What determines when and where reconnection begins

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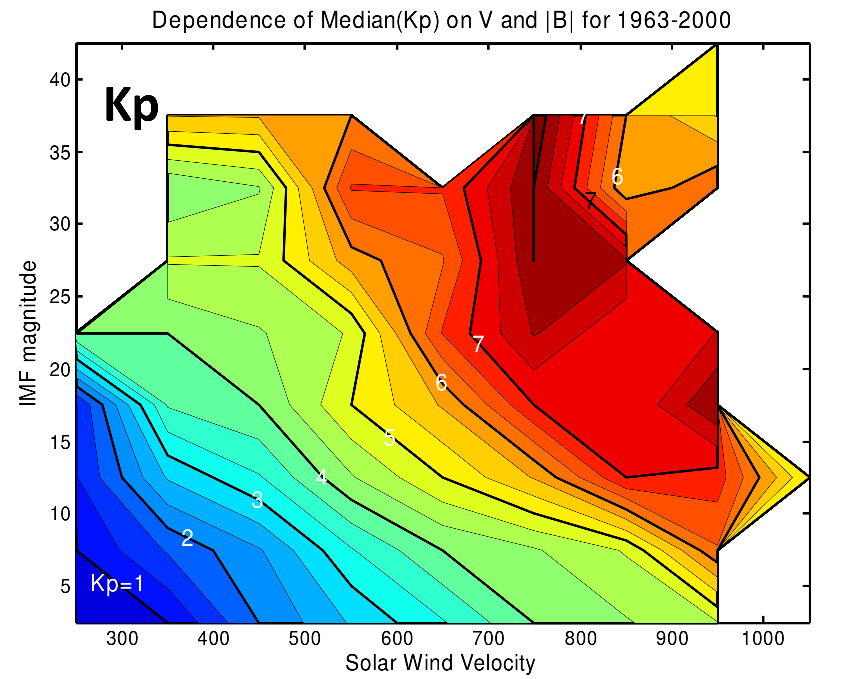
Invited presentation at Unsolved Problems in Magnetospheric Physics, Scarborough, UK, Sept. 6-12.

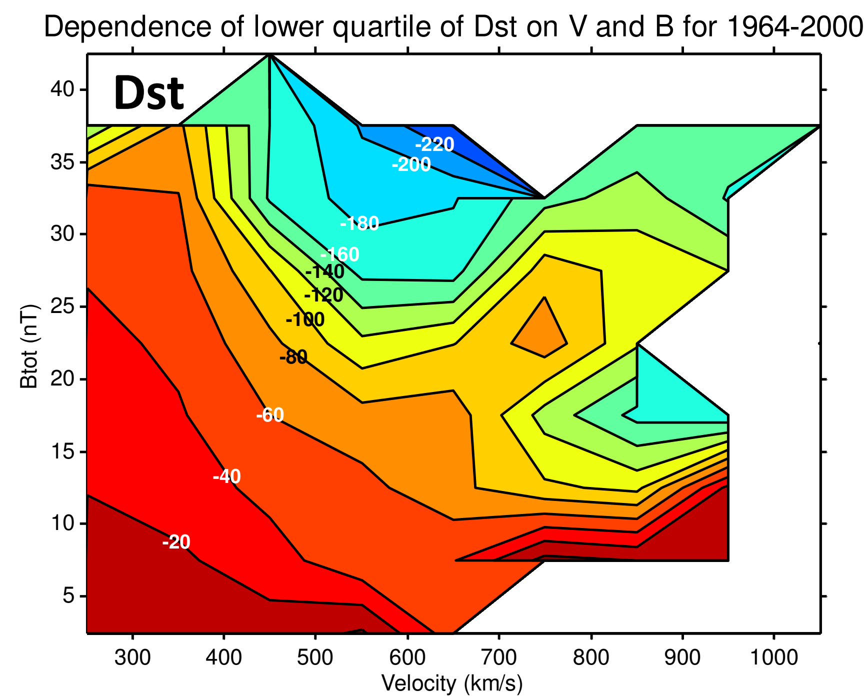
Factors That Might Affect Tail Reconnection

- Presence of the dipole field
- Radial gradients of the magnetic field
- Radial gradients of the pressure
- Effects of ring current on tail field
- Linkage of the magnetic field line to the Earth
- Magnetosphere-ionosphere coupling through conductive ionosphere
- Strength of plasma sheet Bz
- Current sheet thickness
- Current sheet intensity
- Presence of oxygen in plasma sheet
- Tail compression by dynamic pressure
- Reduction in solar wind coupling
- Perturbations by macroscopic instabilities

