Plasma Entropy in the Magnetosphere

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Basic Structure of the Magnetosphere

Magnetopause shields (not perfectly) magnetosphere from solar wind.

Plasma inside magnetosphere is either on open field lines (lobes) or trapped on closed field lines.

Magnetospheric plasma is essentially collisionless and should obey ideal MHD laws (no dissipation)

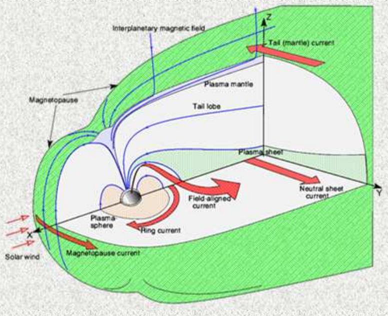
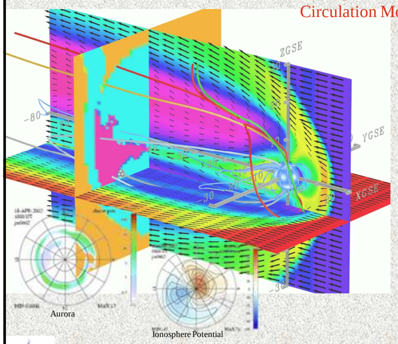


Figure from A. Otto, GEM presentation, 2007

OpenGGCM: Global Magnetosphere Modeling

The Open Geospace General Circulation Model:



- Coupled global magnetosphere - ionosphere - thermosphere model.
- 3d Magnetohydrodynamic magnetosphere model.
- Coupled with NOAA/SEC 3d dynamic/chemistry ionosphere - thermosphere model (CTIM).
- Coupled with inner magnetosphere / ring current models: Rice U. RCM, NASA/GSFC CRCM.
- Model runs on demand (>300 so far) provided at the Community Coordinated Modeling Center (CCMC at NASA/GSFC). http://ccmc.gsfc.nasa.gov/
- Fully parallelized code, real-time capable. Runs on IBM/datastar, IA32/I64 based clusters, PS3 clusters, and other hardware.
- Used for basic research, numerical experiments, hypothesis testing, data analysis support, NASA/THEMIS mission support, mission planning, space weather studies, and Numerical Space Weather Forecasting in the future.
- Funding from NASA/LWS, NASA/TR&T, NSF/GEM, NSF/ITR, NSF/PetaApps, AF/MURI programs.

Personnel: J. Raeder, M. Gilson, W. Li, A. Liwei Lin, K. Germaschewski, Y. Ge,, (UNH), T. Fuller-Rowell, N. Muriyama (NOAA/SEC), F. Toffoletto, A. Chan, B. Hu (Rice U.), M.-C. Fok, A. Glocer (GSFC), A. Richmond, A. Maute (NCAR)

Plasma Entropy

In ideal MHD, specific entropy is conserved along a flow path:

$$\frac{d}{dt}s(\mathbf{r},t) = \frac{d}{dt}\frac{p}{\rho^\gamma} = 0$$

where: $s(\mathbf{r},t) = \frac{p}{\rho^\gamma}$ is the specific entropy,

and: $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla$ is the convective derivative.

Flux Tube Entropy

On closed magnetospheric flux tubes, other conserved quantities can be defined:

$V = \int \frac{ds}{B}$ Is the flux tube volume,

$M = \int \rho \frac{ds}{B}$ Is the flux tube mass,

$S = \int p^{1/\gamma} \frac{ds}{B}$ Is the flux tube entropy,

In case that density and pressure are uniform in a flux tube: $S = pV^\gamma$ Is the conserved flux tube entropy.

What Breaks Entropy Conservation?

- Any diffusive term (mass diffusion, viscosity, heat flux, resistivity).
- Any particle sink/source (charge exchange, ionization).
- Any particle losses/sources at boundaries.
- Any radiative heat exchange.
- Any collisional heating/cooling with other species.
- Particle transport other than $\mathbf{E}\times\mathbf{B}$ drift (gradient drift, curvature drift), although that is equivalent to heat flow.
- Mixing (equivalent to mass diffusion).
- Field line slippage (equivalent to resistivity).

