Dual Lobe Reconnection and the Formation of the Cold Dense Plasma Sheet

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Summary

1. Cluster observations indicate that bi-directional heated electrons are typically seen in the high latitude MSBL during northward IMF.

2. Under the assumption that the MP is the source of this electron heating, MSBL field lines must typically cross the MP at both ends and be closed.

3. Since closed MSBL field lines (IMF north) are produced by dual-lobe reconnection (Song and Russell, 1992), what favors this reconnection?

4. The requirement of a PDL to produce sub-Alfvenic flows before lobe reconnection can take place results in a geometry favorable for dual-lobe reconnection.

5. Dual-lobe reconnection is a candidate for the formation of the CDPS and possibly the primary source of solar wind plasma to the magnetosphere.

6. FAST satellite observations provide additional evidence that dual-lobe reconnection is the source of the CDPS.

Open Model for MSBL during Bz>0

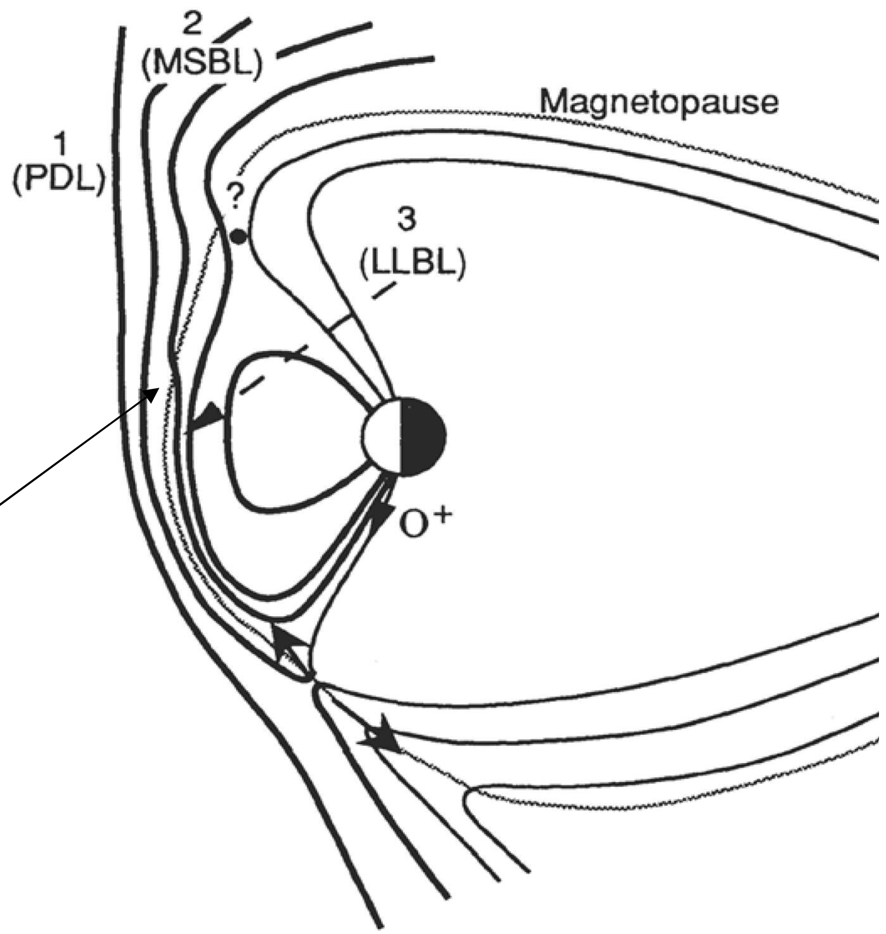
Fuselier et al. (1995) describes a model of single lobe reconnection that explains the low latitude plasma observations. They suggest that it is unlikely that flux tubes reconnect in both hemispheres.

CONCERNS:

The model assumes constant electron heating even across low shear MP.

Model will not result in significant solar wind input to the plasma sheet.

High latitude MSBL observations show that electrons are generally bidirectional not unidirectional.

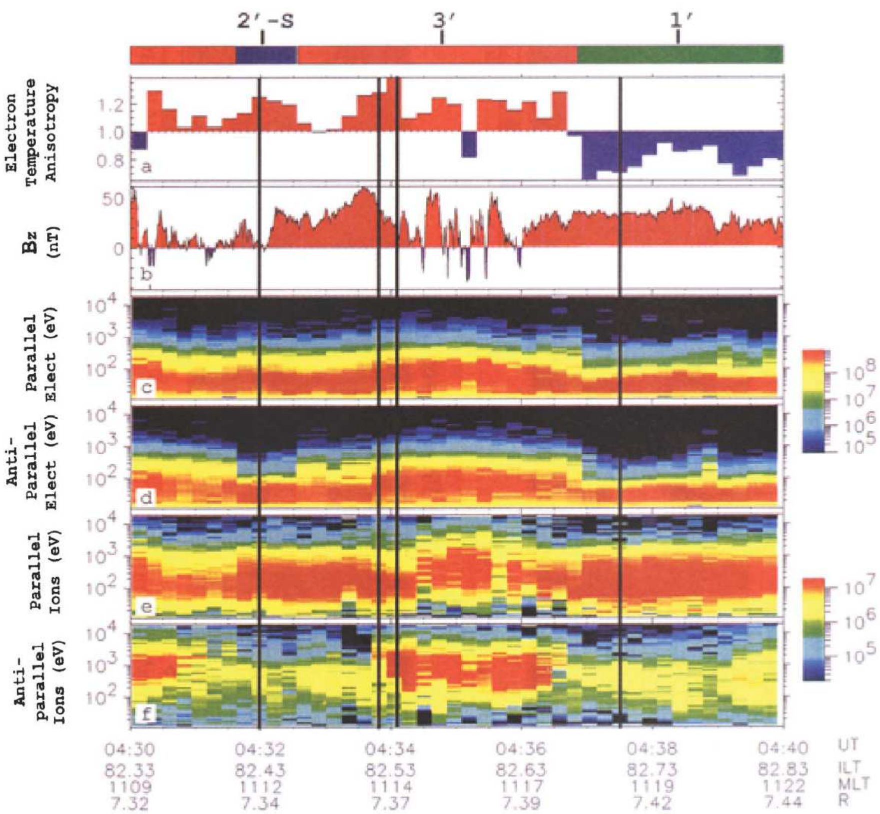


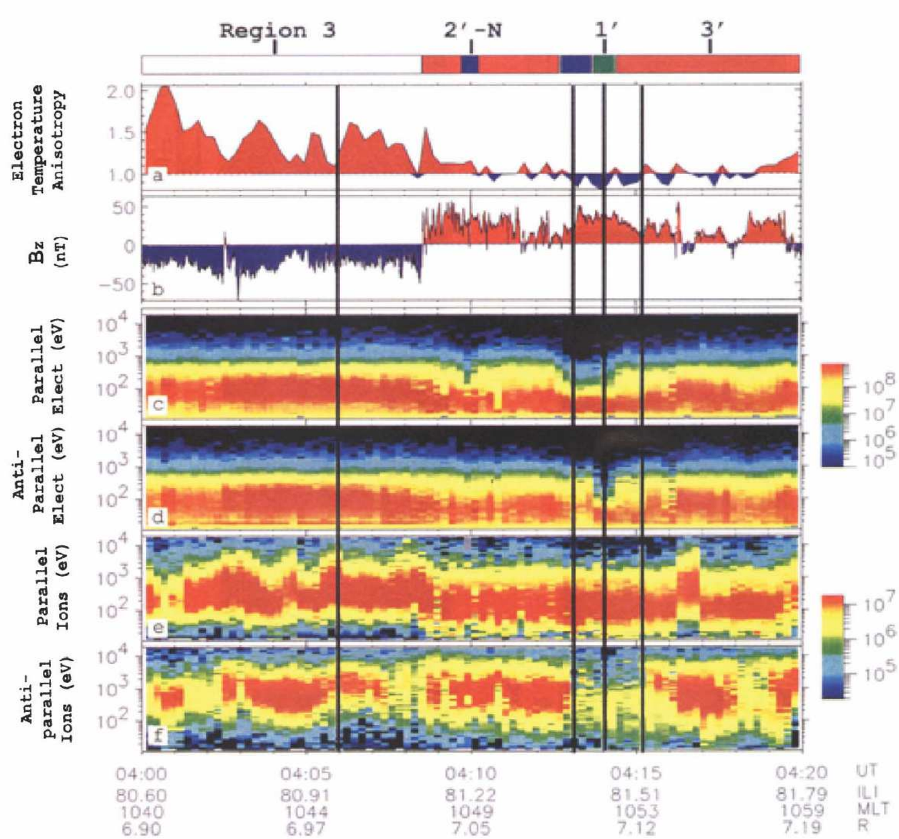
Fuselier et al. (1995, JGR)

Polar Observations

Polar observes closed MSBL at high latitude. Onsager et al. (2001, JGR) used observations of heated electrons to identify open and closed field lines in the MSBL. Although not emphasized, most of the MSBL was on closed field lines in contradiction to the Fuselier et al. (1995) model.

