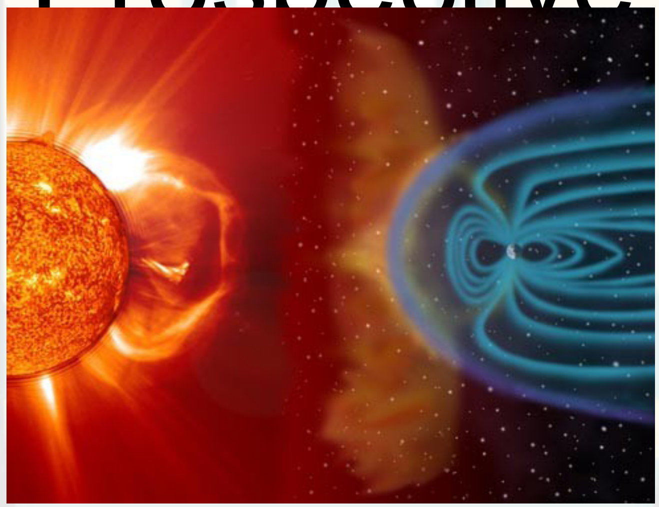
Shear and Interface Instabilities: Space Plasma Prospective



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Carolyn Kuranz, Aaron Miles, Marc Pound, Dmitri Ryutov, Uri Shumlak
WOPA Shear and Interface Instabilities Working Group

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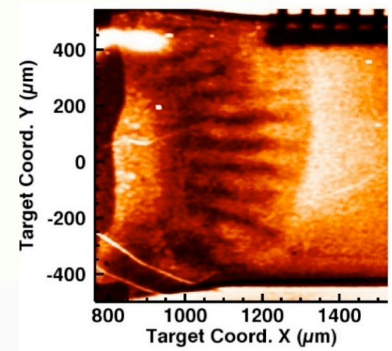
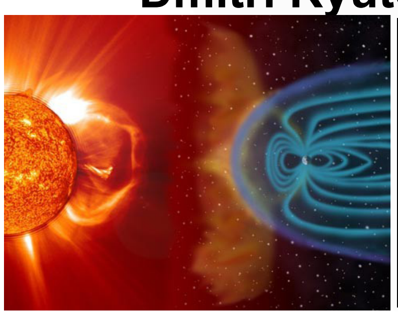
Shear and Interface Instabilities WG

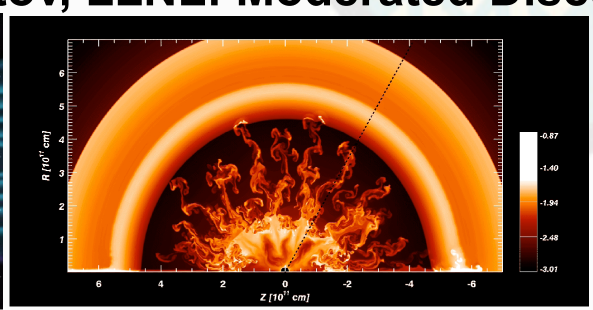
- Considered the purview of our WG to be to examine shear (essentially Kelvin-Helmholtz) and interface (essentially Rayleigh-Taylor) and closely related instabilities in a broad astrophysical context.
- Concentrated upon these instabilities ostensibly in the fluid domain, but with reference to kinetic effects as appropriate.

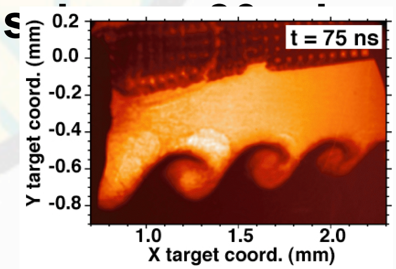


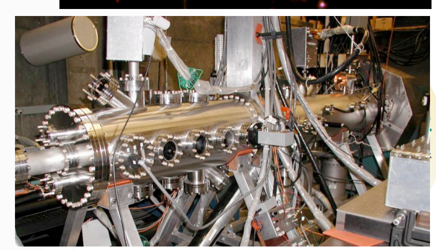
Contributions:

- **Ian Mann, U. Alberta: Space Plasma Prospective – 20 min.**
- **Marc Pound, U. Maryland: Astrophysical Prospective – 20 min.**
- **Aaron Miles, LLNL: Supernovae and Supernova Remnants – 10 min.**
- **Carolyn Kuraz, U. Michigan: High-Energy-Density Laboratory Experiments – 20 min.**
- **Uri Shumlak, U. Washington: Astrophysical Connections from Magnetic Confinement Research – 20 min.**
- **Dmitri Ryutov, LLNL: Moderated Discus**



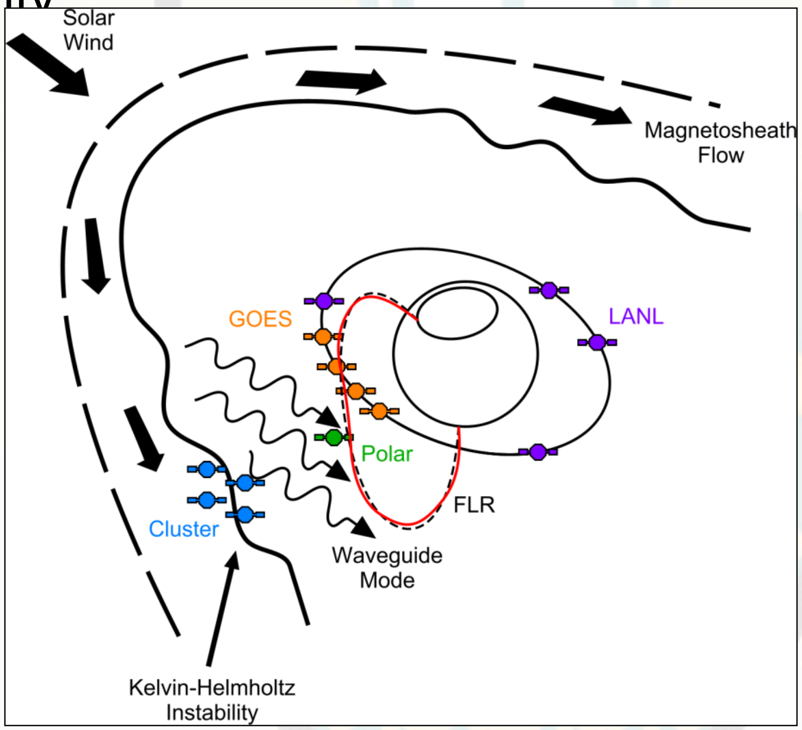


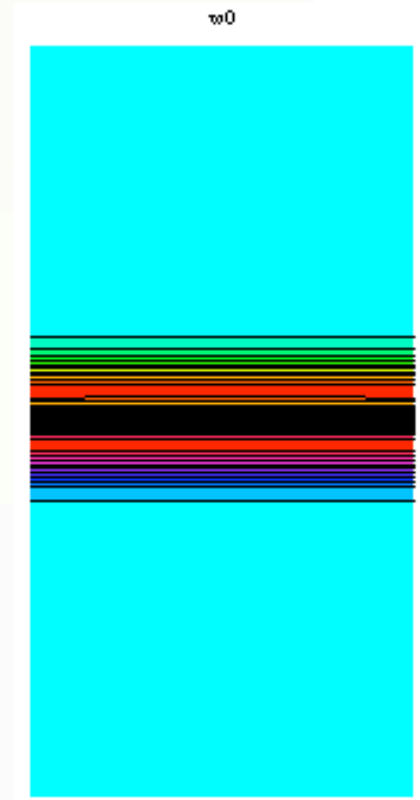




Kelvin-Helmholtz Instability (KHI)

- The KHI is driven by shear flows – the "wind over water instability"





- Traditionally considered to be confined to the shear interface ("surface waves"), but can also drive body mode ("waveguide modes").

