[\mathbf{k}\cdot(\mathbf{v}_2-\mathbf{v}_1)\right]^2 > \frac{1}{\mu_0}\left(\frac{1}{\rho_1}+\frac{1}{\rho_2}\right)\left[(\mathbf{B}_1\cdot\mathbf{k})^2+(\mathbf{B}_2\cdot\mathbf{k})^2\right]$$



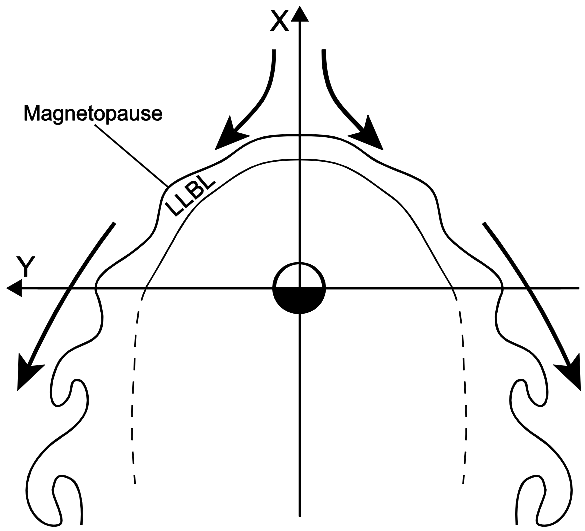
✓ For incompressional plasmas and an infinitely thin velocity shear layer

✓ In general, this condition is valid for KHW with λ > boundary thickness and subsonic velocity-shear regions [e.g., *Ong & Roderick*, 1972; *Miura & Pritchett*, 1982; *Gratton et al.*, 2004; *Gnavi et al.*, 2006]

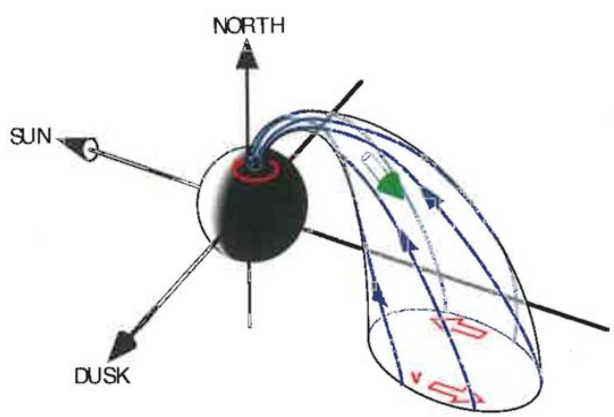
How do the magnetopause and/or LLBL KHW/KHV affect the Earth's magnetosphere and ionosphere?

- Plasma mixing and transport [e.g., *Fairfield et al.*, 2000; *Nakamura et al.*, 2006; *Pegoraro et al.*, 2008; *Nakai & Ueno*, 2011]
- Momentum and energy transport [e.g., *Pu & Kivelson*, 1983; *Miura*, 1984; *Kivelson and Chen*, 1995; *Hasegawa et al.*, 2006; *Turkakin et al.*, 2013]
- A source of ULF pulsations in the Pc4-5 (2-22 mHz) range [*e.g.*, *Kivelson & Southwood*, 1986; *Matie & Mann*, 2001; *Agapitov et al.*, 2009], which modulate particle density/energy fluxes
- Launch nonlinear fast-mode plane waves developed at the ridges of KHW into the magnetosphere [*Lai & Lyu*, 2006]
- Inject high-density, low-entropy plasmas of solar wind origin that rapidly penetrate into the inner plasma sheet via the Kelvin-Helmholtz instability together with interchange instability [*Wiltberger et al.*, 2000; *Lyon*, 2009; *Pembroke et al.*, 2011]
- Generate field-aligned currents associated with the twisted field lines [*THIS* preparation]

Prediction-1



[Adeopted from Hasegawa+, 2009]



[Paschmann, 2003; Fig by Birn]

- ✓ **Nonlinear KHW develop into flow vortices that twist or shear flux tube magnetic fields, thereby generating localized field-aligned currents.**
- ✓ **KHV on the dusk (dawn) flanks of the magnetosphere generate clockwise (counter-clockwise) rotations, which correspond to upward (downward) field-aligned currents inside the flux tubes that map to the poleward edge of auroral region.**

$$\frac{\partial J_{\parallel}}{\partial t} = \frac{1}{\mu_0}\mathbf{B}\cdot\nabla(\nabla\times\mathbf{v})_{\parallel}$$