Median Kp and Lower Quartile of Kp and Dst Depend on V and B

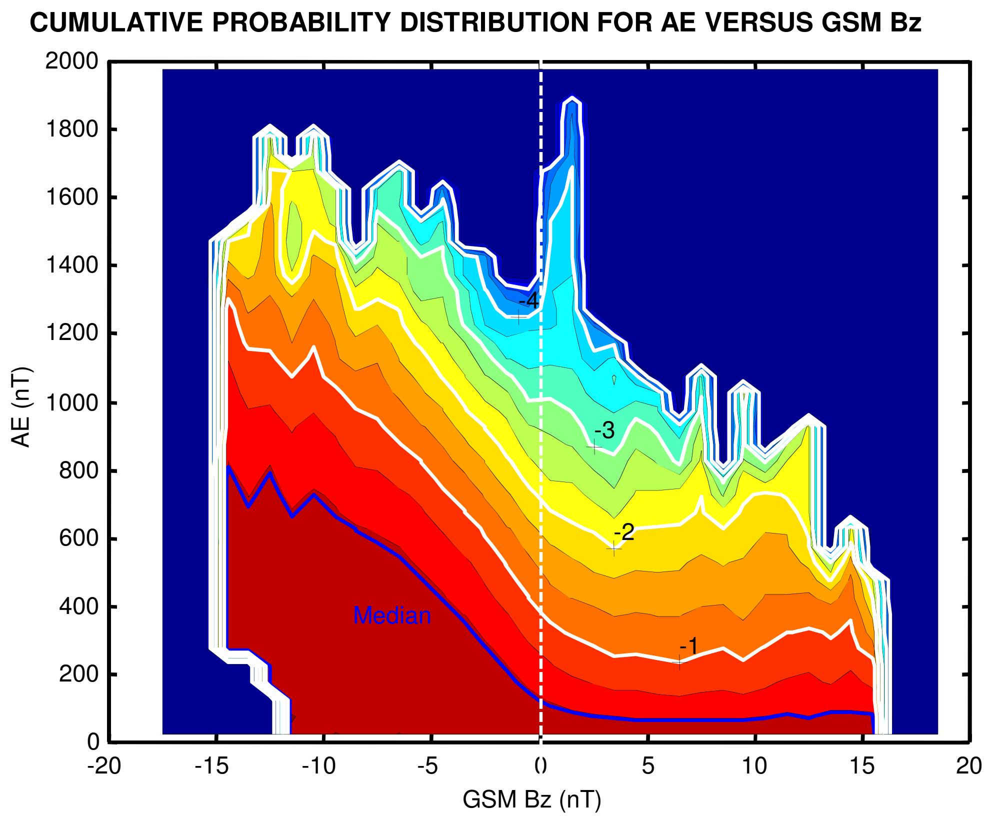
- Create bins of IMF magnitude and solar wind speed
- Determine median Kp and lower quartile of Dst in each bin
- Contour median Kp in speed –magnitude plane
- ***For fixed field strength both Kp and Dst increase with speed***
- ***For fixed speed both Kp and Dst increase with |B|***





WHAT CAUSES MAGNETIC ACTIVITY? IMF - Bz and RECONNECTION!

- Use 30 years of hourly AE and IMF Bz
- For each 1 nT bin of Bz create the cumulative probability distribution for corresponding AE index
- Display contour map of the probability of observing AE exceeding a given value as a function of Bz
- The probability of observing large values of AE decreases very rapidly as Bz changes to positive values
- The median value of AE for Bz > 0 is less than 100, the background level of AE from Sq variations in measurements