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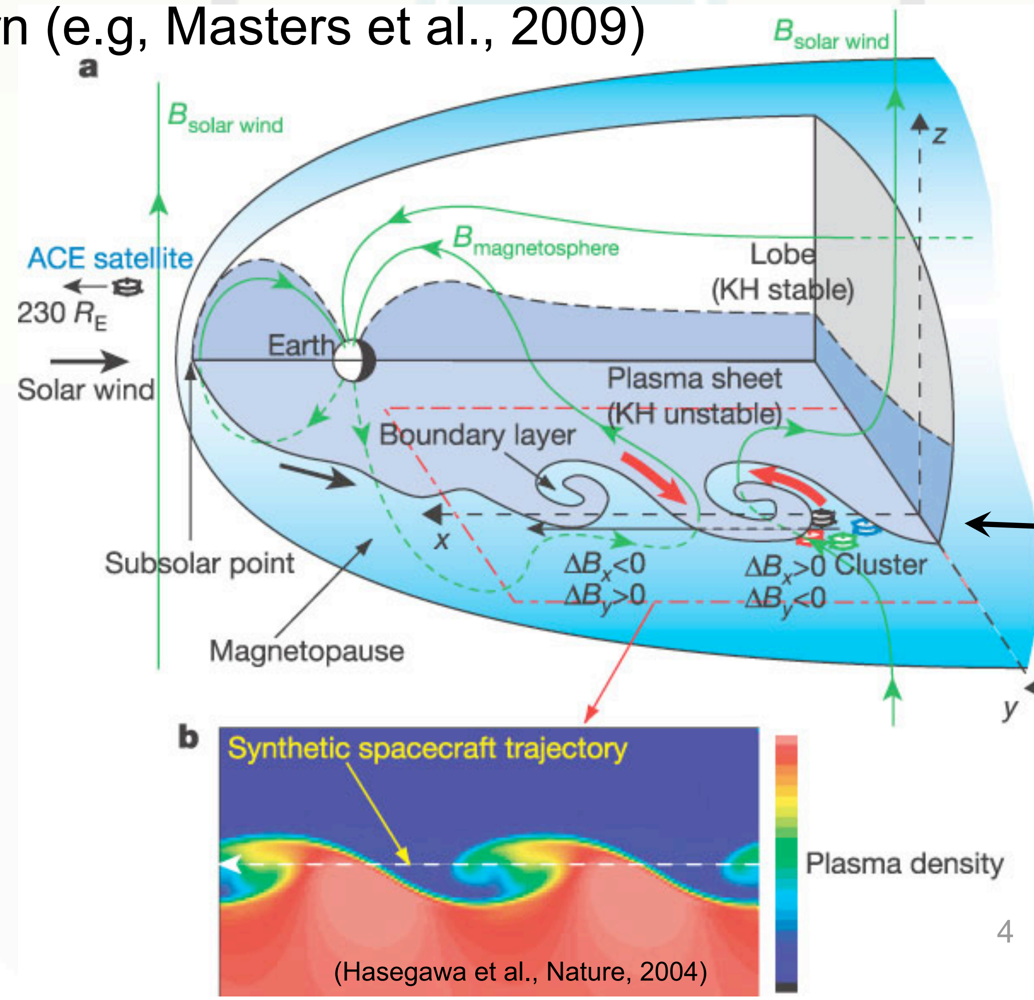
KHI at Planetary Magnetospheres

- Observed at flanks of magnetised planetary magnetospheres.
  - Earth (e.g., Fairfield and Otto, 2000; Hasegawa et al., Nature, 2004; Taylor et al., 2008)
  - Saturn (e.g, Masters et al., 2009)
  - etc



(Hasegawa et al., Nature, 2004)

Wrapped non-linear KH vortices

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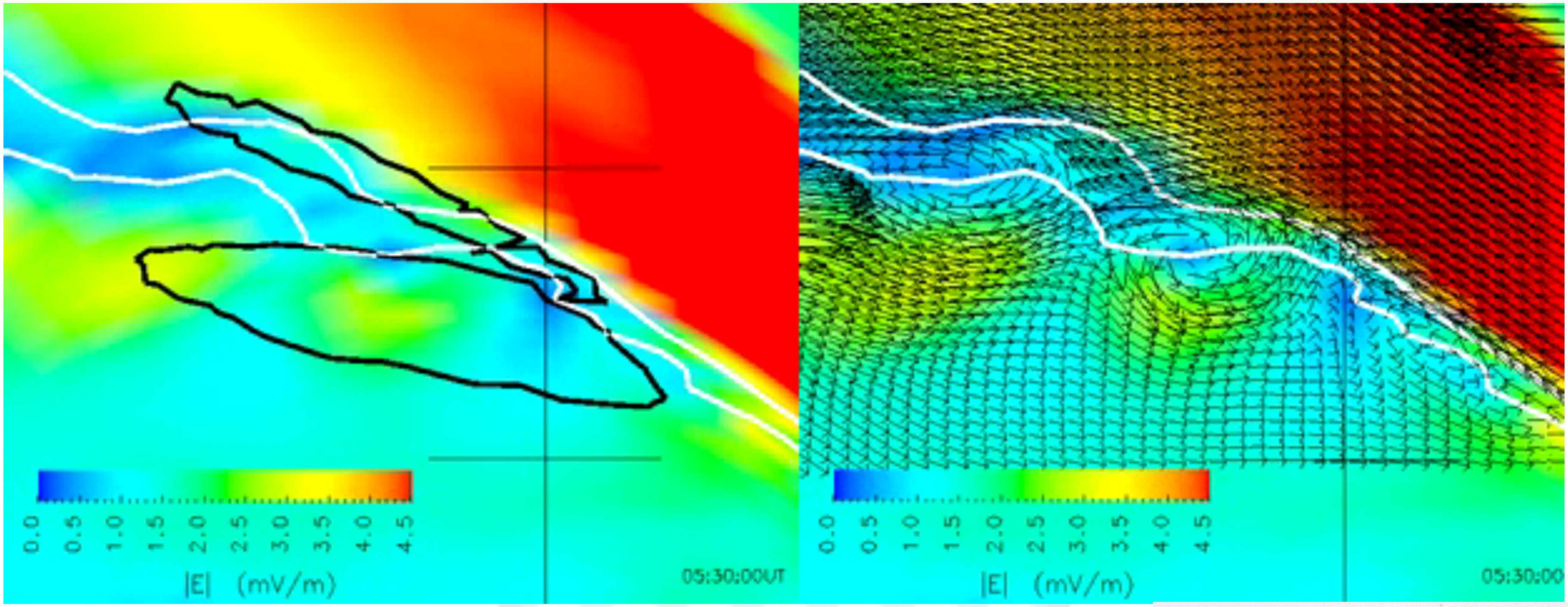
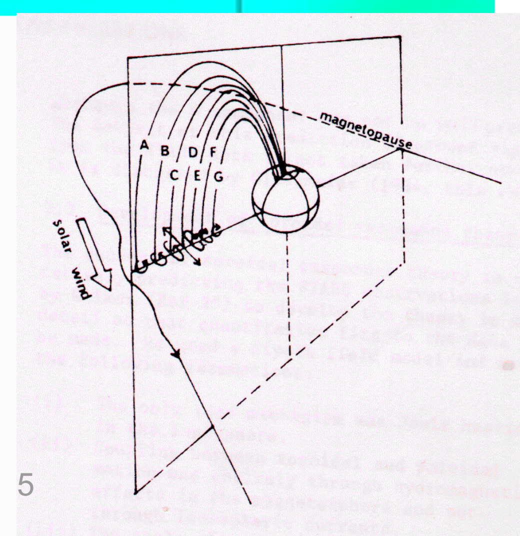
KHI Surface Waves



(LFM Simulations of Earths magnetosphere:
Courtesy of Seth Claudepierre and Scot Elkington)

Click Movie



- KHI surface waves on the flanks (e.g., Claudepierre et al., 2008).
- Energy accumulation in field line resonances inside the magnetosphere.