Prediction-2

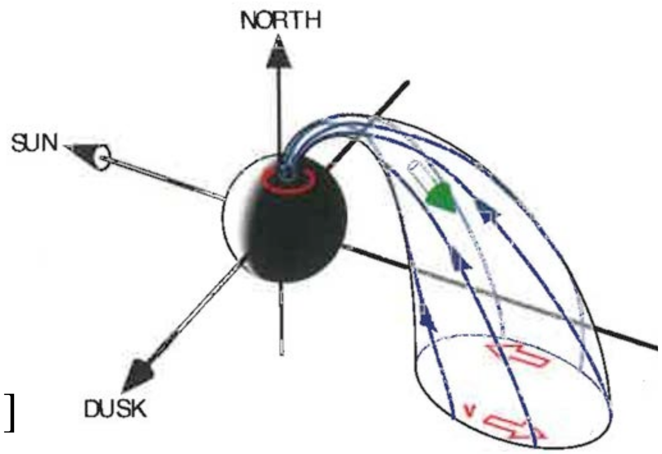
- **Field-aligned current (FAC) generation via flow motion [e.g., Song, 1998]:**

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \qquad \mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

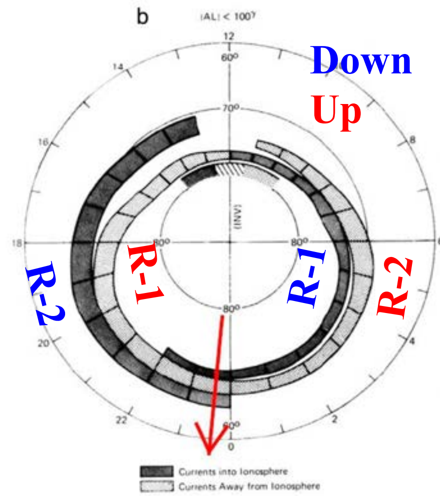
$$\frac{\partial \mathbf{J}}{\partial t} = -\frac{1}{\mu_0}\nabla \times [\mathbf{B}\nabla \cdot \mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{B} - \mathbf{B}\cdot\nabla\mathbf{v}]$$

In case of small perturbations, the first order terms of the above Eq. yield:

$$\frac{\partial J_{\parallel}}{\partial t} = \frac{1}{\mu_0}\mathbf{B}\cdot\nabla(\nabla \times \mathbf{v})_{\parallel}$$



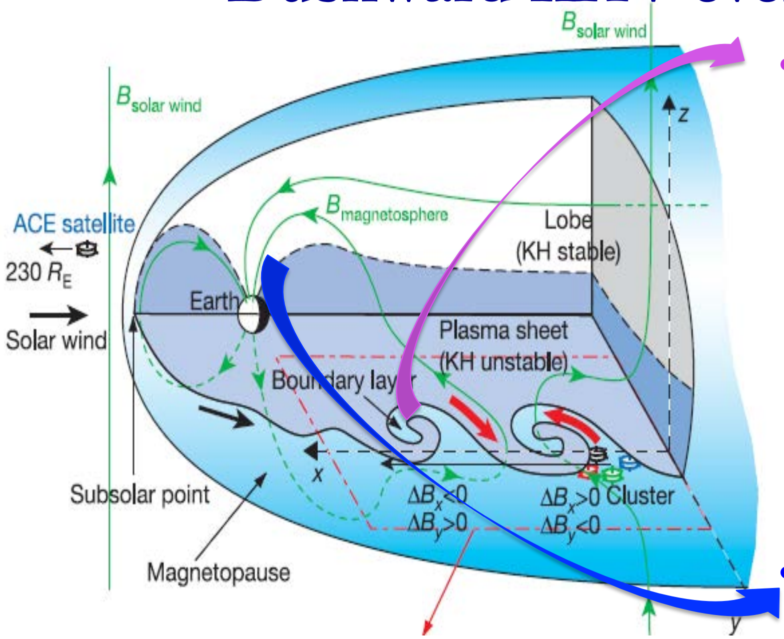
[Paschmann, 2003; Fig by J. Birn]