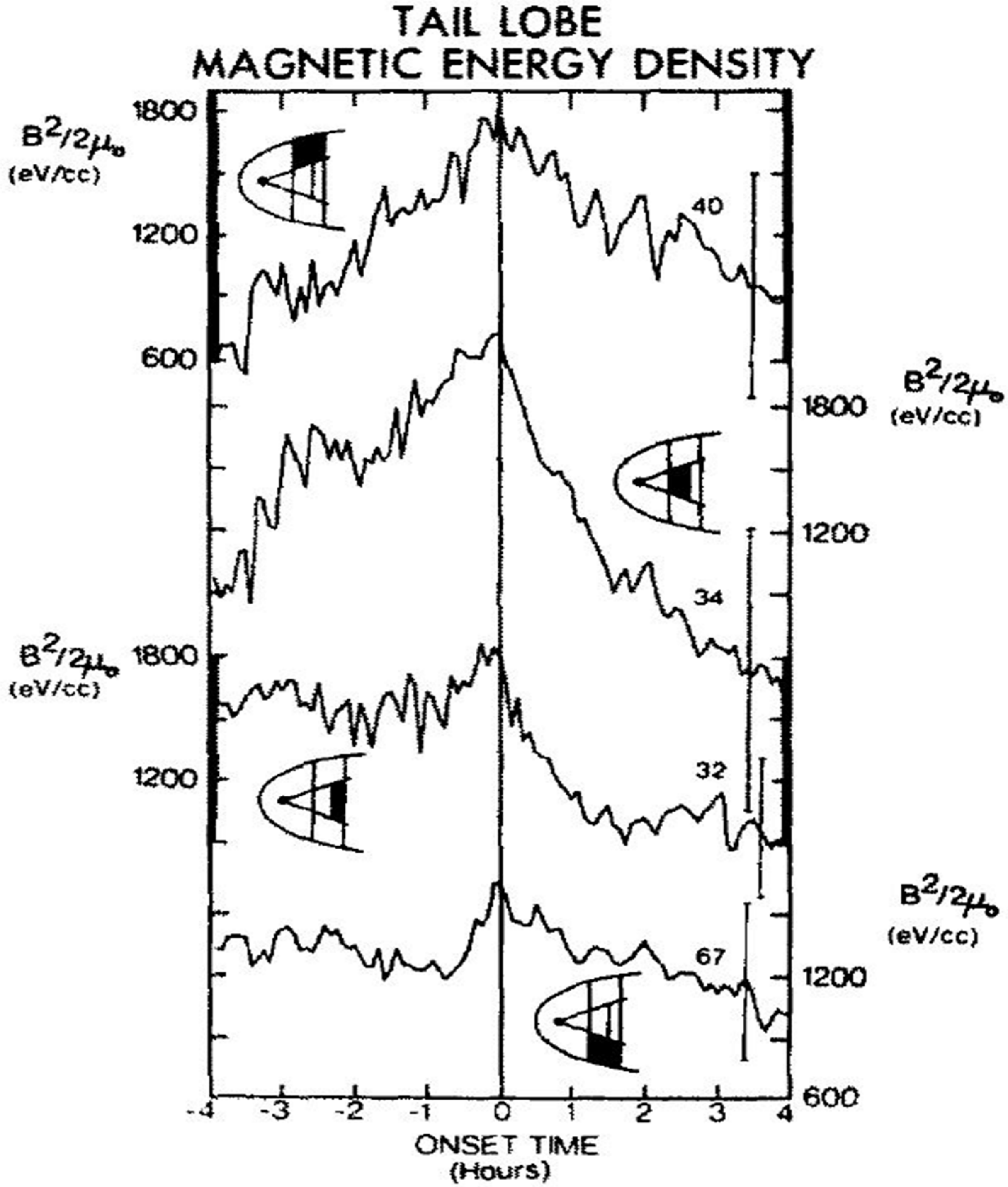


Tail Lobe Energy relative to MPB Onset

Caan et al., (1978), The statistical magnetic signature of magnetospheric substorms, *Planetary and Space Science, 26(3), 269-79.*

- Time the onset of substorms using MPB
- Superpose tail lobe energy density
- The lobe field increases before onset and decreases after onset

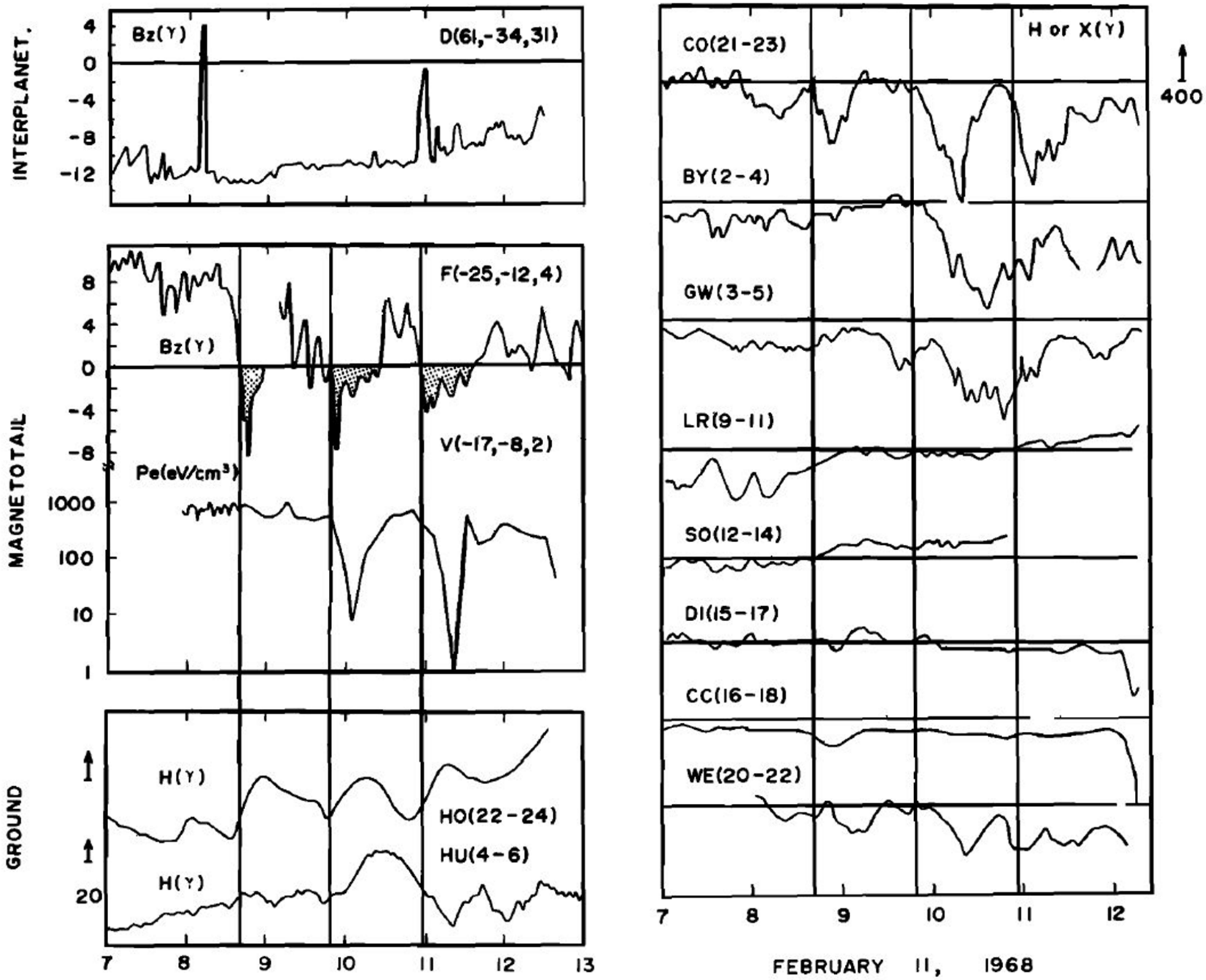
- ***The data suggest that substorms are associated with unloading of open flux from tail lobes***