Entropy Conservation in MHD Codes

- Ideal MHD codes are designed to conserve mass, momentum, energy, and magnetic flux, and to minimize diffusive and dispersive errors.
- However, no code is perfect. In particular, diffusive terms must be introduced to balance dispersive errors when shocks are present.
- At shocks, diffusion is a necessity, because shocks must increase entropy (weak, evolutionary solutions).
- It does not matter how the entropy is produced as long as Rankine-Hugoniot conditions are satisfied.
- Most MHD codes miraculously produce the right entropy at shocks, as long as they produce entropy at all (entropy fix for some algorithms), because the other conservation laws are rigorously enforced. Non-conservative codes usually fail to produce correct R-H jumps.
- As we will see, the magnetosphere (and maybe other systems?) require a lot more entropy production.
- Again, MHD codes miraculously produce such entropy, for still unknown reasons.

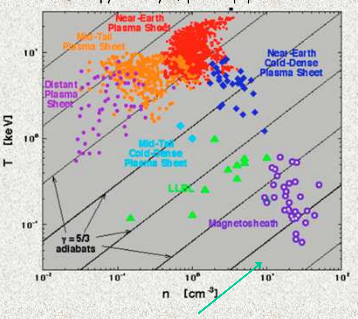
Observed Specific Entropy in the Magnetosphere

Specific entropy (p/N^gamma) is an important tracer for plasma in the magnetosphere.

Ideally, specific entropy should be conserved.

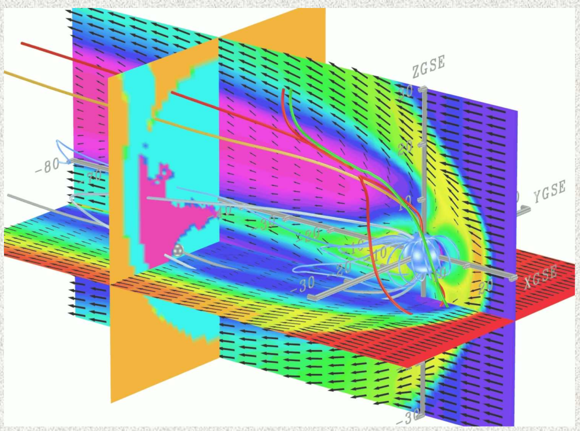
However, the populations in the magnetosphere differ by orders of magnitude.

Entropy density of plasma populations



Solar wind: less dense, cooler

From Borovsky, GEM'06



Major Questions

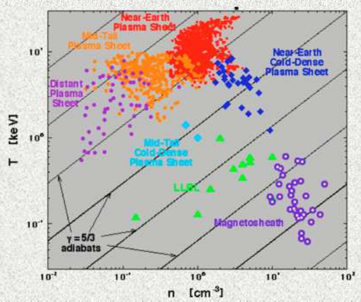
Why is specific entropy not conserved?

Where is the plasma heated?

What are the heating processes?

Unfortunately we cannot follow plasma parcels in the magnetosphere with satellites, but we can use global simulations!