3' – bidirectional 2' unidirectional





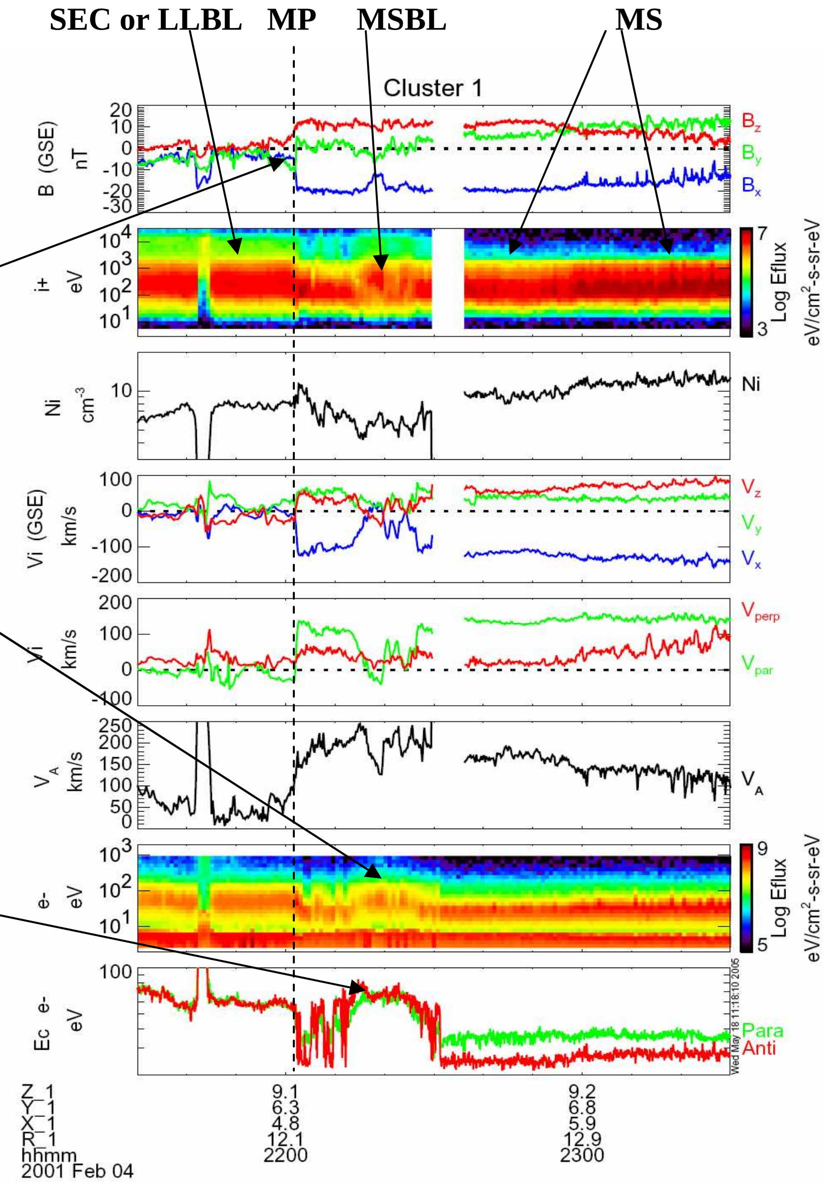
Cluster Observations

A high latitude Cluster crossing of the MP during northward IMF.

A high shear MP crossing is seen in the magnetic field data (top panel).

Bidirectional heated electrons are observed for ~25 minutes outside the MP in the MSBL.

The characteristic energy increases by a factor of ~2, with similar heating to the LLBL. The heating is not abrupt but rises gradually as the s/c penetrate deeper into the MSBL.

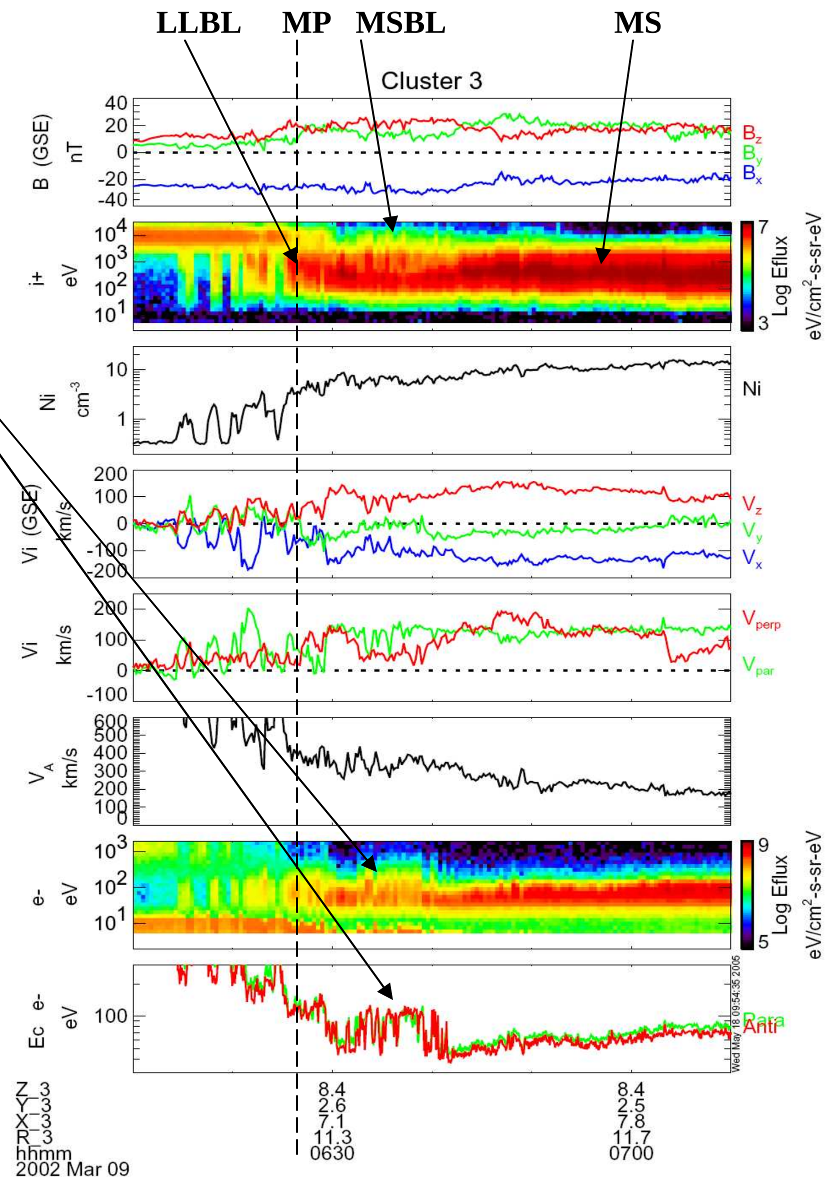


Cluster Observations

6 additional Cluster high latitude MP crossings during northward IMF were examined and found to contain predominantly bidirectional heated electrons in the MSBL.