Plasma Sheet Thinning after Onset

Nishida and Hones (1974), Association of Plasma Sheet Thinning With Neutral Line Formation in the Magnetotail, Journal of Geophysical Research, 79(4), 535-547, doi:10.1029/JA079i004p00535.

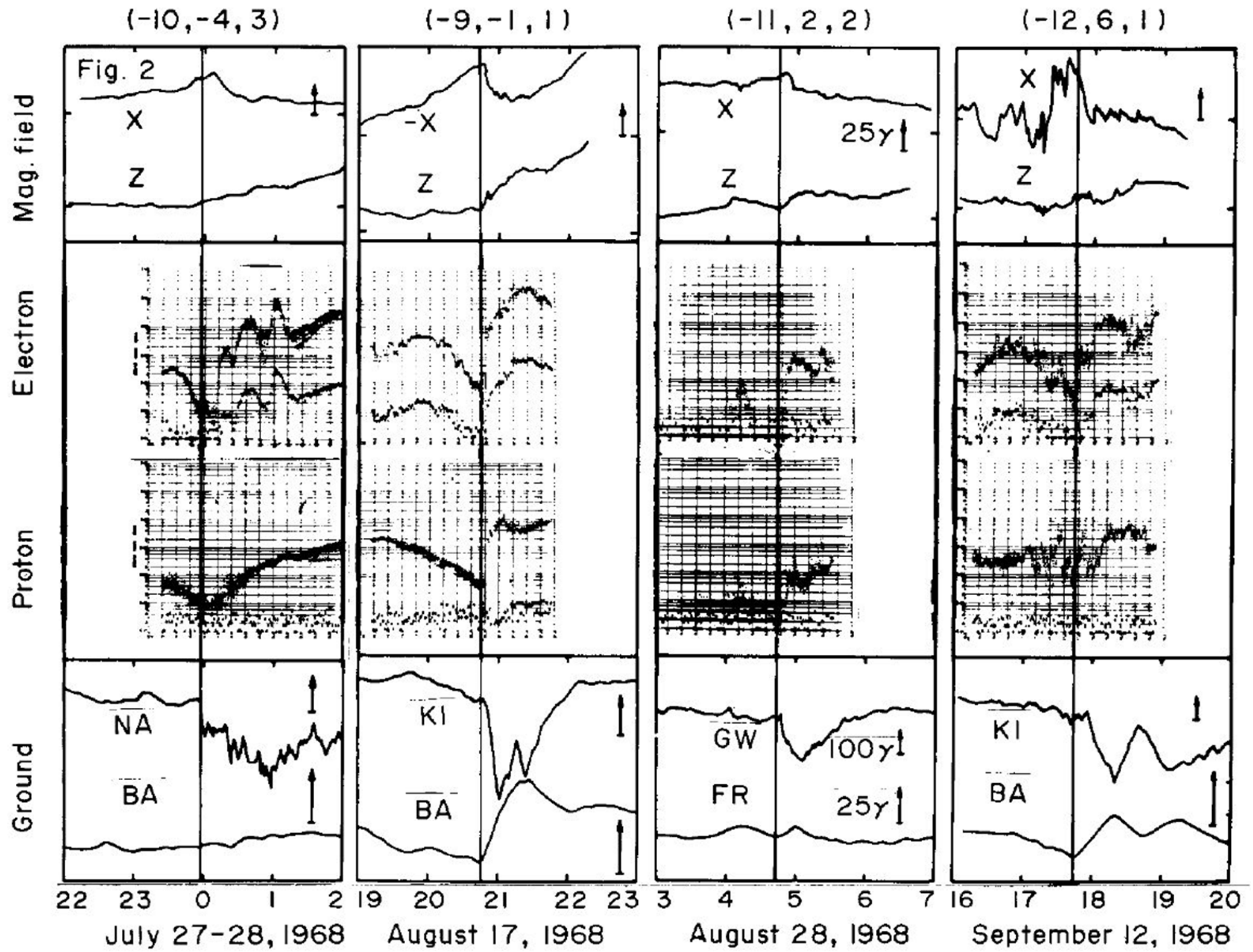
- Use MPB to define substorm onset
- At 22 Re southward turn of Bz is detected
- Often there is a drop out of plasma sheet
- ***It is suggested an x-line formed earthward of -25 Re and sent a plasmoid tailward***