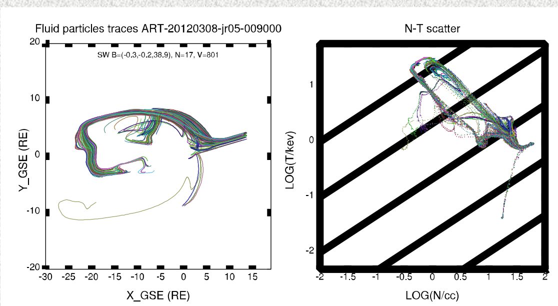
Entropy density of plasma populations



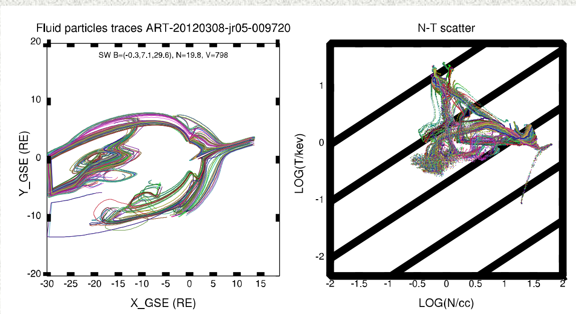
From Borovsky, GEM'06

What do OpenGGCM simulations say about entropy?

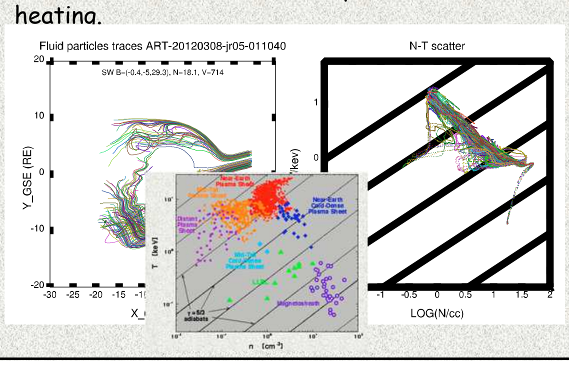
Method: follow plasma parcels from SW and trace out entropy in N/T plane; only fluid particles that end up in the plasma sheet:



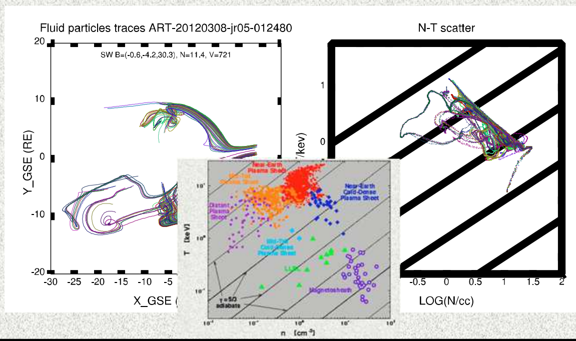
Plasma parcels are traced for 2h. In N-T plane they should only move along adiabats or towards upper left.



NBZ case compares quite well with J.B. N-T diagram. Big jump in s at bow shock, adiabatic/isothermal MSH expansion, then heating.



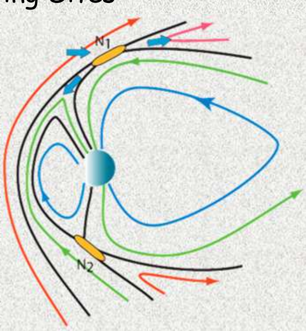
Sometimes there seems to be non-adiabatic cooling. 2. law violation? Not likely, possibly mixing/diffusion w/colder plasma.



Search for the Heating Sites

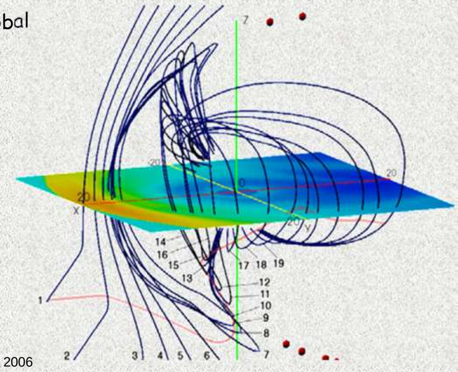
How does plasma get into the magnetosphere?

During northward IMF Bz dual lobe reconnection can capture magnetosheath field lines and thus very effectively transport plasma into the magnetosphere.