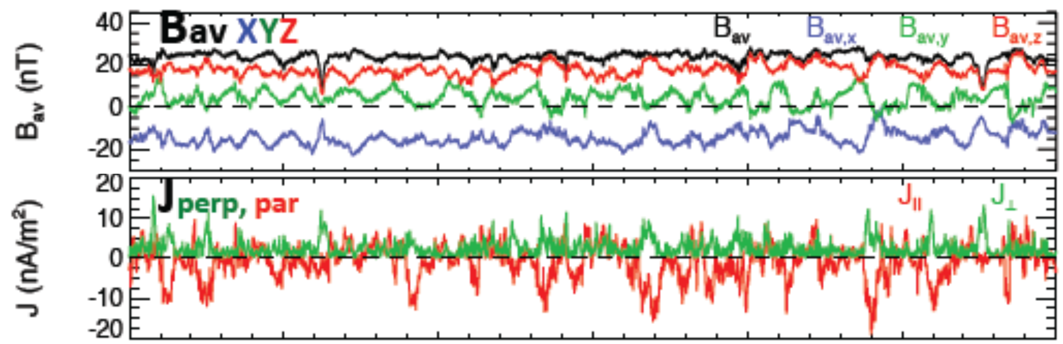
[Iijima and Potemra, 1976]

- ✓ **KHV on the dusk (dawn) flanks of the magnetosphere generate clockwise (counter-clockwise) rotations, which correspond to upward (downward) field-aligned currents inside the flux tubes.**
- ✓ **The sense of rotations at dawn/dusk-ward KHV is consistent with Region-1 current system.**

Duskward KHV event on 2001-11-20/1200-1300 UT

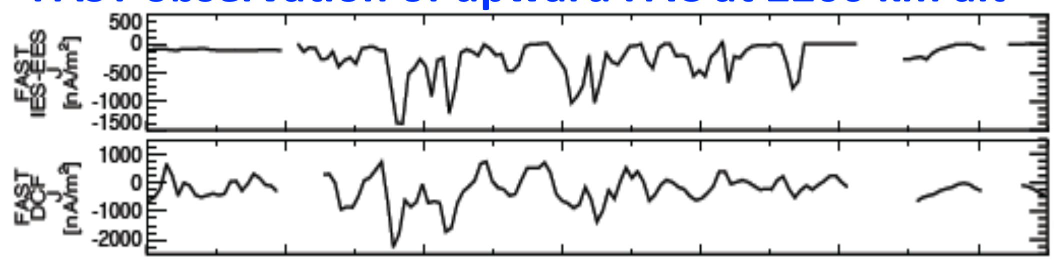


- Cluster observation of KH vortices at [-5,18,-3] R_E



✓ Periodic enhancements in $-J_z$, $-J_{||}$ (< 20 nA/m²)

- FAST observation of upward FAC at 2200 km alt



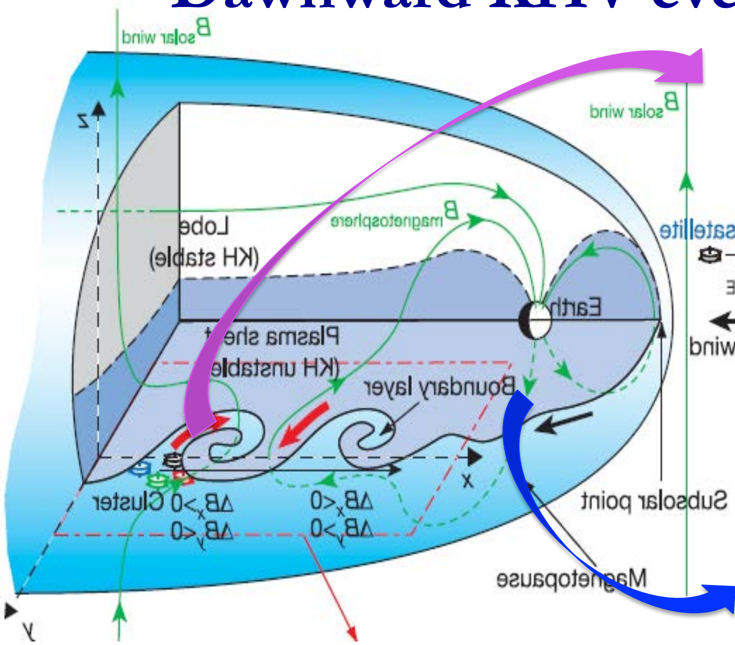
✓ **Upward (- sign) FAC densities** calculated from **dB** and **electron/ion flux** (hundreds-2000 nA/m²)