Lavraud et al., 2005 reports a study of all Cluster MSBL crossings and found bidirectional electrons in 19 of 37 events with the remaining labeled "unclear".

However, 3 "unclear" bidirectional events were examined: all 3 lacked a MSBL even though 2 were reported to have unidirectional heating.



Problem

Since Dual-Lobe Reconnection (Song & Russell, 1992) appears to dominate the observations, what mechanism favors this process?

Near simultaneous dual-lobe reconnection might be expected to be rare since most periods of northward IMF have similar magnitude for Bx or By which could favor one hemisphere over the other.

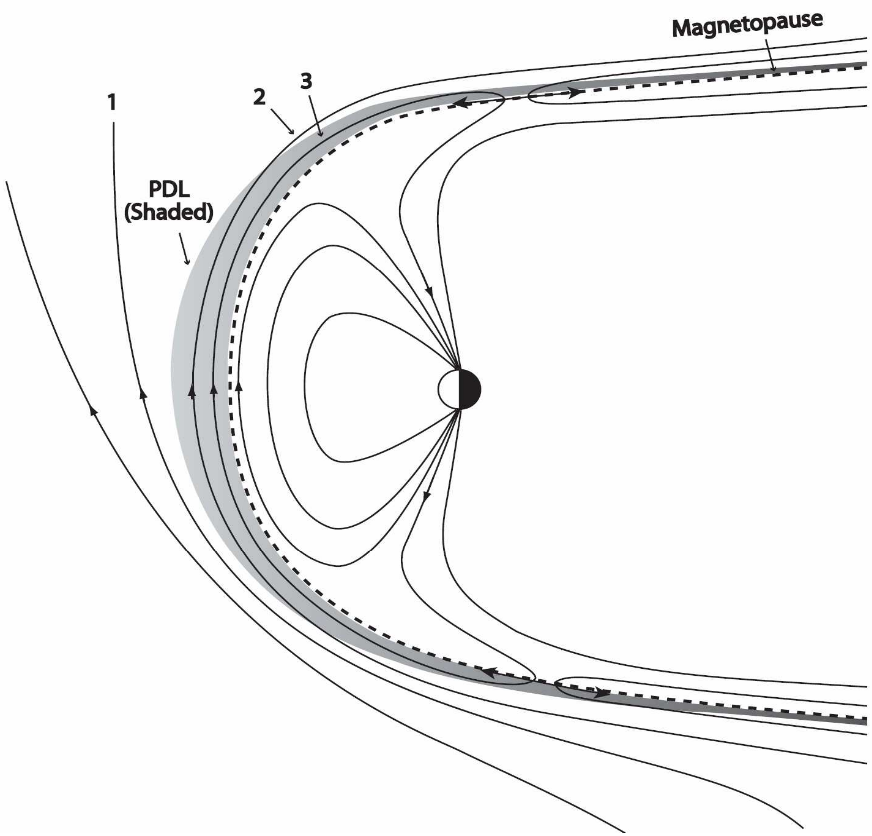
Significant negative Bx could favor reconnection in the north, or at least result in the northern hemisphere reconnection occurring long before southern hemisphere reconnection.

Similarly, significant By could favor single lobe-reconnection since the highest lobe-to-sheath magnetic shear in one hemisphere would not necessarily have as favorable a shear in the opposite hemisphere.

PDL Formation

We propose that dual-lobe reconnection is favored because a PDL must form at the sub-solar point and propagate to the lobes in order to have sub-Alfvenic lobe flows. Sub-Alfvenic lobe flows are required in order for magnetic stress to propagate to the Earth.

The PDL formation begins as the field lines drape across the sub-solar region. The depletion forms in the sub-solar region and propagates toward the poles reaching both poles at about the same time. IMF Bx does not significantly favor one hemisphere because draping must occur first. However, dipole tilt in the X-Z plane will affect the relative distance to the sub-solar region.

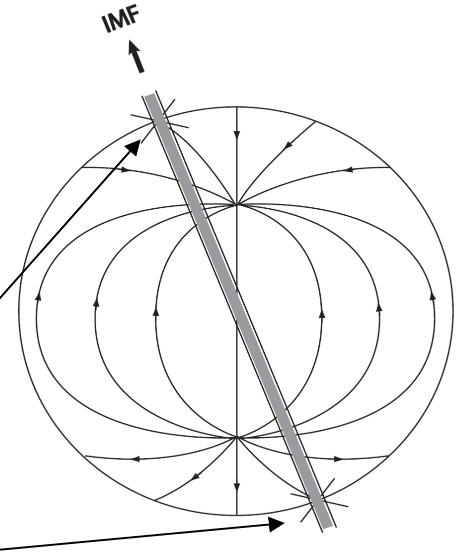


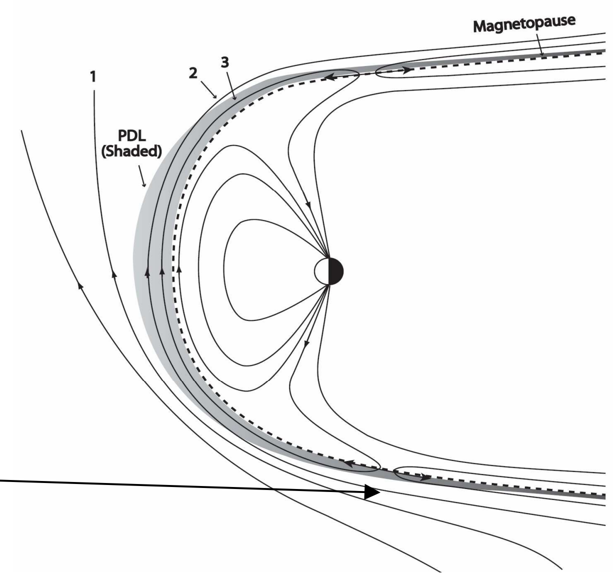
Symmetry Between Hemispheres

A PDL is observed for all cases of lobe reconnection. The PDL is deepest on those field lines crossing the sub-solar region.

Field line draping at the sub-solar region results in symmetric lobe shear that produces identical conditions in both hemispheres. IMF By does not favor one hemisphere over the other.

Lobe to PDL magnetic shear will be high even with significant IMF By since both lobe and draped magnetic fields are primarily in the X direction.



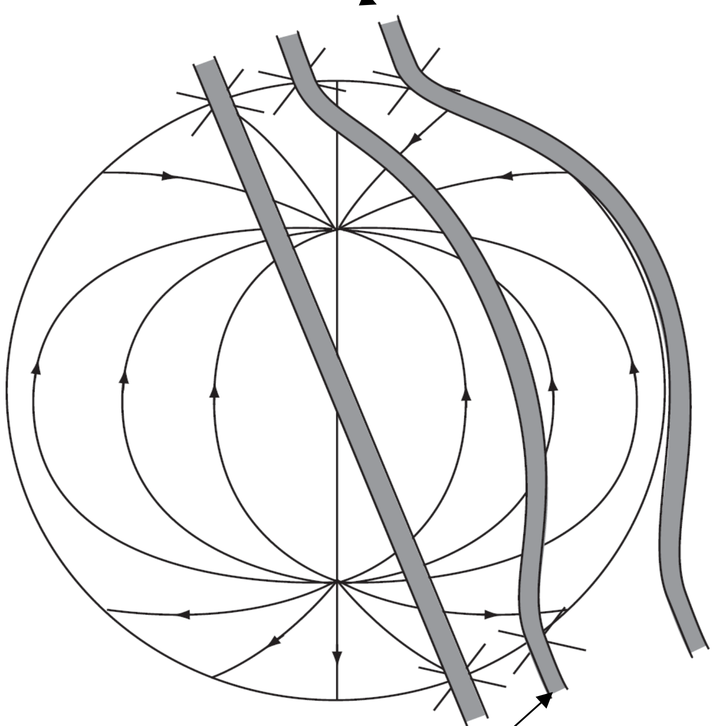


Single Lobe Reconnection

Single lobe reconnection may occur, however these flux tube will be quickly swept back into the tail. These reconnections contribute to the cusp precipitation but may not contribute significantly to the build up of a LLBL. Convection to the tail may explain the reduced probability of observation.