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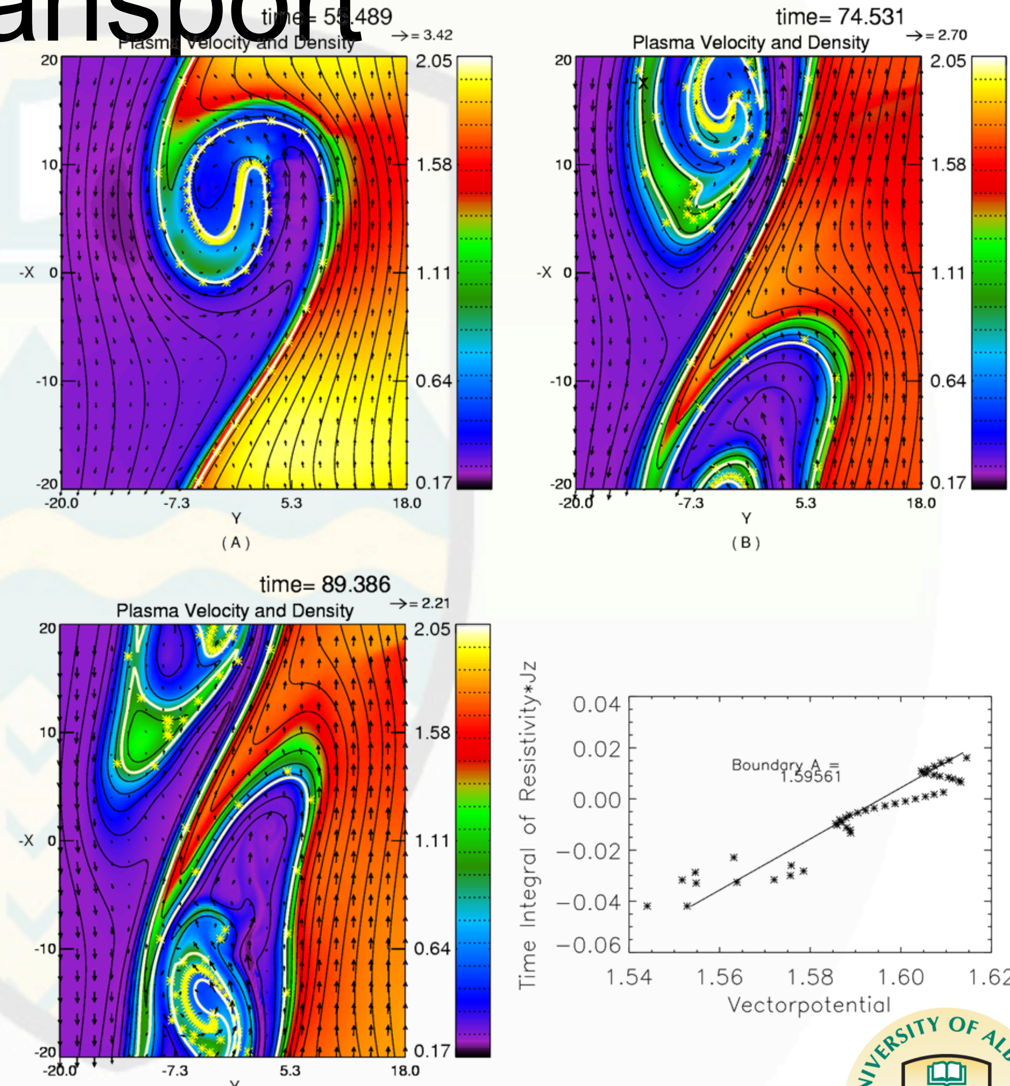
KHI Key Issues 1: Mass Transport

- Traditional KHI surface wave does not transport mass across the (distorted)magnetopause
- Transport due to magnetic reconnection in non-linear KHI vortices (e.g., Nykyri and Otto, GRL, 2001).
- Observed with Cluster four-spacecraft constellation (e.g., Nykyri et al., 2006).



(Nykyri and Otto, 2001, 2003)

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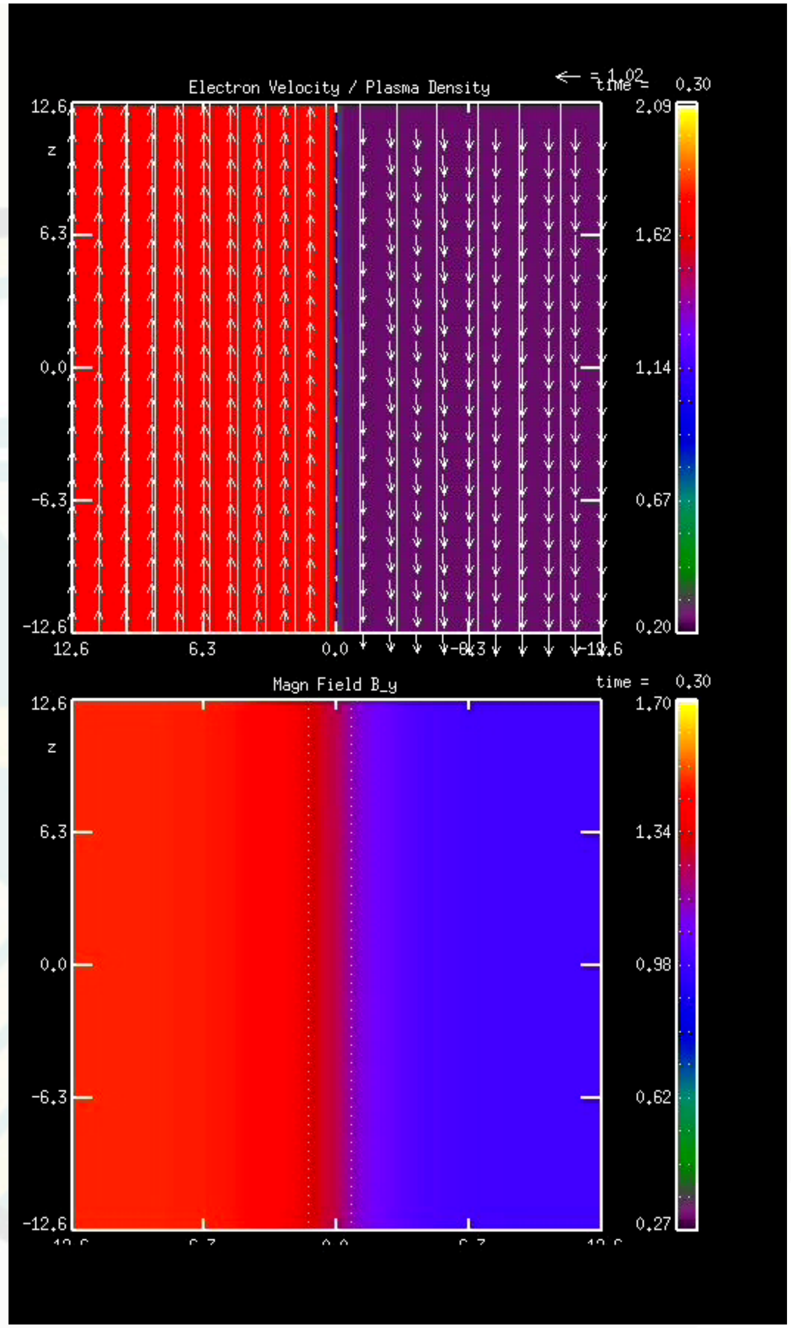
Reconnection in MHD Vortices

- 2D Hall-MHD simulations, courtesy of Katariina Nykyri.