✓ Counter-clockwise rotation of vortices

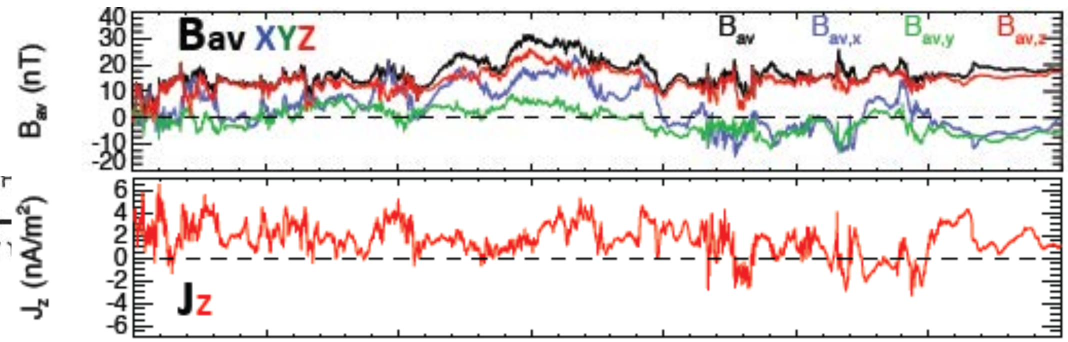
$$\frac{\partial J_{\parallel}}{\partial t} = \frac{1}{\mu_0}\mathbf{B}\cdot\nabla(\nabla\times\mathbf{v})_{\parallel}$$

✓ … generates upward FAC in the northern ionosphere.

Dawnward KHV event on 2006-07-28/0330-0430 UT

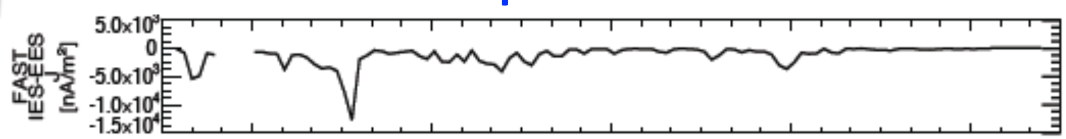


- Cluster observation of KH vortices at [-13,-13,-4] R_E



✓ Q-periodic enhancements in $+J_z$, $+J_{||}$ (6 nA/m^2)

- FAST observation of upward FAC at 2600 km alt



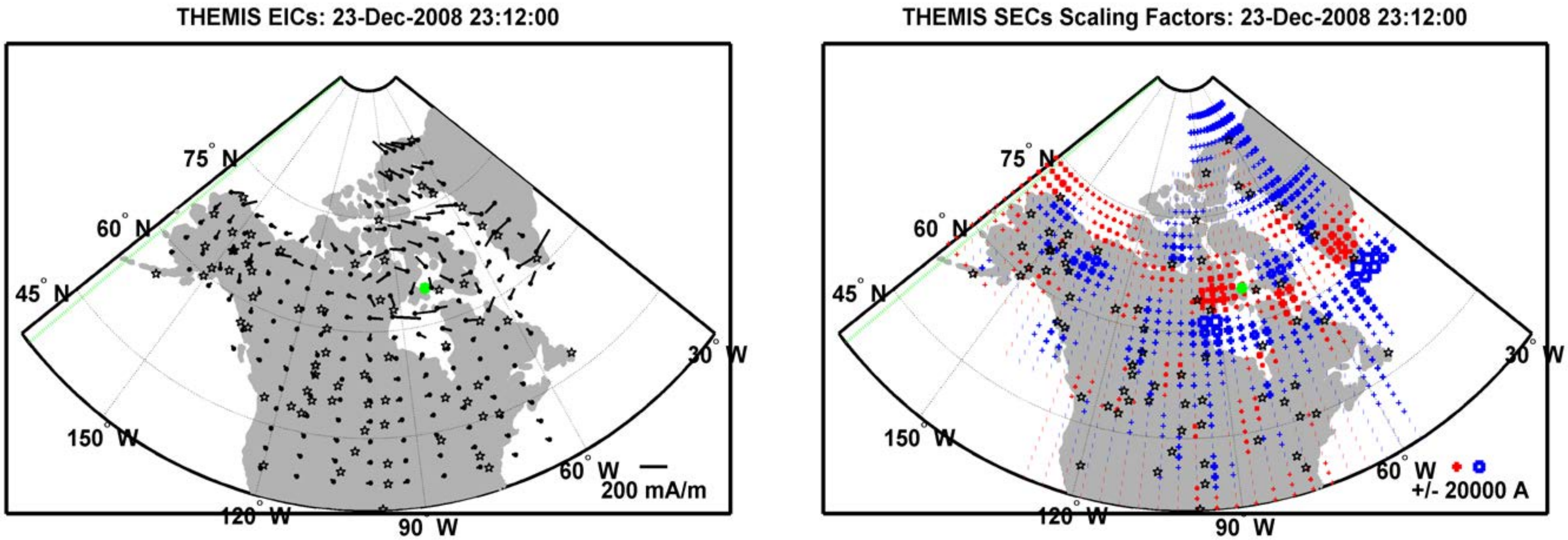
✓ **Upward (- sign) FAC densities (at the southern hemisphere)** calculated from **electron/ion flux** ranges 1000-5,000 nA/m^2.