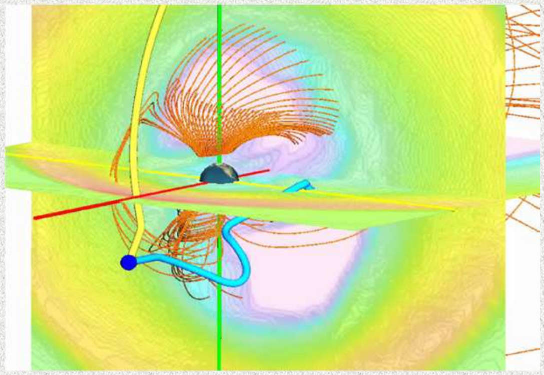
e.g. Crooker et. al., JGR, 1979;
Song and Russell, JGR, 1992; Li et al., JGR, 2005;
Dorelli et al., 2007

This has been shown in global simulations,

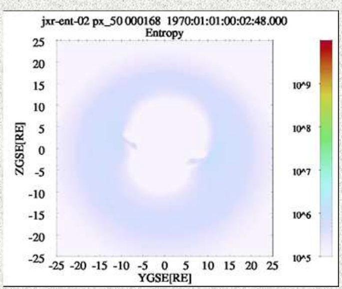


Li et al., JGR, 2005, 2006

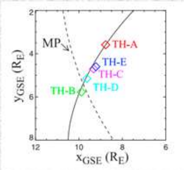
Tracing of a fluid element with the "attached" field line:

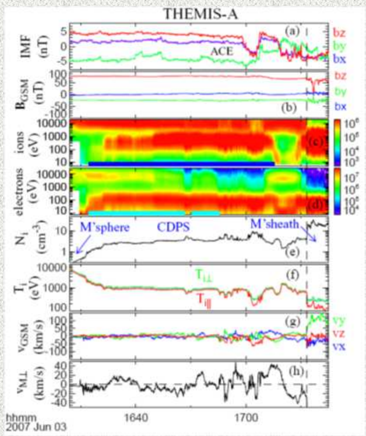


Warmer LLBL clearly present in simulations.
But heating mechanism still an open question.

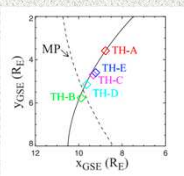


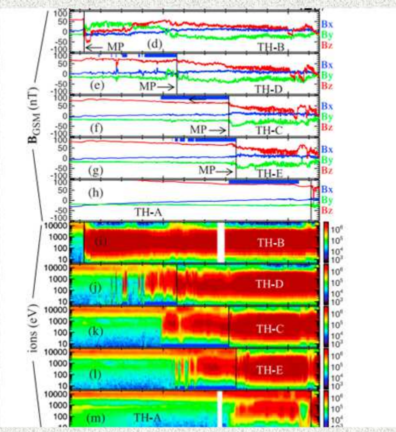
Confirmed with THEMIS data (Oieroset et al., 2008):





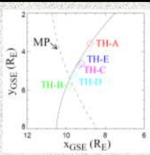
no ambiguity with five spacecraft,

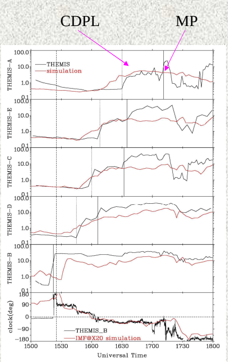


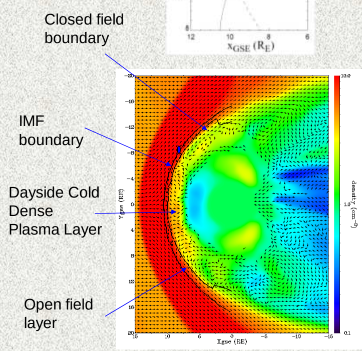


Oieroset et al., GRL, 2008

… and by observations and simulations together.







… and the auroral signature was demonstrated by Frey et al. (2003, GRL) to be a cusp proton precipitation spot.