Single lobe reconnection primarily stirs the lobes and does not add plasma to the closed portion of the magnetosphere.

Flux tubes that slide off the sub-solar PDL are still heavily draped maintaining high shear in the X-direction with similar shear in both hemispheres.

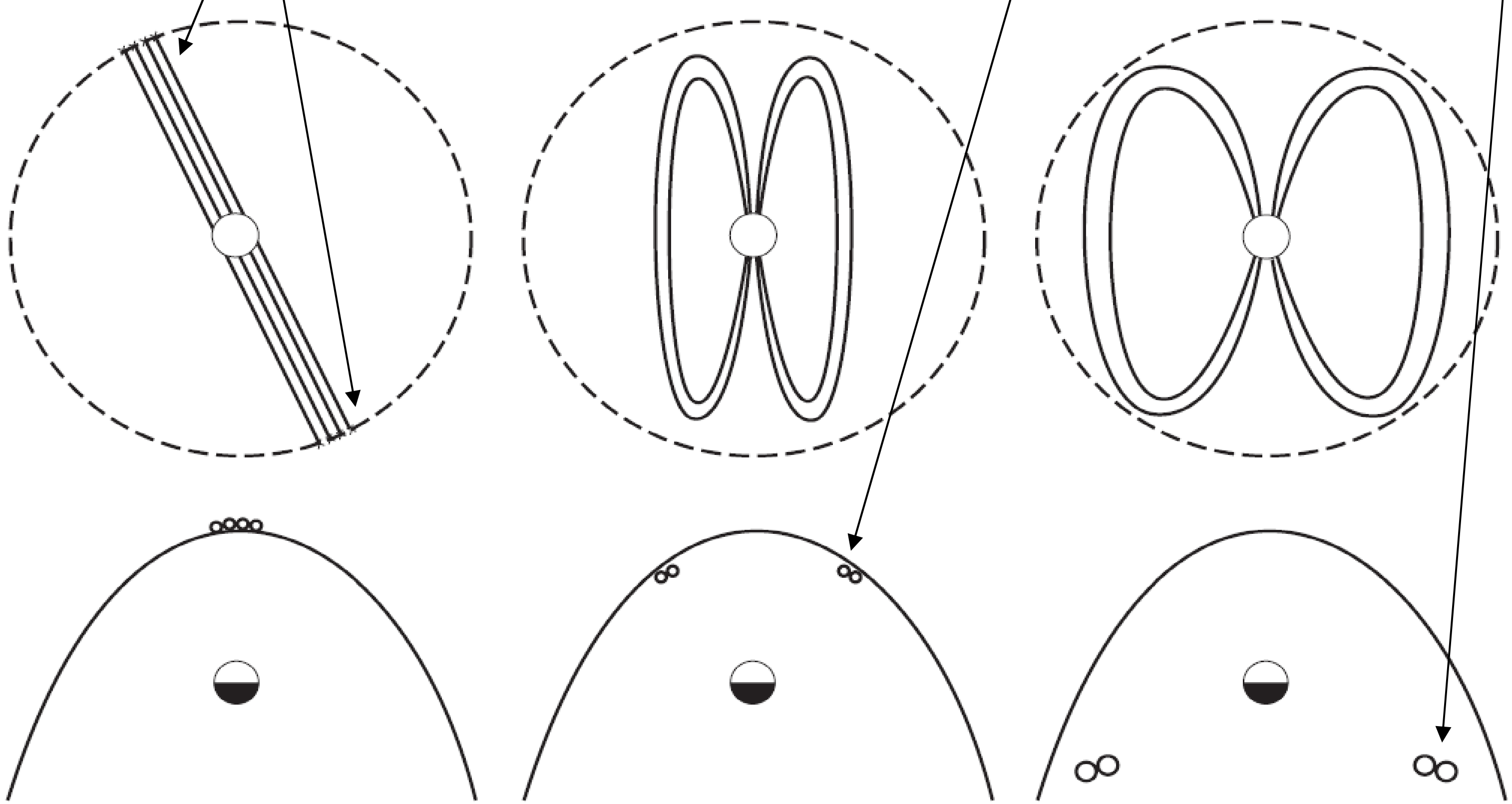


Field Line Relaxation

Dual-lobe reconnection generally produces a twisted flux tube relative to the dipole tilt.

Flux tube relaxation results in a weak magnetic shear at low latitudes. Interchange instability causes a thin layer of LLBL flux tubes to form.

For long northward IMF, LLBL flux tube drift to the tail forming the Cold Dense Plasma Sheet (CDPS).



Ionospheric Signatures of Dual-Lobe Reconnection

A dual-peaked Velocity Dispersed Ion Signature (VDIS) in the cusp should appear on occasions when reconnection in the opposite hemisphere occurs a few minutes before the local hemisphere reconnection.

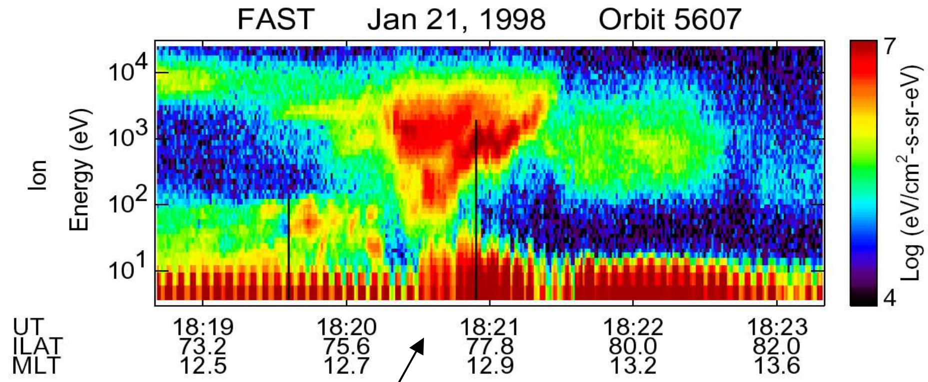
A continuous transition between cusp precipitation and Cold Dense Plasma Sheet (CDPS) precipitation should be observed.

VDISs should be present within the CDPS as the ions bounce between hemispheres. The number of ion peaks should increase away from noon.

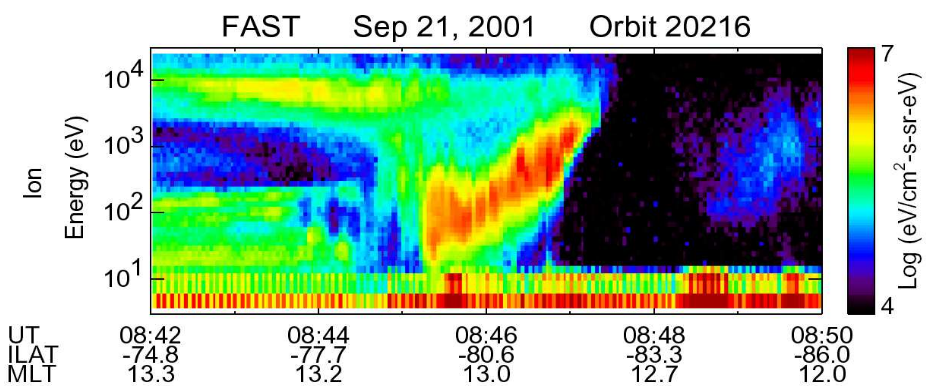
VDIS in the CDPS should be caused by spatial dispersion associated with convection and not temporal dispersion. Therefore the energy-latitude dispersions should be consistent with field line length and not depend on satellite motion.