Plasma Sheet Thinning Prior to Onset

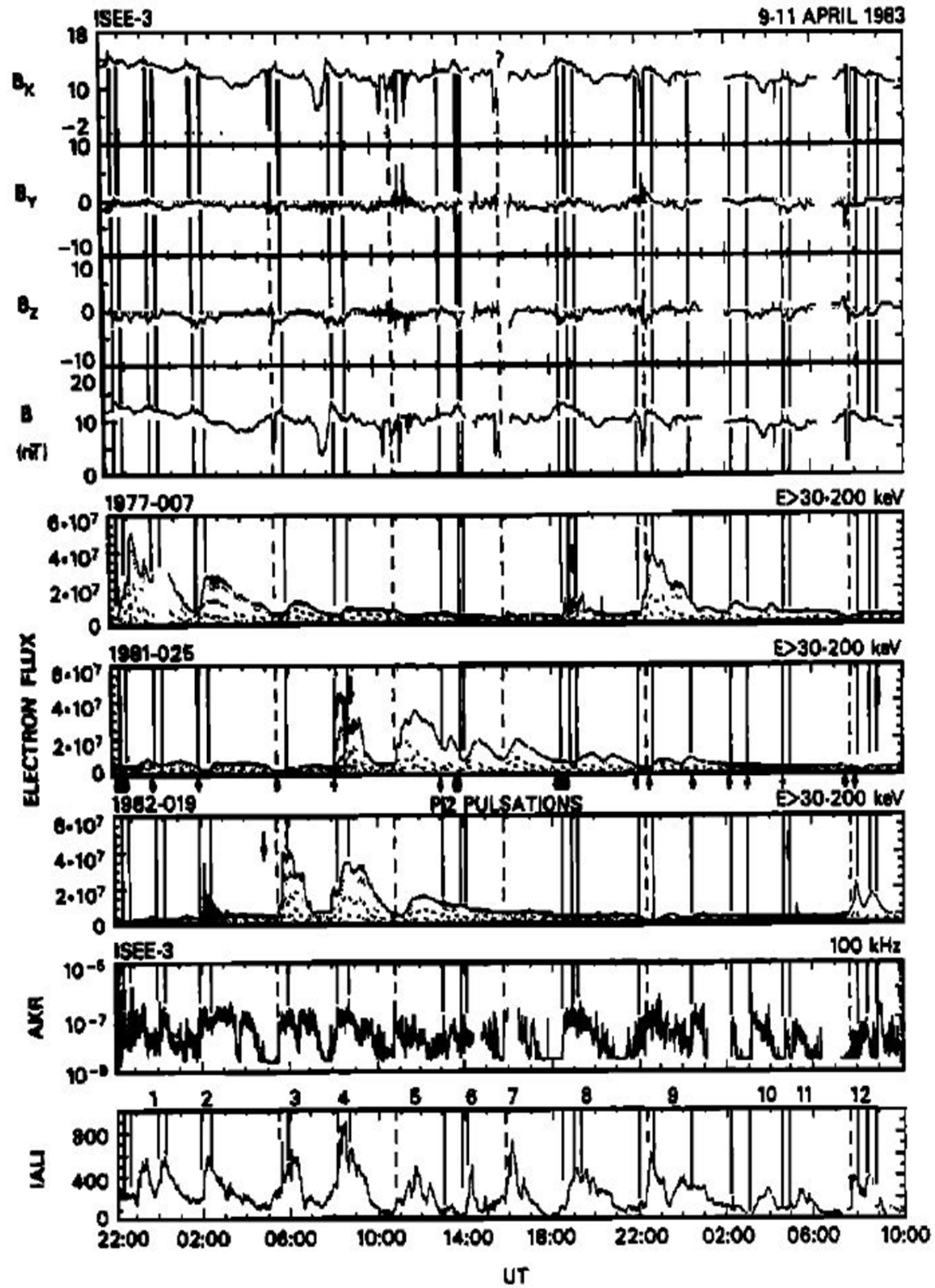
Nishida, A., and K. Fujii (1976), Thinning of the near-Earth (10 ~ 15 Re) plasma sheet preceding the substorm expansion phase, *Planetary Space Science, 24(9), 849-853.*