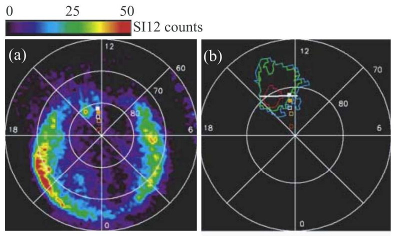
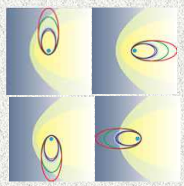
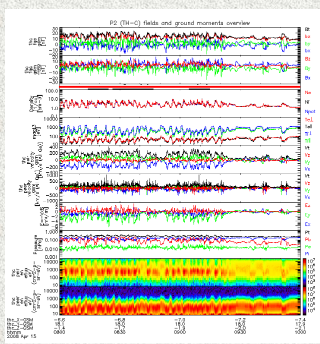


Figure 2. IMAGE/SI12 proton aurora image (in magnetic local time-latitude) on 2002-03-18 at 14:58:56 UT during the time Cluster was crossing the reconnecting MP tailward of the cusp. A bright proton spot poleward of the oval appears at ~14 MLT and ~81° latitude.

If it is not dual lobe reconnection, it could be Kelvin-Helmholtz waves

- THEMIS orbits are ideal to observe flank magnetopause.
- THEMIS observes "wavy structures" during ~50% of MP crossings. Lately we detemined ~20% are KH waves.
- Some periodic structures may be FTEs, some may be directly driven by the SW of foreshock waves, but most are KH.

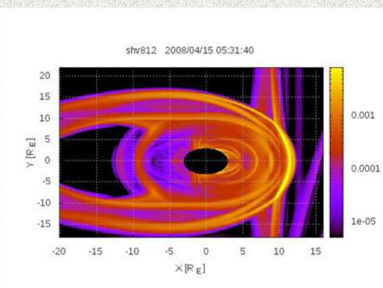




THEMIS-C, April 15, 2008 0800-1000 UT

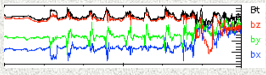
Kelvin-Helmholtz waves in OpenGGCM

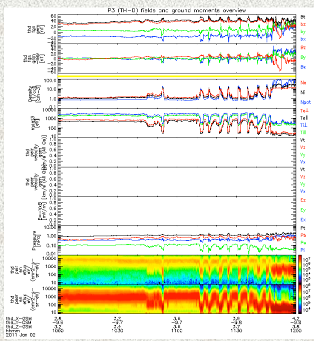
- OpenGGCM by and large reproduces KH waves.
- Contrary to conventional wisdom, KH waves are NOT restricted to small IMF clock angle and large V_{SW}.
- KH at V_{SW} as low as 300 km/s and for Parker spiral IMF, both in data and in simulations.



Kelvin-Helmholtz or Flux Transfer Events?

- Sometimes periodic structures at flank MP have FTE signatures.
- Strong bipolar BN signatures and enhanced core field, but bipolar B_N separated by zero B_N intervals.
- FTEs possibly trigger KH.





THEMIS-D, January 2, 2011 1000-1200 UT

Kelvin-Helmholtz or Flux Transfer Events?

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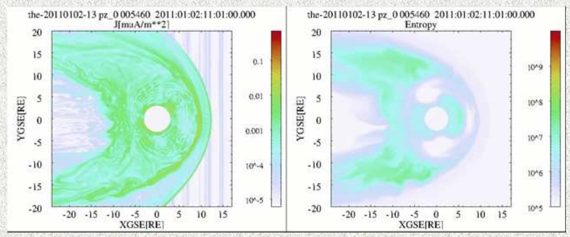
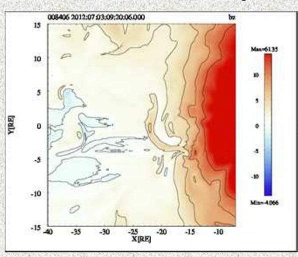
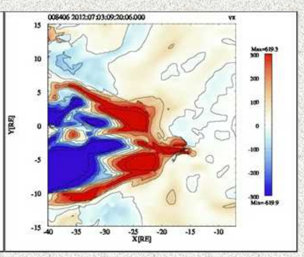