Reverse VDIS signatures in the Cusp

Clear VDIS signatures of lobe reconnection can be found during northward IMF, however the difficulty in finding these signatures indicates the local time extent of these injections is not large.



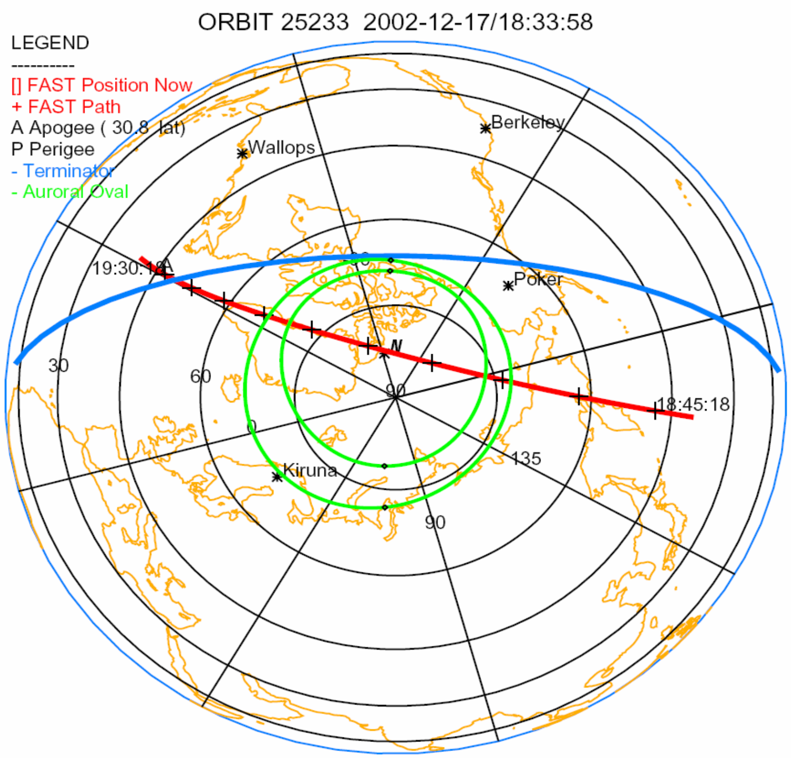
Multiple peaked VDIS signatures are sometimes seen indicating a lobe injection from the opposite hemisphere may have occurred a few minutes prior to lobe reconnection in the local hemisphere.



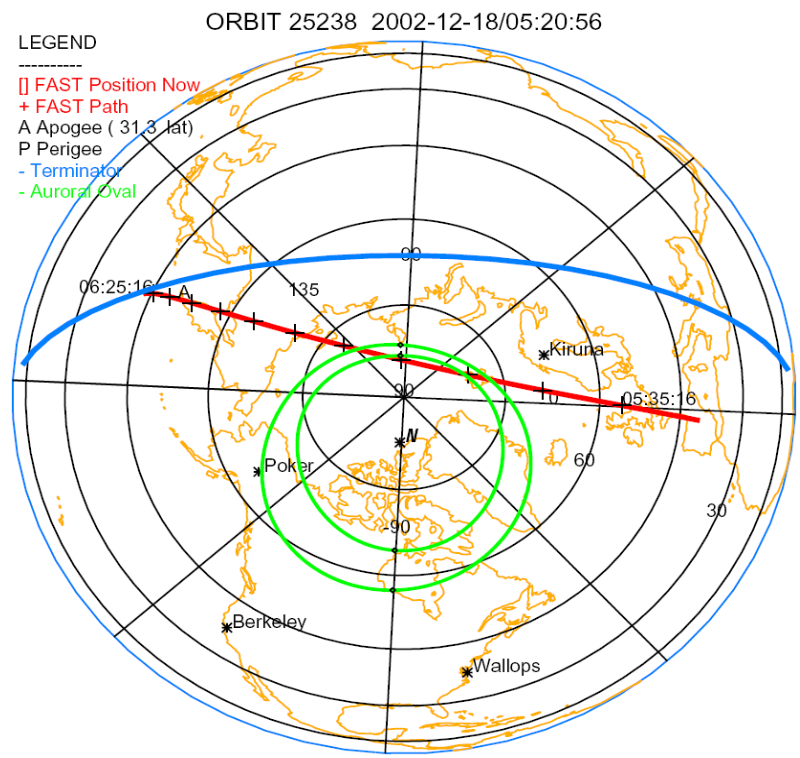
FAST Orbits

As the Earth rotates, the FAST orbit varies from a near Dawn-to-Dusk crossing to an orbit that skims the Cusp. This orbit allows an investigation of the continuity of the CDPS and Cusp.