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KHI Key Issue 1: Mass Transport

- What is the importance of secondary magnetic reconnection for mass transport in the KHI?
- Under what conditions is this most important and most efficient?
- Important consideration of convective verses absolute instability for mass transport in a given application.
- How does this develop in 2D and 3D?; What is the role of (any) line-tying?

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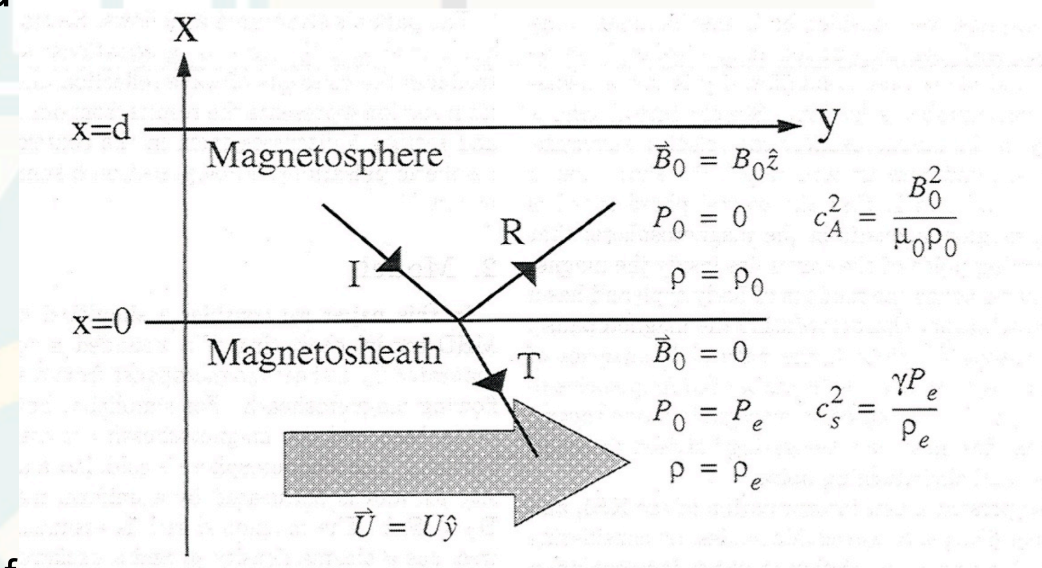
KHI Key Issue 2: Wave Over-reflection

- New opportunity to understand shear flow instability using concept of over-reflection.
- Incident wave can be “over-reflected” at shear boundary.
- Work done by Maxwell stresses cause wave amplification.
  - Offers new basis for understanding the development of shear instabilities.
  - Also explains shear-flow excitation of body modes in a confined domain. (e.g. Walker, 1998; Mann et al.,1999)



See also excellent book: “*Magnetohydrodynamic Waves in Geospace: The Theory of ULF Waves and Their Interaction with Energetic Particles in the Solar-Terrestrial Environment* ” by ADM Walker, IoP Publishing, (2004).

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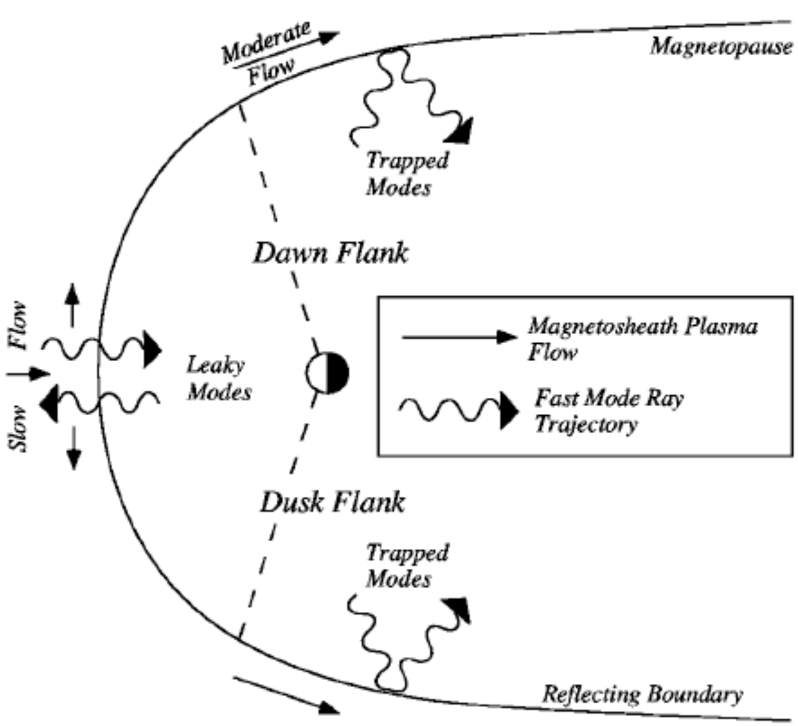
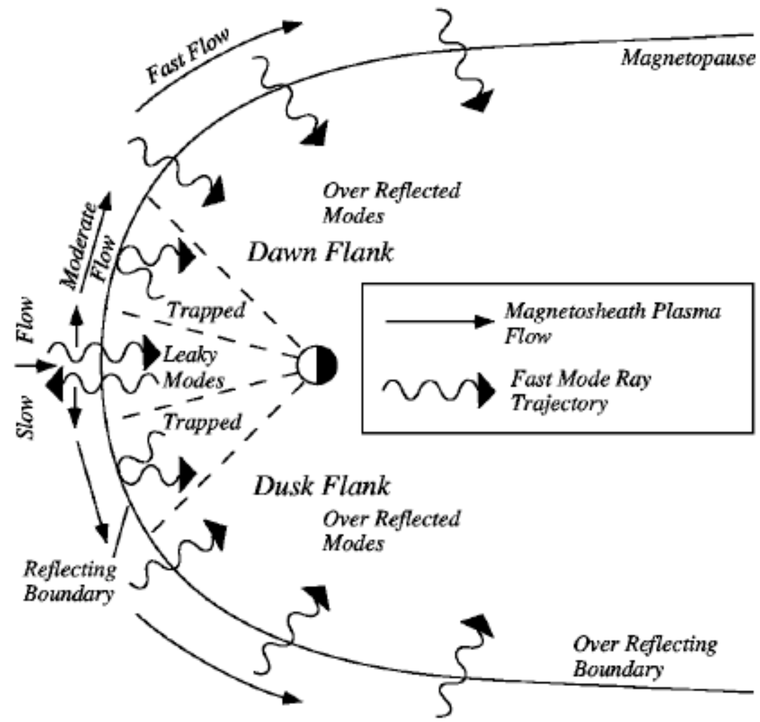
KHI Key Issue 3: Coupling to body modes

- KHI shear flow instability is traditionally assumed to excite the surface mode confined to the boundary.
- Upper cut-off speed where the mode reaches the relevant plasma speed on one side of the interface.
- However, when bounded by an inner bounday such as in planetary magnetospheres can result in the shear-flow excitation of unstable body – or waveguide – modes (e.g., Mann et al., 1999).