✓ Clockwise rotation of vortices

$$\frac{\partial J_{\parallel}}{\partial t} = \frac{1}{\mu_0}\mathbf{B}\cdot\nabla(\nabla\times\mathbf{v})_{\parallel}$$

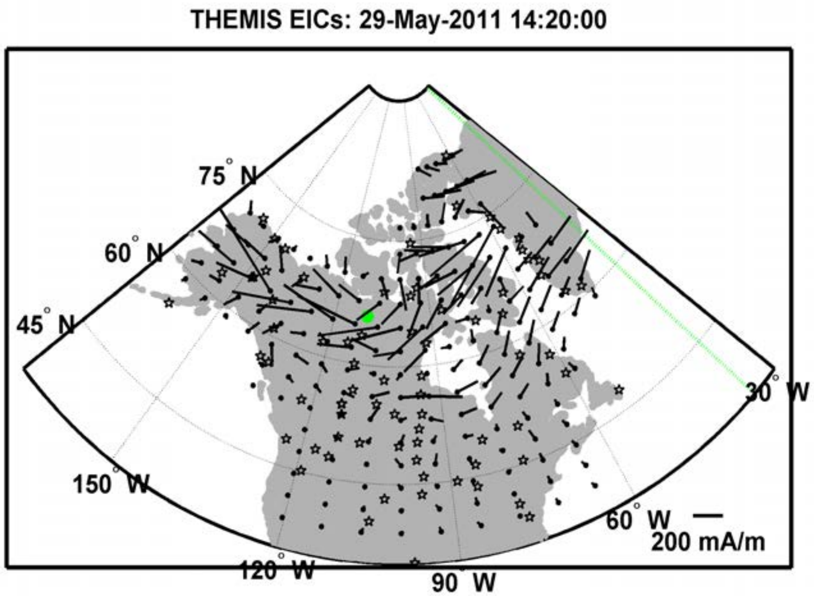
✓ … generates downward FAC in the northern ionosphere.

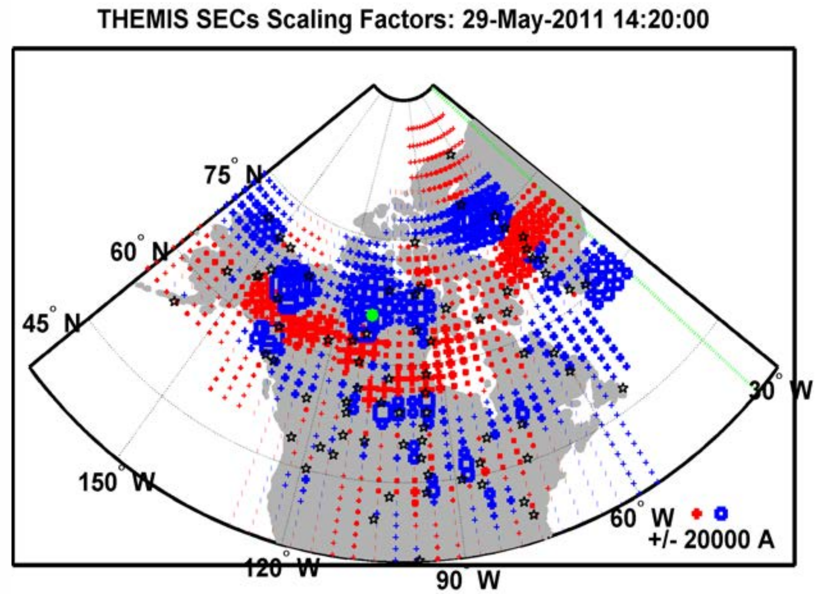
THEMIS GMAG-EIC observations for duskward KHV