- Close to the Earth there is growth of lobe field and plasma sheet thinning prior to onset
- ***Suggested that thinning of the plasma sheet is the cause of neutral line formation***



ISEE 3 Observations of TCR

Slavin et al (1992), ISEE 3 plasmoid and TCR observations during an extended interval of substorm activity, *Geophysical Research Letters, 19(8), 825-828828, doi:10.1029/92gl00394.*



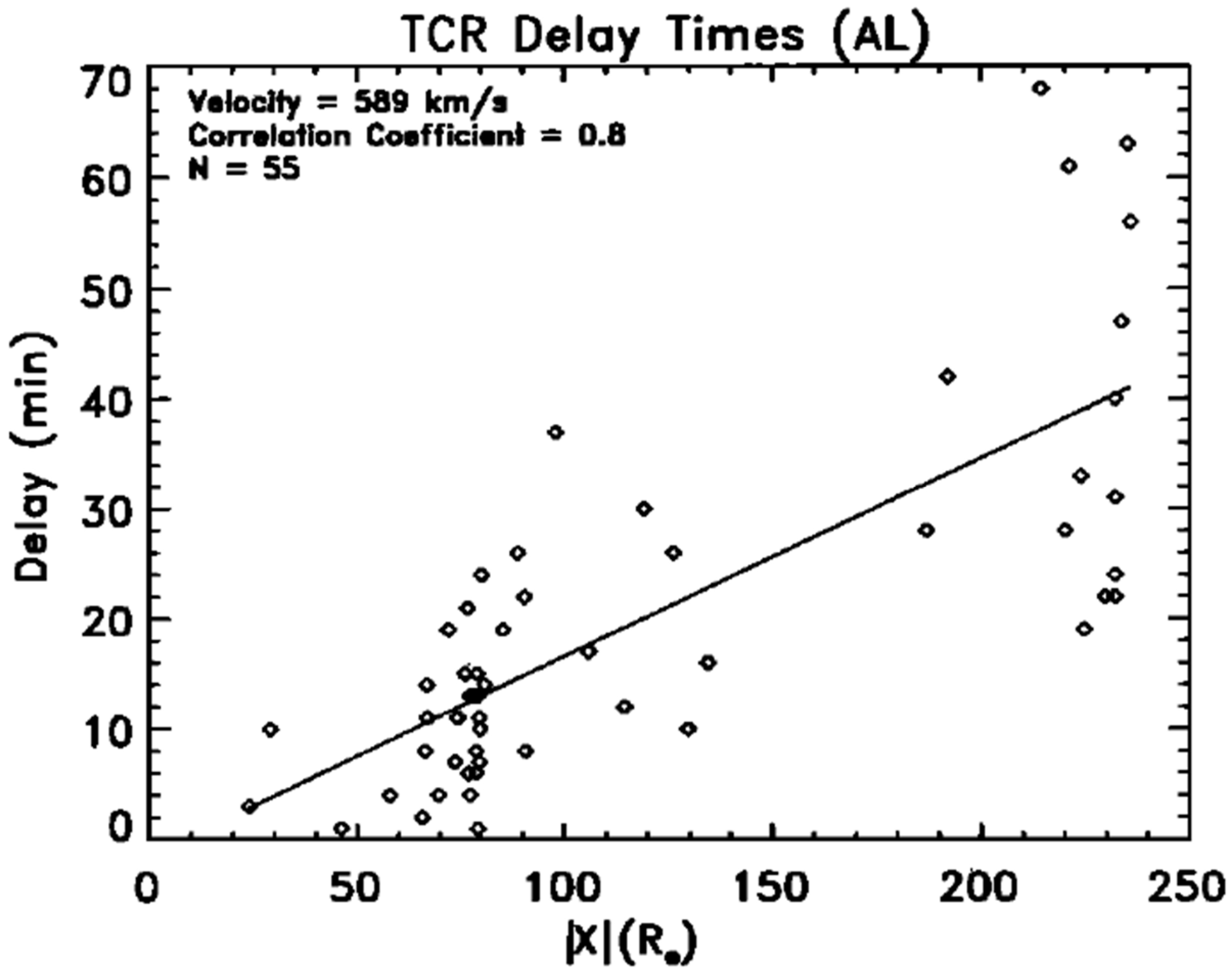
- 9 of the 12 large substorms were preceded by **growth phas**e enhancements in lobe field intensity;
- All of the substorms produced one or more **plasmoid(s)** and/orTCR(s)
- These arrived at ISEE 3 11 min, on average, after expansion phase onset;
- The plasmoids traveled at a mean speed of 400 km/s, the same as measured flow speed