KH Excitation of Waveguide Modes





SLOW SOLAR WIND

FAST SOLAR WIND

(Mann and Wright, 1999)

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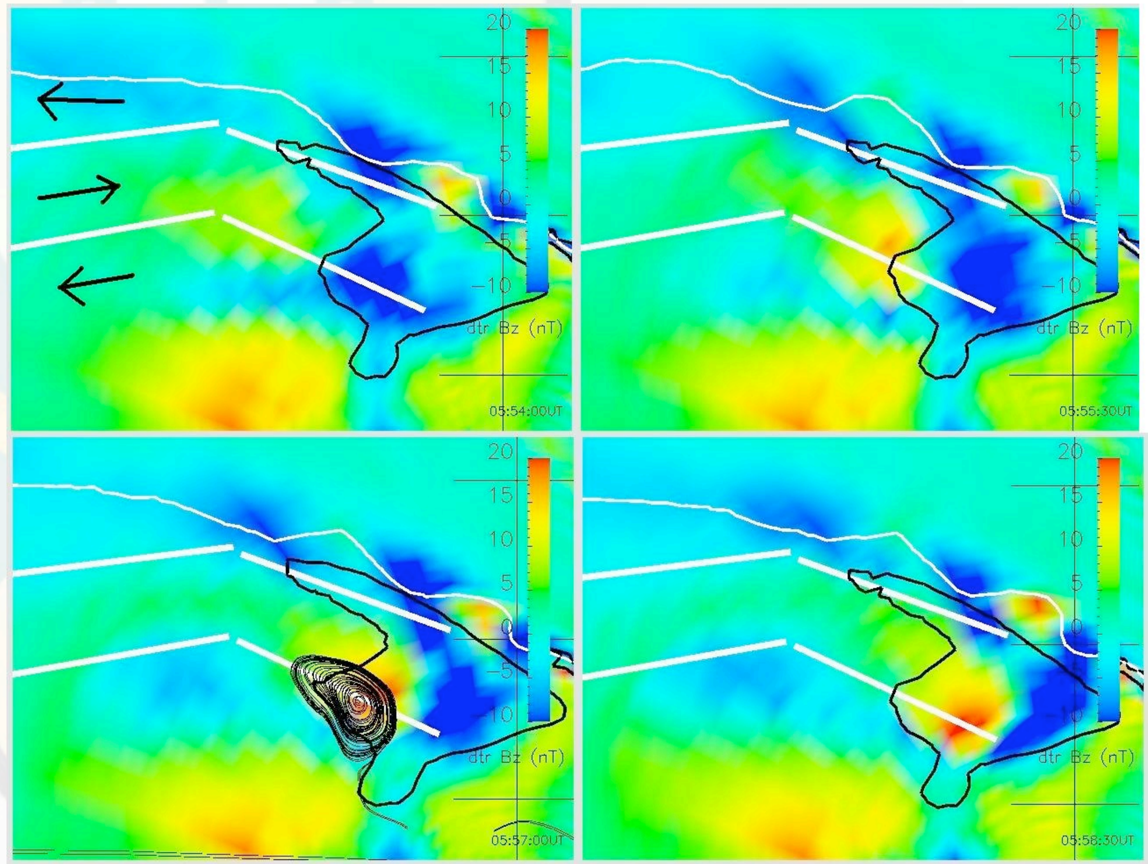
KHI Key Issue 3: Coupling to body modes

- Recent studies have also suggested coupling of KH boundary flows to inner plasmasheet flows channels.
- Important development of shear-flow modes in plasmasheet flows (Seth ClaudePierre, Personal Communication, 2009).
- May play a critical role in internal vortices, E-field generation, and modifying convection in the plasmasheet.

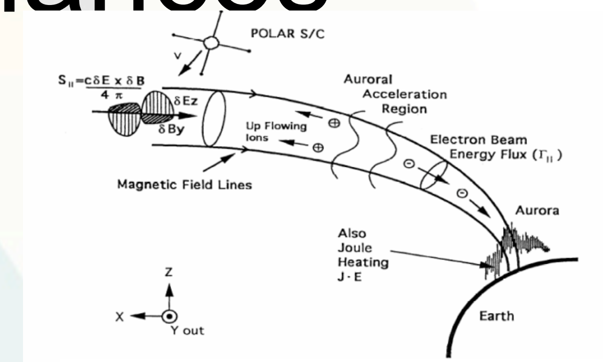


(Seth ClaudePierre, Aerospace Corp., Personal Communication, 2009)

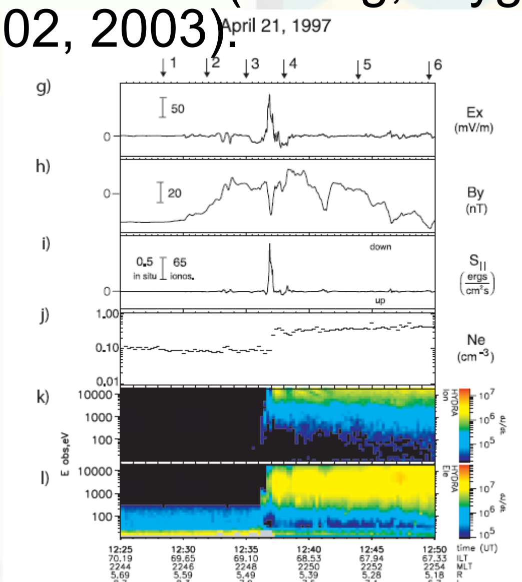
Key Issue 4: Shear Flow inside Field Line Resonances

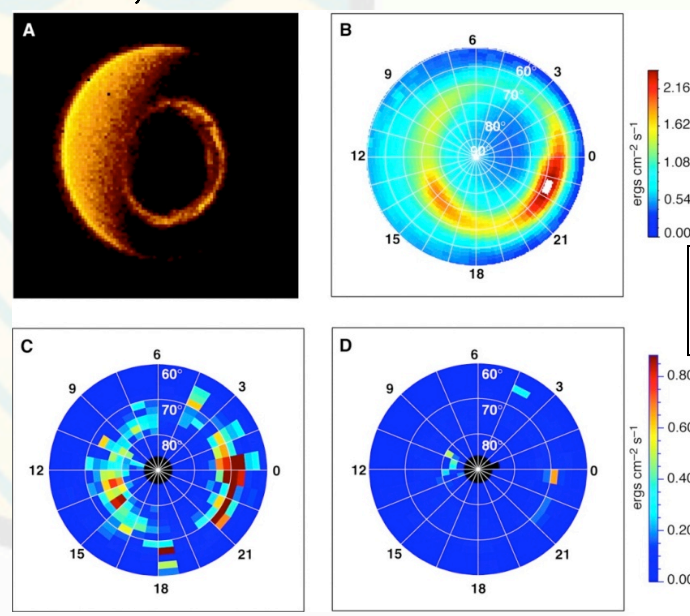
- New discoveries highlight role of Alfven waves in the generation of some Alfvenic aurora (e.g., Wygant et al., 2000).

- Statistics of Polar link ~6 Re altitude incident Alfven waves to large scale auroral emissions (Keling, Wygant et al., 2000, 2002, 2003).