- **Near the footprint of Cluster, a counter-clockwise rotation of EIC indicates upward field-aligned current (+260 nA/m^2) from current continuity [Amm and Viljanen, 1999; Keiling+, 2009; Weygand+, 2011].**
- **A structured (bead-like) FAC patterns along the east-west direction**
- **The bead-like pattern propagates tailward.**

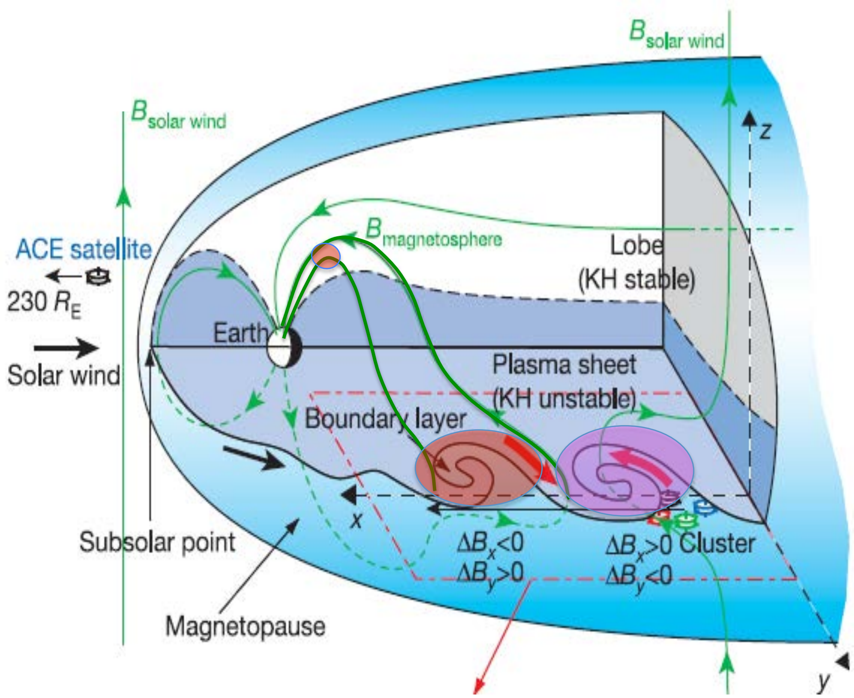
THEMIS GMAG-EIC observations for dawnward KHV





- **Near the footprint of Cluster, a clockwise rotation of EIC indicates downward field-aligned current (-1927 nA/m^2) from current continuity [Amm and Viljanen, 1999; Keiling+, 2009; Weygand+, 2011].**
- **A structured (bead-like) FAC patterns along the east-west direction**
- **The bead-like structures propagates tailward.**

Field-Aligned Current (FAC) associated with dawn/dusk KHV



Cluster statistics: 41 KHW/KHV events conjunctive to FAST/THEMIS GMAG array

- **J_{MAG}** (current density) **at KHV** (Cluster at 9-18 R_E) ≈ 3-15 nA/m^2
- **J_{ION}** (current density) **at FAST** (2500 km alt), **GMAG** (EIC-SEC) ≈ 200 - 2000 nA/m^2
- **Flux tube current conservation:**