Time Delay of ISEE 3 TCR with Distance

- Observed 116 TCR at different distance
- 37 isolated TCR
- 36 paired TCR (18 pairs)
- 11 multiple events with 43 TCR
- Estimated dimensions L=35, W=15, H=15 Re

- ***91% of TCR followed substorm onset or intensification***
- ***Estimate a TCR and substorm occurs every 4-6 hou**rs*
- ***Probable origin near 20 Re***

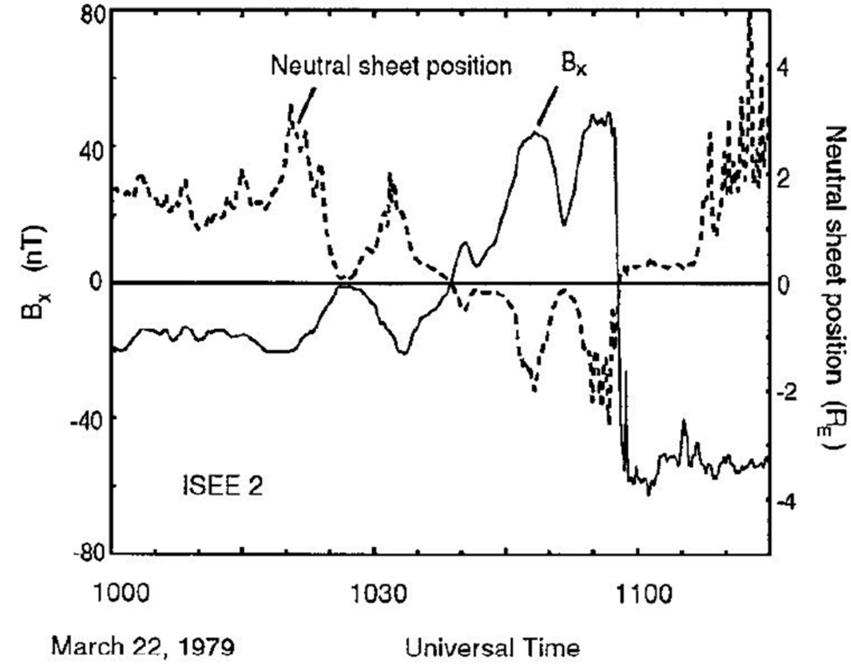
Slavin, J.A (1993), ISEE 3 observations of traveling compression regions in the Earth's magnetotail, Journal of Geophysical Research, 98(A9), 15425-1544615446, doi:10.1029/93ja01467.

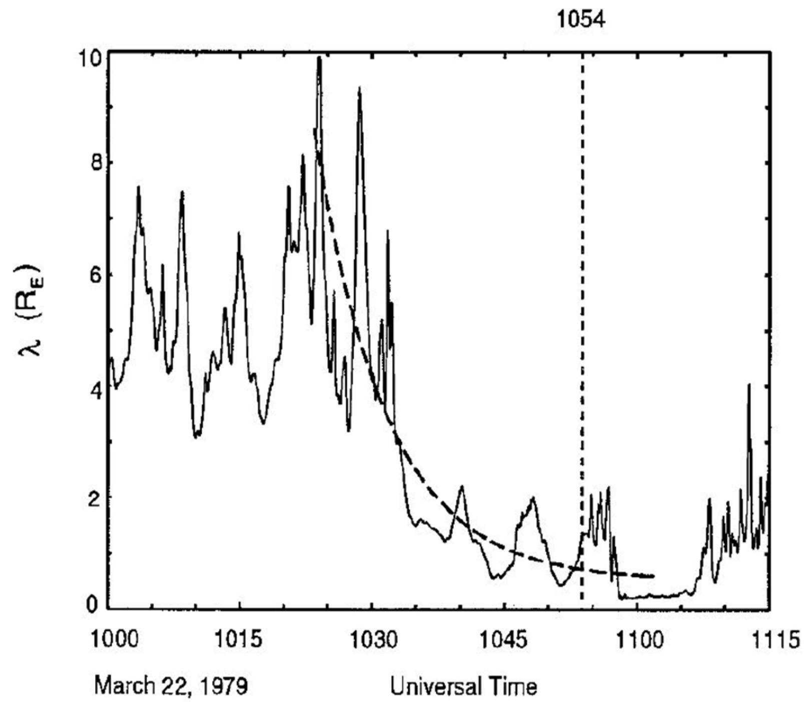


Plasma Sheet Thinning

McPherron, et al. (1987), in *Quantitative Modeling of Magnetosphere-Ionosphere Coupling Processes, edited by Y.Kamide and R.A. Wolf, pp. 252-257*
Sanny, Jet al. (1994), Growth-phase thinning of the near-earth current sheet during the CDAW-6 substorm, J. Geophys. Res., 99(A4), 5805-5816.