Dawn-to-Dusk

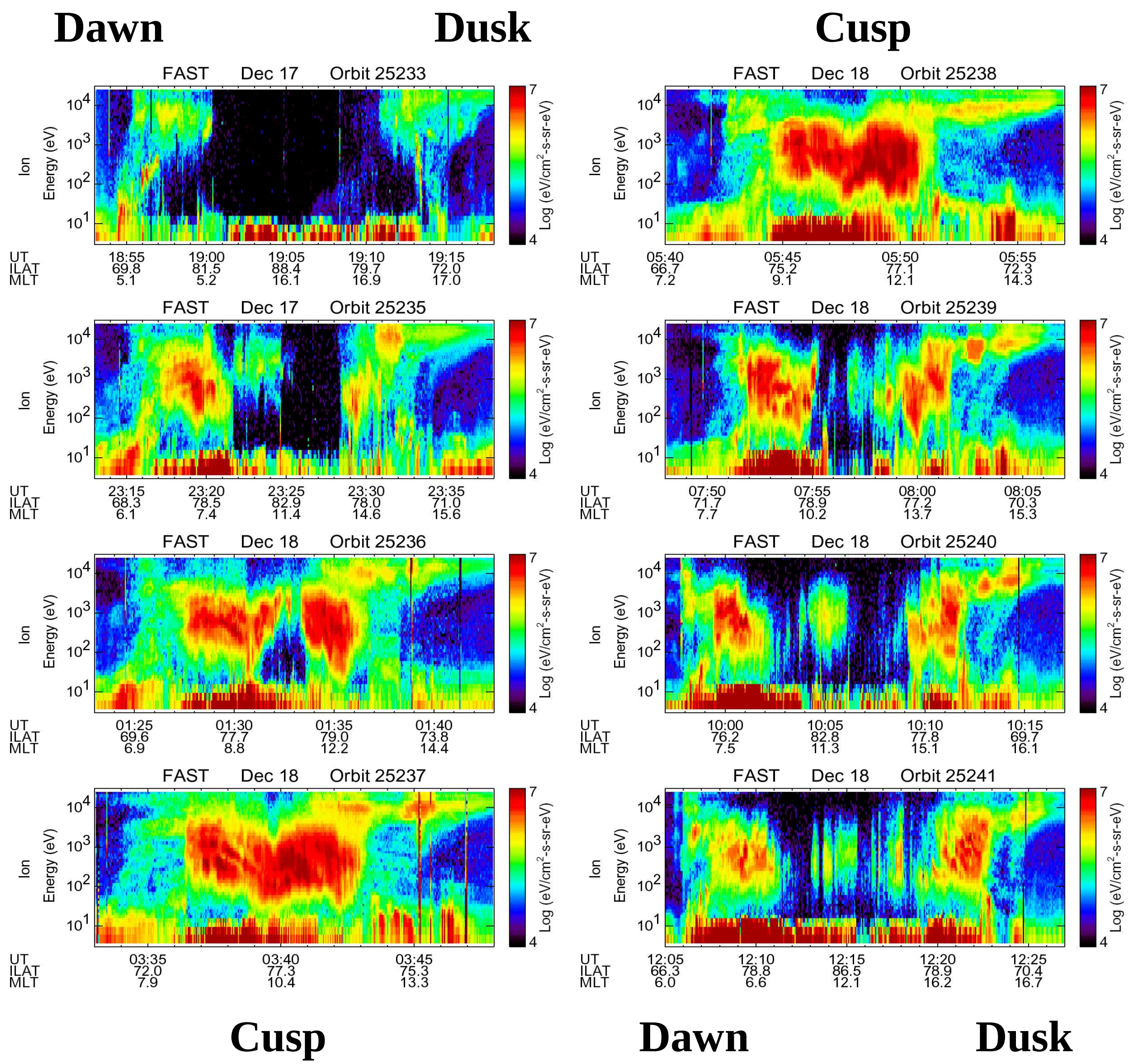


Skimming Cusp



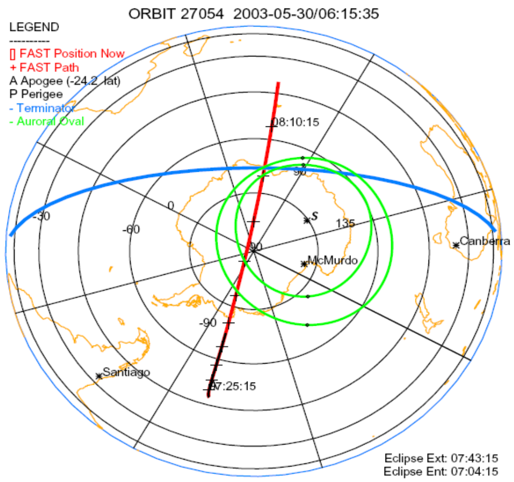
FAST CDPS Ions   Dec. 17-18, 2002

Consecutive FAST crossings of the auroral oval show that the CDPS observed near dawn and dusk has continuity with ion precipitation in the Cusp. VDIS are present throughout the CDPS.

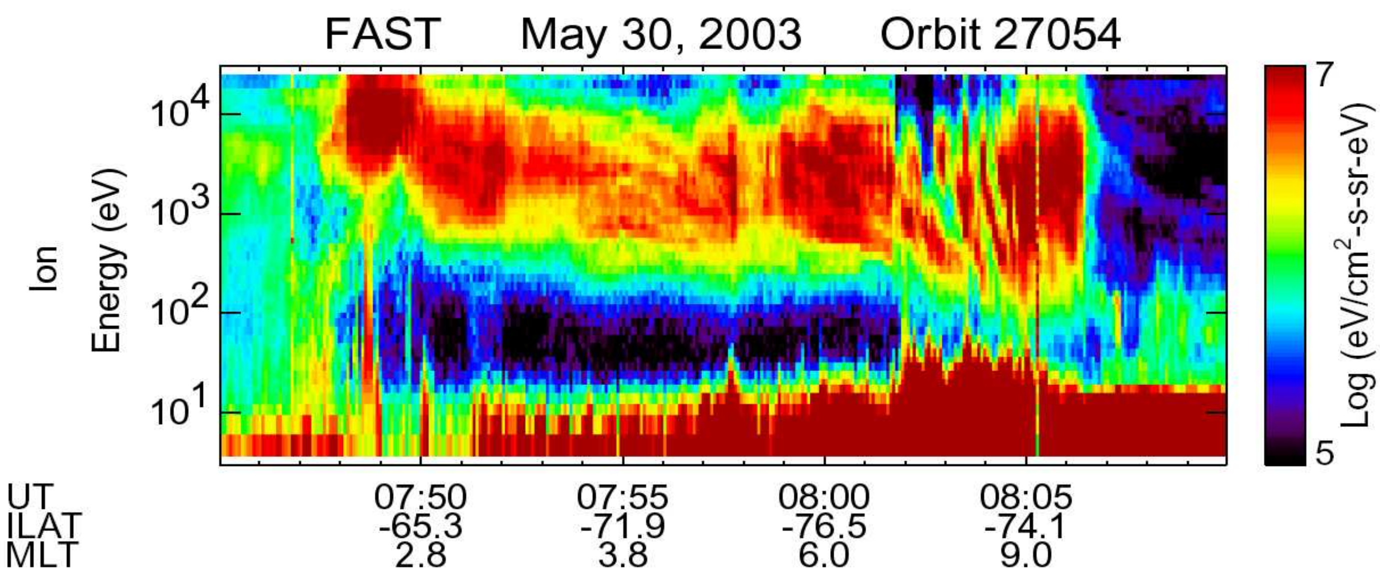


Local Time Changes in Dispersion

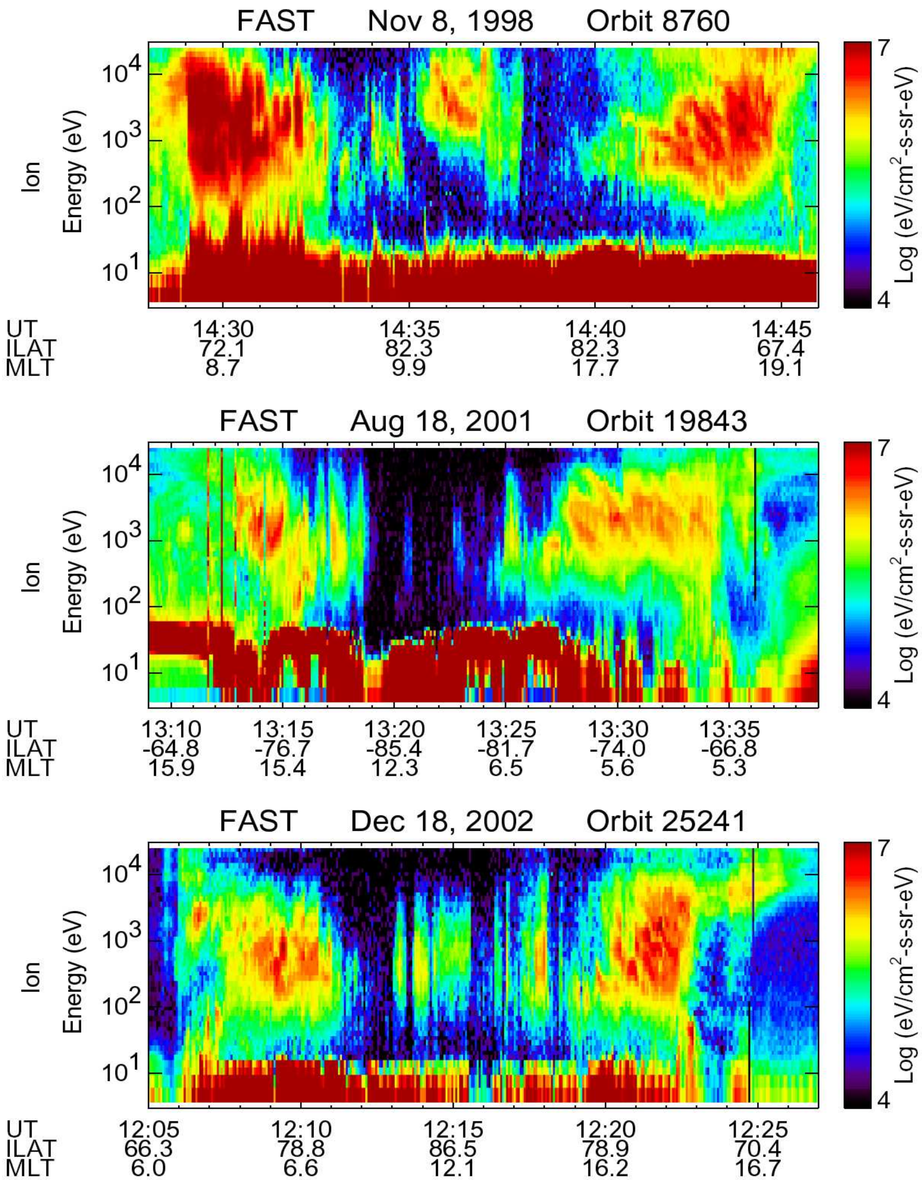
When FAST skims the dawn oval, the local time dependence of the CDPS is revealed. The number of overlapping VDISs increases away from noon down the flanks of the oval as expected from bounce drift of injections originating from noon.