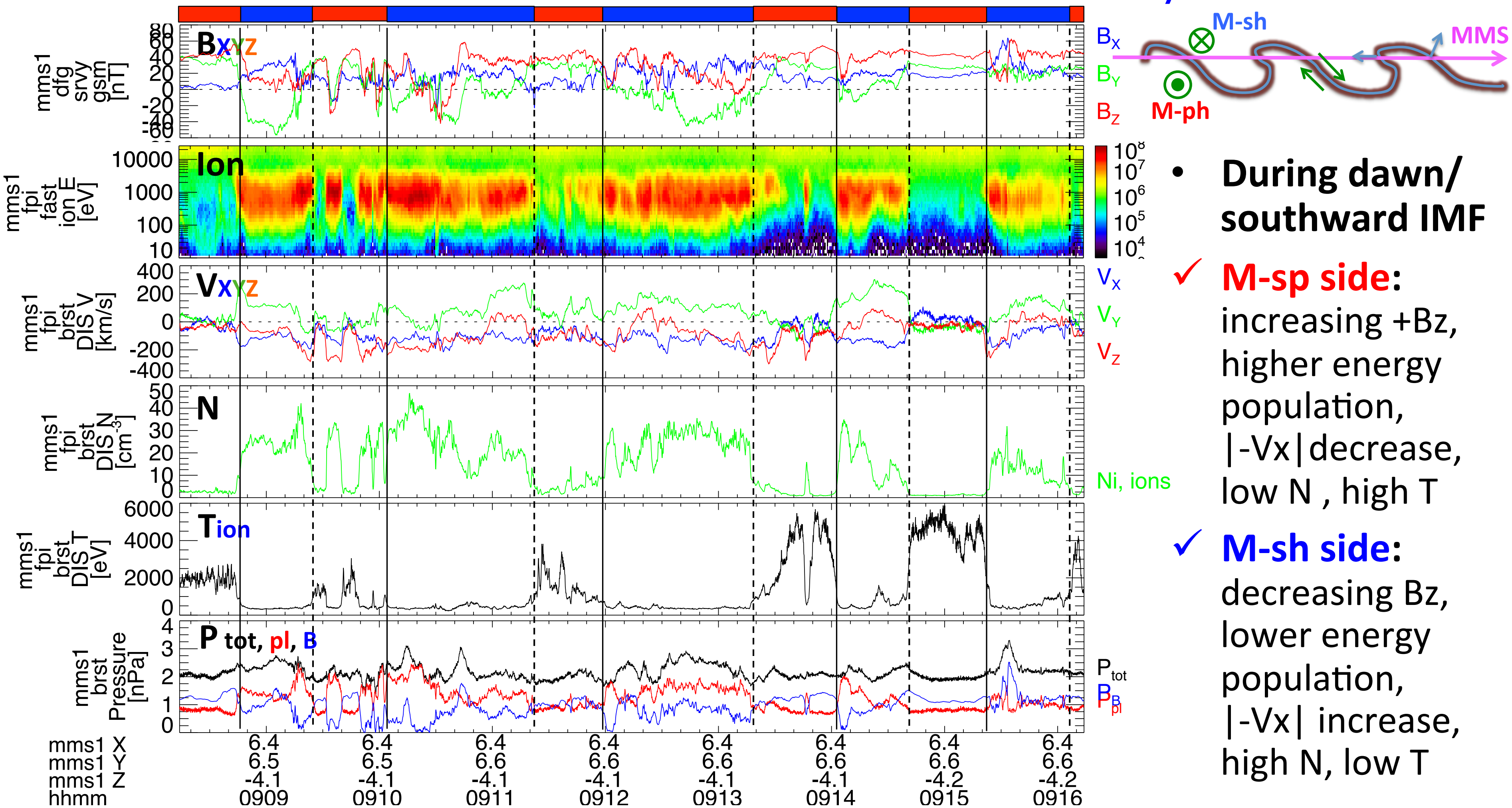
  $$(J_{ION} / J_{MAG})_{pred} \approx (R_{Cluster}/R_{FAST/1RE})^3$$