Wygant et. al [JGR, 2000]





Keiling et al. [Science, 2003]

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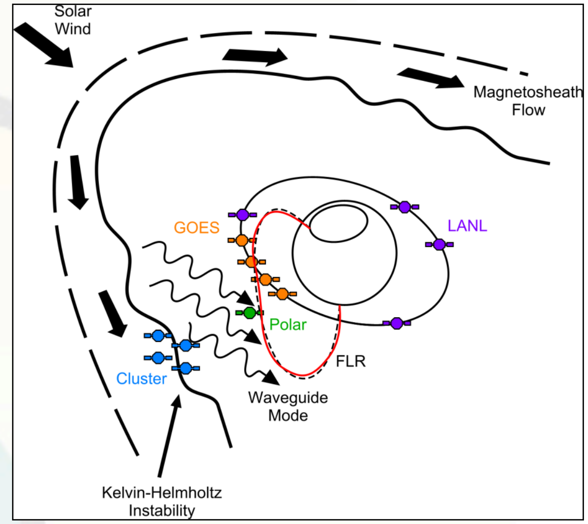
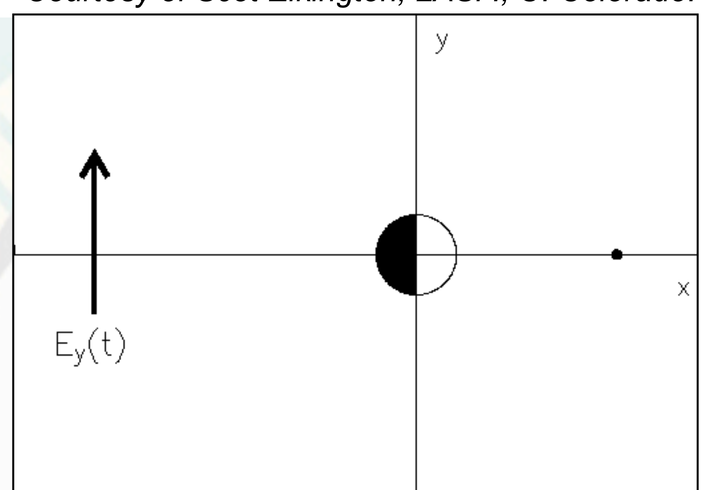
Upcoming Radiation Belt Application

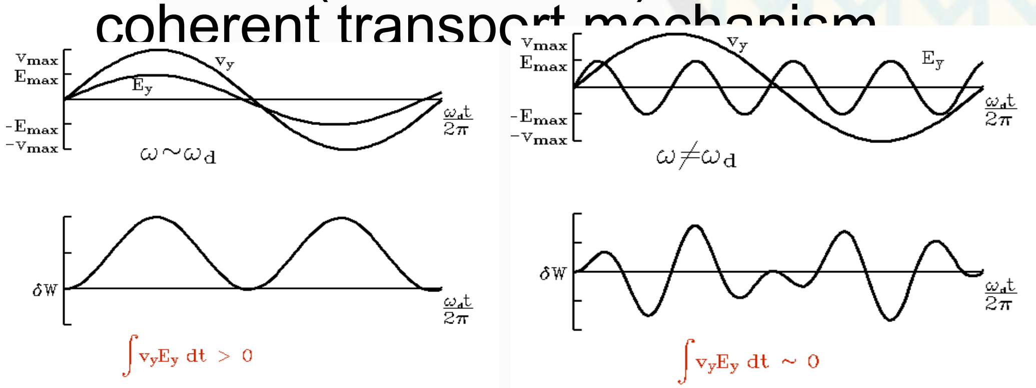


Courtesy of I.J. Rae, U. Alberta.

- Acceleration, transport and loss of energetic electrons in the Van Allen radiation belts is a key target for NASA Living with a Star (LWS) and international Living with a Star (ILWS) programs.
- Radiation belt science is a high international priority in space science.
- Discovery of the potential importance of KH-driven ULF waves in the magnetosphere as an acceleration and inwards (or outwards) diffusive or coherent transport mechanism

Courtesy of Scot Elkington, LASP., U. Colorado.





Interchange Instabilities

- Interchange instability in the Earths magnetosphere has been attributed to (e.g., Xing and Wolf, 2007):
  - Auroral features [Golovchanskaya and Maltsev, 2003], eg., as a result of FAC generation from the Vasyliunas equation;
  - Substorm features [Mingalev et al., 2006];
  - Bursty bulk flows [Pontius and Wolf, 1990; Chen and Wolf, 1993];
  - Auroral undulations [e.g., Sazykin et al., 2002];
  - The shape and size of the plasmapause [e.g., Lemaire, 1975];

- Focus on applications in the plasmasheets of planetary magnetospheres.

- Interchange instability controlled by relative orientation of gradients in the flux tube volume and pV^{γ} which are not necessarily parallel under the action of shear flow (e.g., Xing and Wolf, 2007).

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Interchange Instabilities

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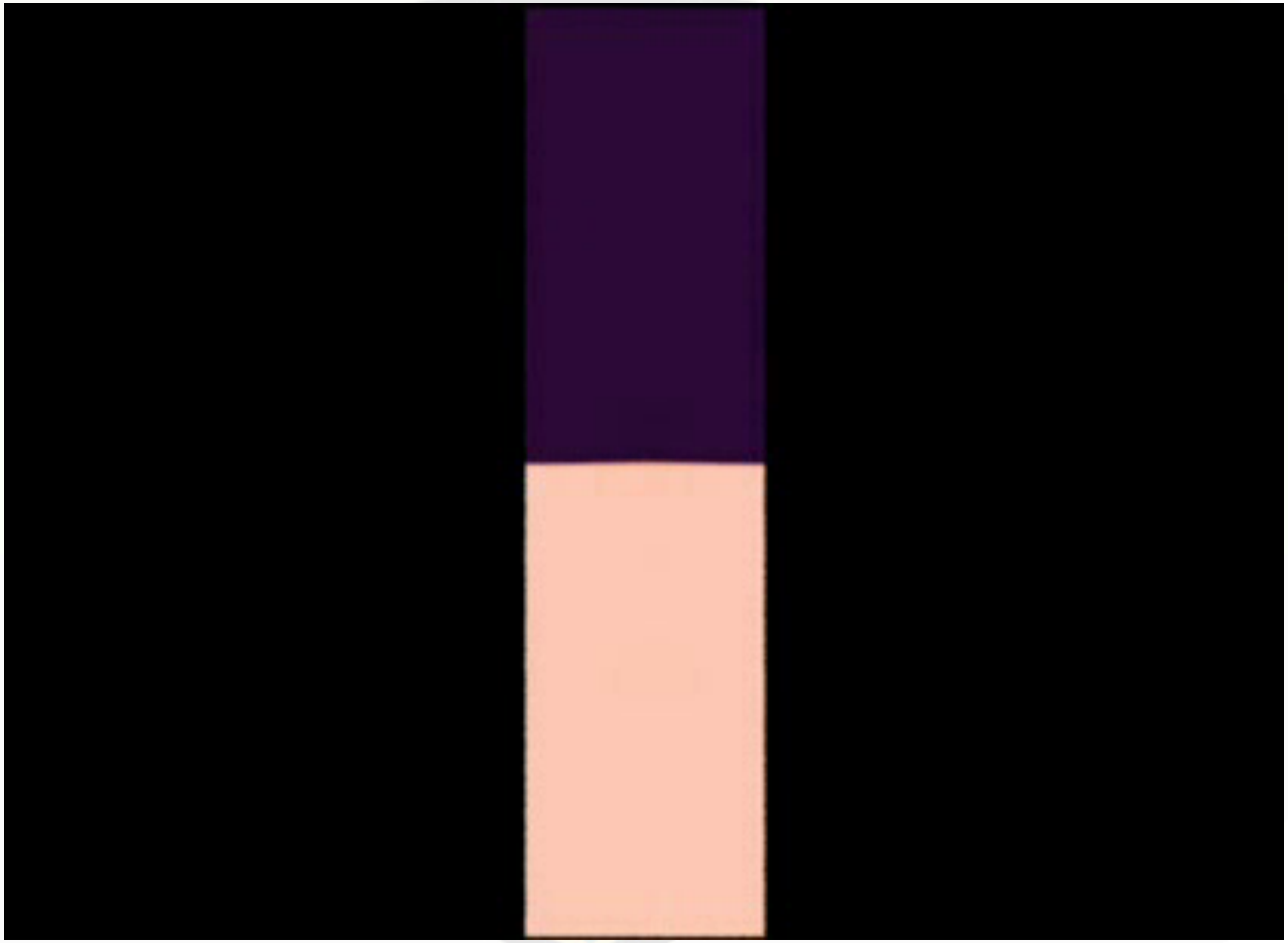