Toward midnight **Toward noon**



Latitudinal Dispersion Signature



Three typical dawn-dusk crossings of the CDPS.

The energy of the VDIS increase with increasing latitude.

This dispersion signature is independent of whether the spacecraft is traveling north or south.

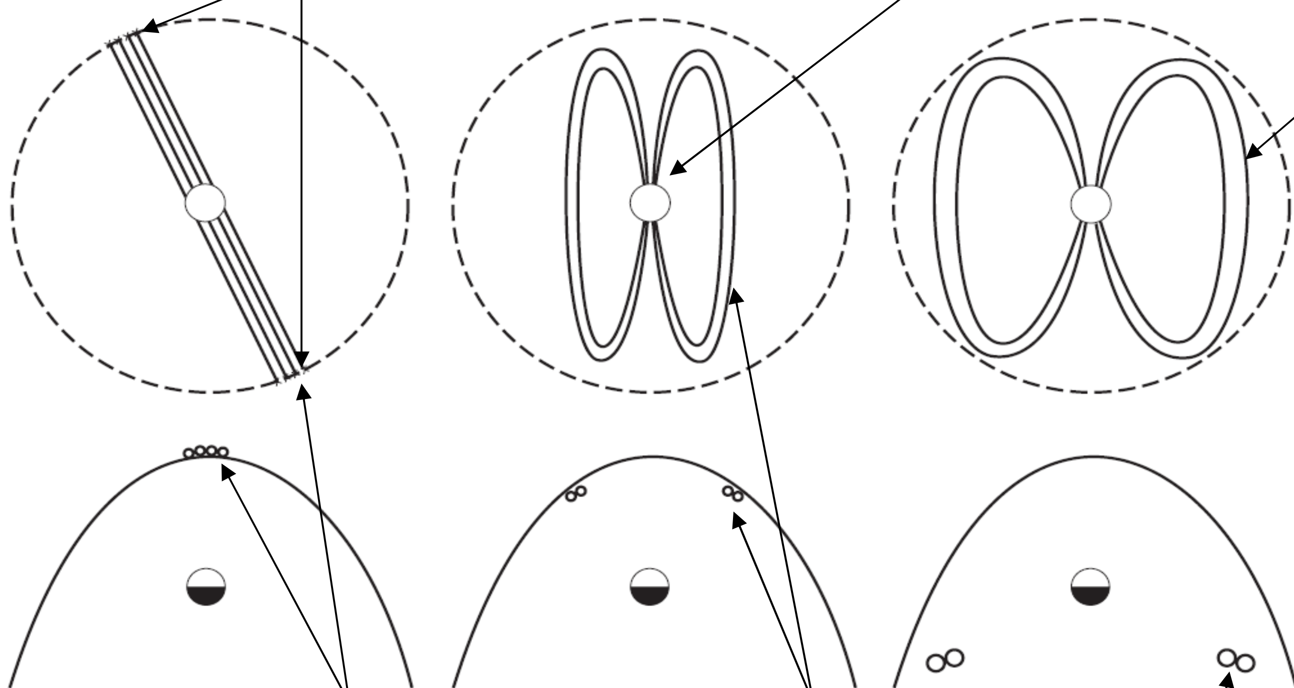
Therefore VDIS in the CDPS are spatial dispersions as observed in the cusp.

Model For Dispersion Signature

Lobe reconnections in both hemispheres inject ions along the magnetic field -- 4 injections.

Ion injections mirror forming multiple peaks. Field aligned ions are more easily observed at low altitudes by FAST.

FAST does not sit long enough on a single flux tube to see velocity dispersion.



Higher latitude flux tubes are longer. Ions injected at about the same time in the cusp and arriving at about the same time on higher latitude flux tubes along the flank must have higher energy (longer path).

For continuous convective flow, adjacent flux tubes had injections at about the same time.

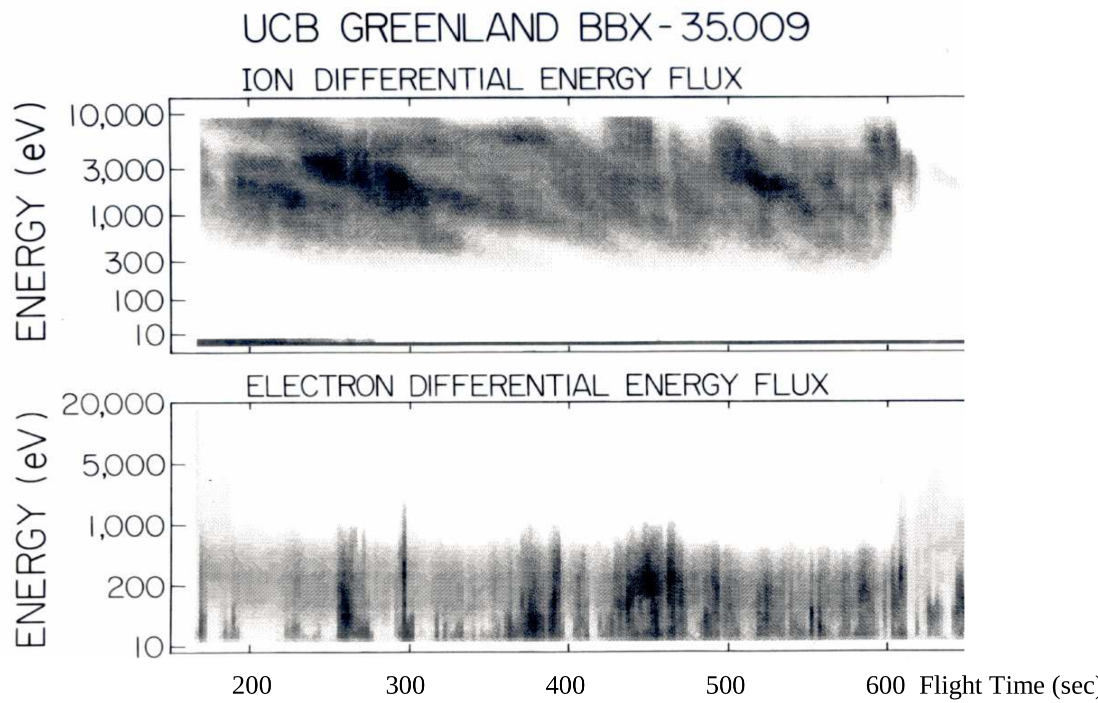
Flux tubes reorient and spread out along the MP forming the LLBL and eventually the CDPS. (Interchange Instability)

The dispersive signature is a path length effect!