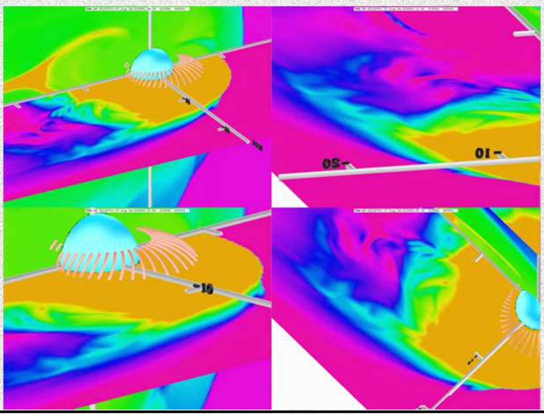
Heating in the tail: Bursty Bulk Flows (BBFs) and Dipolarization Fronts (DFs)

- Earth's magnetotail is a very busy place:
- Bz and Vx taken at the current sheet defined by z(Bx=0).
- Spatially/temporally limited reconnection sites produce fast flow channels and "dipolarize" the field (see next movie). Also cause plasmoids/flux ropes that are mostly blown out the back of the tail.
- Energy conversion: magnetic → heat and flow (reconnection); flow → heat? But how: turbulent cascade? Viscous heating?





Topology and evolution of BBFs/DFs



E.J in the current sheet plane

- Increase of entropy in the tail must ultimately come from field energy (Poyting's theorem).
- In a plasma, E.J has a adiabatic and a dissipative component.
- One needs to be very careful in separating these numerical simulation results.

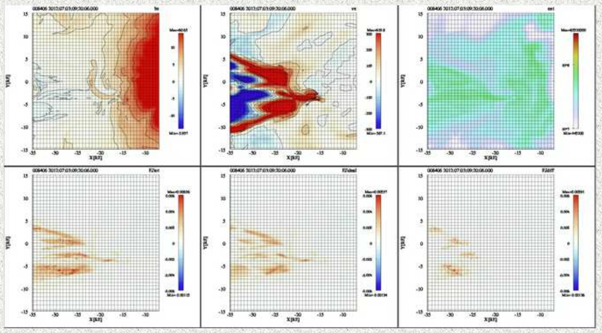
$$\mathbf{E}^{\mathrm{tot}} \cdot \mathbf{j} = (-\mathbf{v} \times \mathbf{B} + (\eta^{\mathrm{phys}} + \eta^{\mathrm{num}})\mathbf{j}) \cdot \mathbf{j} =$$

$$\mathbf{v} \cdot (\mathbf{j} \times \mathbf{B}) + \eta^{\mathrm{tot}} |j|^2$$

adiabatic dissipation

E.J in the current sheet plane

- Trying to find (E.J)_dissipative.
- Bz and Vx taken at the current sheet defined by z(Bx=0).
- E.J_tot, v.(JxB), and difference on bottom → no dissipation at DF!



Summary

- The magnetosphere (solar corona, astro plasmas, …) is not as isentropic as often assumed.
- Heating occurs in stages: SW → bow shock → boundary layers → distant tail → inner tail.
- Heating must be related to entry processes (plasma crossing current sheets).
- Most plasma enters during northward IMF Bz, and there are even multiple processes: Dual lobe reconnection, KH waves.
- Heating mechanisms in the plasma sheet likely related to reconnection, but not only in the diffusion regions (which ought to be small), but possibly also in the flow breaking (turbulent cascade?).
- Pinpointing the dissipation processes in detail requires more work.

Two more announcements:

1. "Trillian", a CRAY X6m-E with 4096 cores of fun.

2. Post-doc / researcher position available at UNH: Requirements: Fortran/C/MPI in Linux/Unix environment, MHD/fluid numerics, plasma/magnetosphere background. If interested, send resume to j.raeder@unh.edu.