Movie from:
http://hmf.enseeiht.fr/travaux/CD0001/travaux/optmfn/hi/01pa/hyb72/rt/rt.htm

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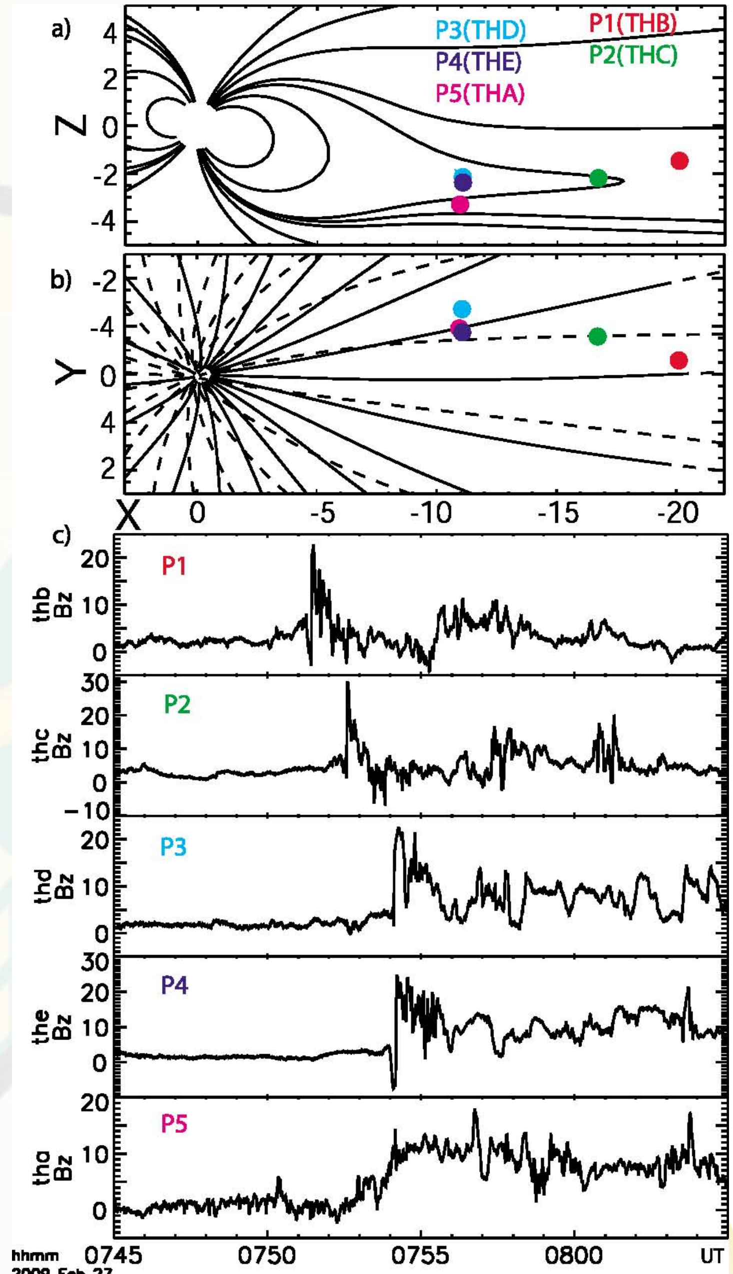
Interchange Instability in Planetary Magnetospheres

- THEMIS results highlight interchange instability in Earthward "dipolarisation fronts" (DFs).
- DFs have scales at the ion inertia length (Runov et al., 2009).
- Simulations suggest dissipation and heating at kinetic scales in the DF can be as important as energisation in tail reconnection (e.g., Sitnov, Personal Comm., 2009).
- Shear-flow at edges of DF also drive field aligned currents connecting to the ionosphere (e.g., Walsh et al., 2008).



(Runov et al., 2009)

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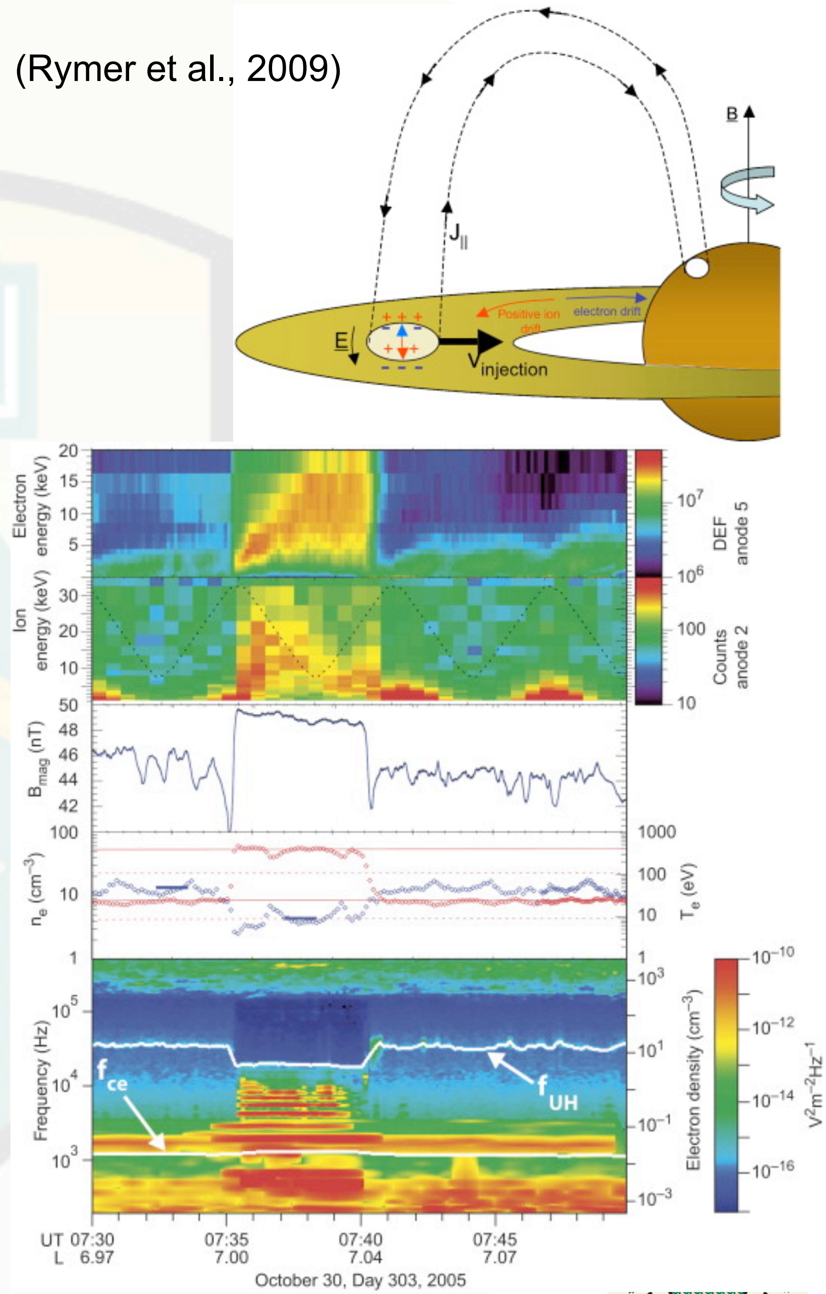
Interchange at Saturn

(Rymer et al., 2009)



- Interchange instability results in transport in Kronian system (e.g., Rymer et al., 2009).
- Plays a role in injection into inner Kronian system.