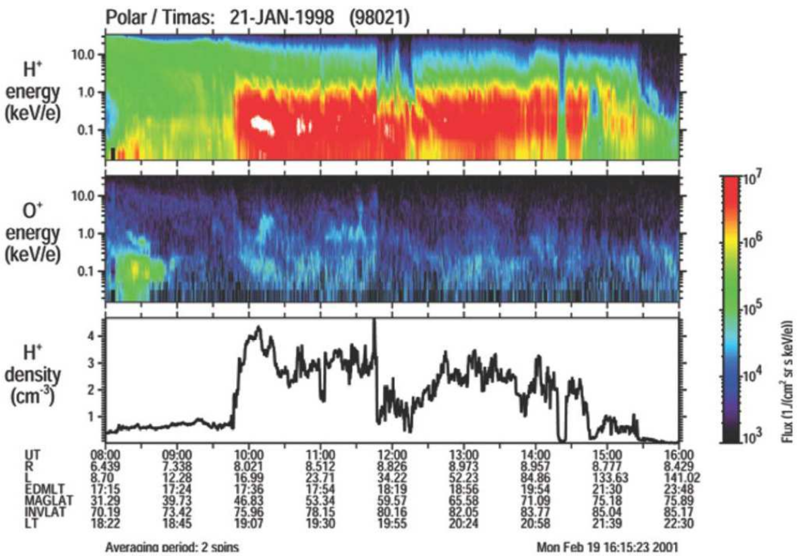
Related Observations 1

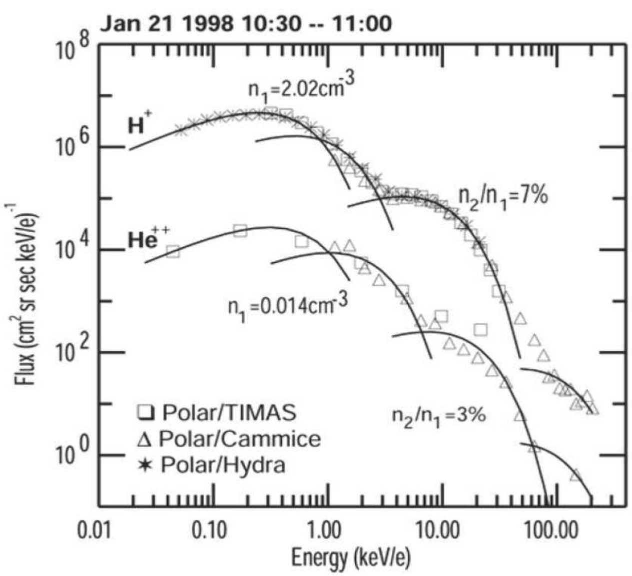
Similar, overlapping ion injections have been reported by Carlson and Torbert (1980), Woch and Lundin (1992), Clemmons et al. (1995), Sandahl et al., 1998; Sauvaud et al., 1998; Ober et al., 2000; Stenuit et al., 2001; Lundin et al.. There is no need to invoke flank ion injections from some unknown source. Cusp injections coupled with bounce drift are adequate.

Figure from Clemmons et al. 1995, JGR.
9-10 MLT



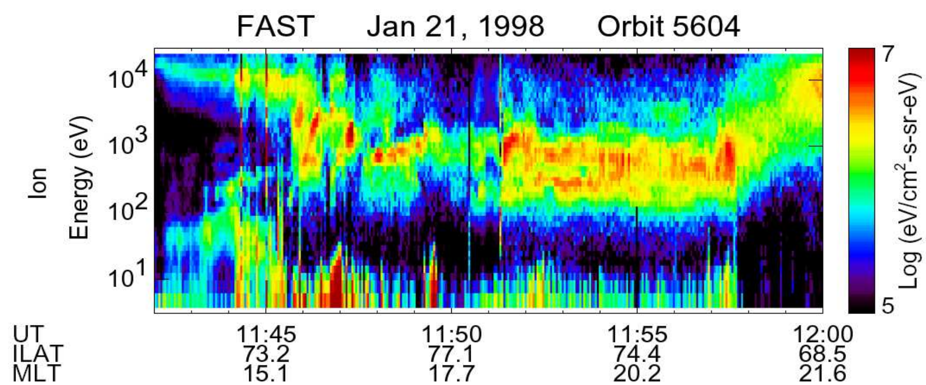
Related Observations 2





Fuselier et al. (JGR, 2002) interprets Polar data in terms of a single lobe reconnection, convection around the duskside, and a second reconnection to close the field line. The "n_2" component is attributed to a separate population from the quasi-parallel bow shock.

FAST shows multiple dispersive peaks indicating dual-lobe reconnection with "n_2" being just another peak. An "O+" band (not shown) is also observed by FAST indicating reconnection acceleration rather than just ion outflow.



Conclusion

The dual-lobe reconnection model and PDL requirement is consistent with high latitude MSBL observations and provides an explanation of why near simultaneous reconnection can be favored.

The dual-lobe reconnection model explains “near” co-location of the low latitude transition between unidirectional and bidirectional electrons and the magnetic shear reported by Fuselier et al. (1995). The magnetic shear is caused by field line relaxation as described by Song and Russell, (1992).

The dual-lobe reconnection model does not require electron heating at a low shear MP. Electron heating at a high shear MP can be explained by simple curvature drift in a reconnection flow jet (McFadden et al., 2005, in preparation).

Low altitude measurements by FAST during long periods of northward IMF show that formation of the Cold Dense Plasma Sheet is consistent with the dual-lobe reconnection model.

Summary

1. Cluster observations indicate that bi-directional heated electrons are typically seen in the high latitude MSBL during northward IMF.

2. Under the assumption that the MP is the source of this electron heating, MSBL field lines must typically cross the MP at both ends and be closed.

3. Since closed MSBL field lines (IMF north) are produced by dual-lobe reconnection (Song and Russell, 1992), what favors this reconnection?

4. The requirement of a PDL to produce sub-Alfvenic flows before lobe reconnection can take place results in a geometry favorable for dual-lobe reconnection.

5. Dual-lobe reconnection is a candidate for the formation of the CDPS and possibly the primary source of solar wind plasma to the magnetosphere.

6. FAST satellite observations provide additional evidence that dual-lobe reconnection is the source of the CDPS.

Summary of FAST Observations

1. **FAST shows the CDPS ions are continuously present from the cusp to the tail flanks of the auroral oval.**

2. **Velocity Dispersed Ion Signatures (VDIS) are present throughout in the CDPS with increasing energy with increasing latitude.**

3. **Similar VDIS signatures in the CDPS are seen in both the dawn and dusk flanks of the auroral oval.**

4. **VDIS signatures in the CDPS evolve from single ion energy peaks near the cusp to multiple overlapping peaks near the dawn and dusk flanks.**

5. **CDPS flux tubes are observed to drift back across the polar cap where they can lobe-reconnect a second time.**

6. **Clear cusp VDIS signatures during northward IMF are rare indicating a relatively narrow local time mapping of lobe reconnected field lines.**

7. **A VDIS near noon may not be the cusp but could be a second bounce.**

FAST Conclusion

FAST observations support the Dual-Lobe Reconnection model as the source of the Cold Dense Plasma Sheet (CDPS). Continuity of the CDPS ions with cusp ions indicate a "cusp source" and not injections in the tail flank. VDISs within the CDPS are consistent with a cusp injection source and bounce drift. The drift is likely an ExB drift driven by the interchange instability.

Previous observations that invoked ion injections along the tail flank [Carlson and Torbert, 1980; Woch and Lundin, 1992; Clemmons et al., 1995; Sandahl et al., 1998; Sauvaud et al., 1998; Ober et al., 2000; Stenuit et al., 2001] are likely incorrect interpretations of cusp ion injections that occur during lobe reconnection. A VDIS does not necessarily indicate a recent injection.

Electron Heating Conclusion

The moderate electron heating associated with the MP is consistent with the expected energization by curvature drift along the convection electric field of a high-shear open MP. Electrons receive velocity kicks of twice the Hoffmann-Teller velocity at each crossing.

Simple curvature drift can't explain the observed spectrum which shows too little energy gain at low energies. However, when combined with resonant acceleration energy loss through the interaction with an ambipolar field (pressure gradient) associated with the expansion of dense magnetosheath ions into the tenuous magnetosphere, the observed spectra can be explained.

Spectra fits using this simple model result in estimates of average Hoffmann-Teller velocity, MS ion expansion velocity, and ambipolar potential that are consistent with expected values.

Suggested Models for CDPS Formation

Dual-Lobe Reconnection as described by Song and Russell (1992, JGR) coupled with the Interchange Instability to carry the ions from the LLBL to the magnetotail.

Kelvin-Helmholtz Instability along the magnetotail flank coupled with reconnection or diffusive mixing, as described by Hasegawa et al. (2004, Nature).

Diffusion of solar wind plasma from the magnetosheath across the flanks toward the plasma sheet center Terasawa et al. (1997, GRL).

Leakage of solar wind ions along slots between the tail lobes and plasma sheet and convected inward along the plasma sheet boundary layer, as described by Lennartsson (1992, JGR).