  $$\approx 700 - 2000$$

- **Total FAC driven by a single KHV:**

  (Flux tube cross-section of a KH vortex) x 3-15 nA/m^2 ≈ (0.8 – 6) MA

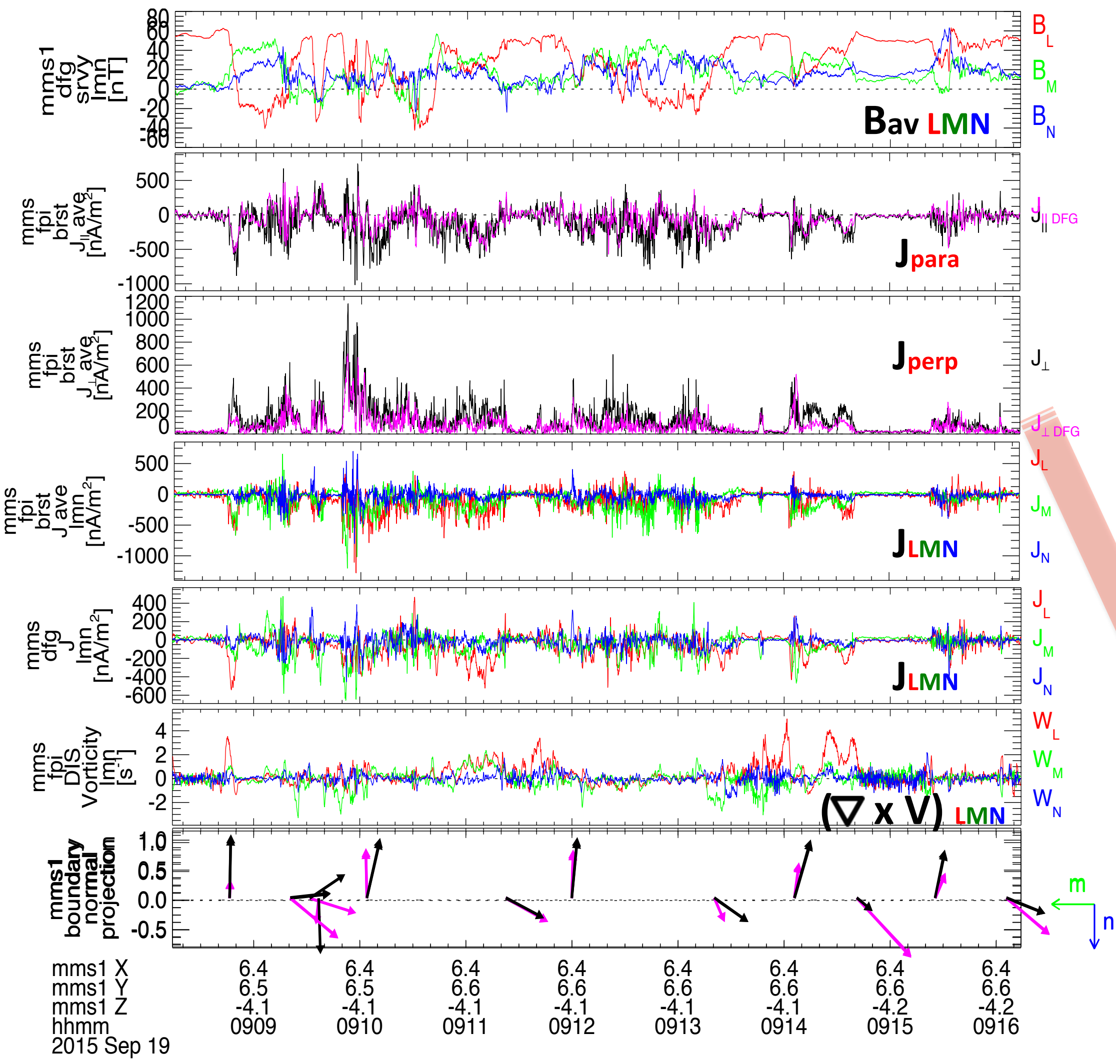
MMS observation of Duskwad KHW on 2015-09-19/0908-0916 UT



- **During dawn/ southward IMF**

✓ **M-sp side**: increasing +Bz, higher energy population, |-Vx|decrease, low N , high T

✓ **M-sh side**: decreasing Bz, lower energy population, |-Vx| increase, high N, low T



Current Density and Vorticity associated with KHW/KHV

- Using 4-spacecraft Curlometer technique [**Dunlop et al., 1988**]
- **At duskward flank of the magnetopause:**
  - ✓ Counter-clockwise rotation of vortices

$$\frac{\partial J_{\parallel}}{\partial t} = \frac{1}{\mu_0} \mathbf{B} \cdot \nabla(\nabla \times \mathbf{v})_{\parallel}$$

  - ✓ … generates upward FAC in the ionosphere.

Periodic enhancements in -Jz, -J||

Summary

- ✓ **Nonlinear KHW develop into flow vortices that twist or shear flux tube magnetic fields, thereby generating localized field-aligned currents.**
- ✓ **Kelvin-Helmholtz vortices on the dusk (dawn) flanks of the magnetosphere generate clockwise (counter-clockwise) rotations, which correspond to upward (downward) field-aligned currents inside the flux tubes.**
- ✓ **The sense of rotations at dawn/dusk-ward KHV is consistent with Region-1 current system.**
- ✓ **Statistics using In-situ Cluster/MMS observations of KHV and FAST, EIC for the ionospheric monitor suggests that KHV, at least partially, and possibly significantly, contribute to Region-1 FAC.**
- ✓ **Using MMS data, flow vorticity has, for the first time, been calculated.**

=> Flow vorticity and FAC show a certain level of correspondence.