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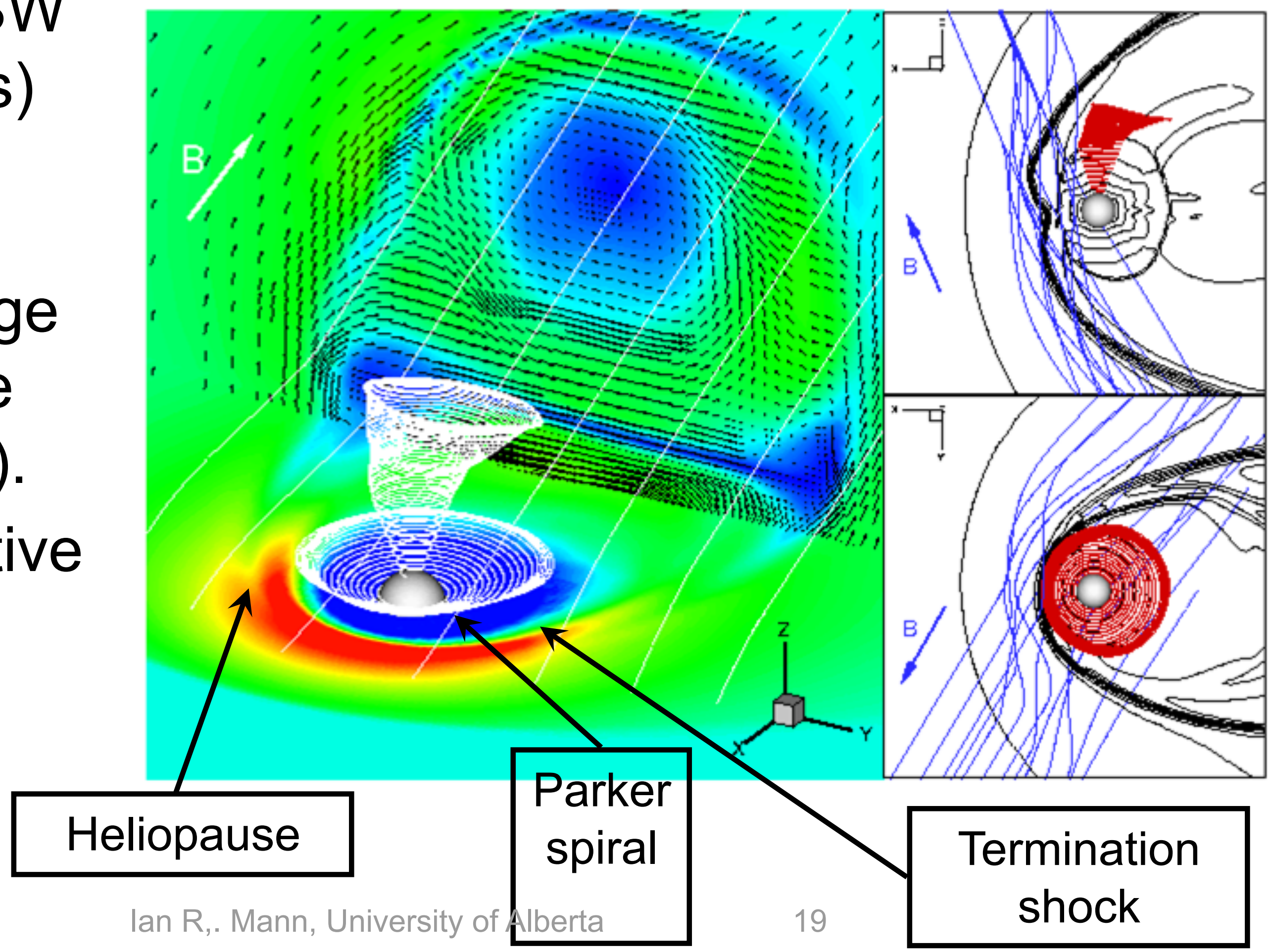
Shear and Interface Instabilities at the Heliopause

- Both interchange (at the nose due to SW pressure changes) and KHI (flank heliopause) may operate at the edge of the heliosphere (e.g., Zank, 1999).
- What is their relative importance?
- Region will be sampled by Voyagers.

(Simulations: Kabin et al., 2000)



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Shear and Interface Instabilities at the Heliopause

- What are the relative importance of KHI and interchange instabilities in shaping the edge of the heliosphere, and coupling to the inner heliosphere?
- What is the role of charge exchange physics in the RT instability at the heliopause (e.g., Borovikov et al., Ap. J., 2009).
- What role is played by ISM magnetic field? (cf. Opher et al., Nature, 2009).

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Outstanding Questions:

- Kelvin-Helmholtz instability (KHI):
  - What is the role and importance of magnetic reconnection in rolled up KH vortices for mass transport?
  - How important is the excitation of body modes by shear-flow instabilities in astrophysical plasmas?
  - Can over-reflection formalism provide a new paradigm for interpretation of shear-flow instabilities?
  - What role does shear flow play in the high altitude excitation of kinetic Alfven waves, and the generation and structuring of Alfvenic aurora?
- Interchange instabilities in Planetary Magnetospheres
  - What is the role of kinetic (ion) scale processes in energisation and heating in dipolarisation/interchange fronts in planetary magnetospheres?
  - How important is this energy release compared to that local to the diffusion region in (tail) magnetic reconnection?
- Shear and interchange instabilities at the Heliopause
  - What is the relative importance of interchange and KH instabilities at the edge of the heliosphere?
  - How do these structures couple back to the inner heliosphere?

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Future Projects and Mission Opportunities

- Current:
  - THEMIS mission skimmed Earths magnetopause (KH development), and has excellent data on Earthward dipolariation fronts (DFs) and role of (ion) kinetic physics. Support from Cluster (KH and reconnection) & Geotail.
- Future:
  - Address the role of shear-flow generated ULF waves in controlling dynamics of radiation belt electrons (NASA Radiation Belt Storm Probes (RBSP), Canadian ORBITALS, and JAXA ERG missions).
  - NASA Magnetospheric Multi-Scale (MMS) will provide electron scale data from Earths plasmasheet , including dipolarisation front flows.
  - Proposed ESA Cross-Scale, and proposed JAXA-CSA SCOPE, missions will skim magnetopause, and sample plasmasheet reconnection and turbulence at coupled fluid, ion, and electron scales.
  - Deeper entry of Voyagers into the heliosheath, and eventually crossing of Heliopause should be exciting!