- During CDAW 6 substorm the neutral sheet was swept across the two spacecraft allowing the Harris sheet model to determine the location of natural sheet and thickness of plasma sheet (dash line top)
- During growth phase the plasma sheet thinned from a half thickness of 5Re to less than 1 Re (dash line bottom)
- After expansion onset at 1054 UT the plasma sheet further thinned to ~ 500 km



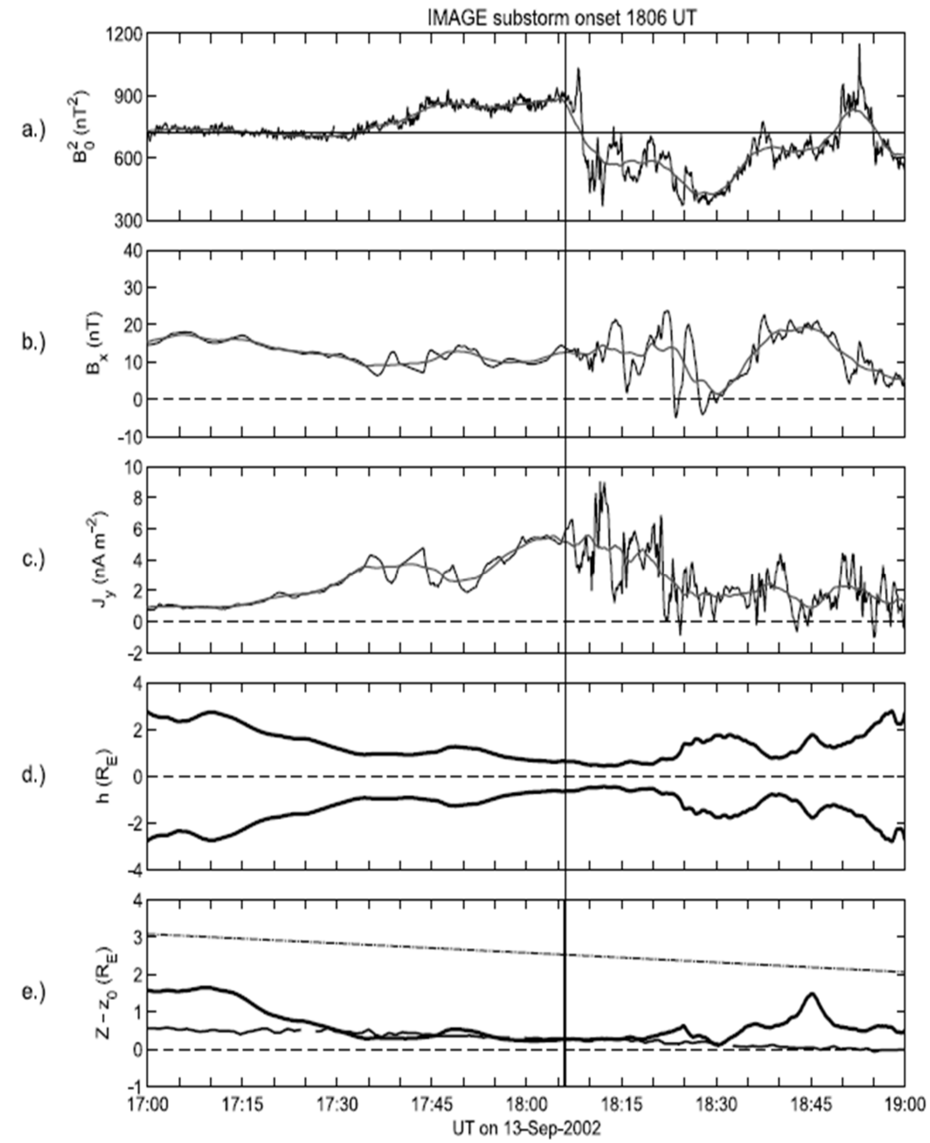


Cluster Example of Current Sheet Thinning

Thompson, S.M., et a. (2005), Dynamic Harris current sheet thickness from Cluster current density and plasma measurements, *Journal of Geophysical Research-Space Physics, 110(A2), doi:10.1029/2004ja010714.*

- There is a 30 minute increase in lobe energy during growth phase
- The cross tail current density generally follows the Harris shape
- The current sheet decreased from about 6 Re to 1 Re at onset

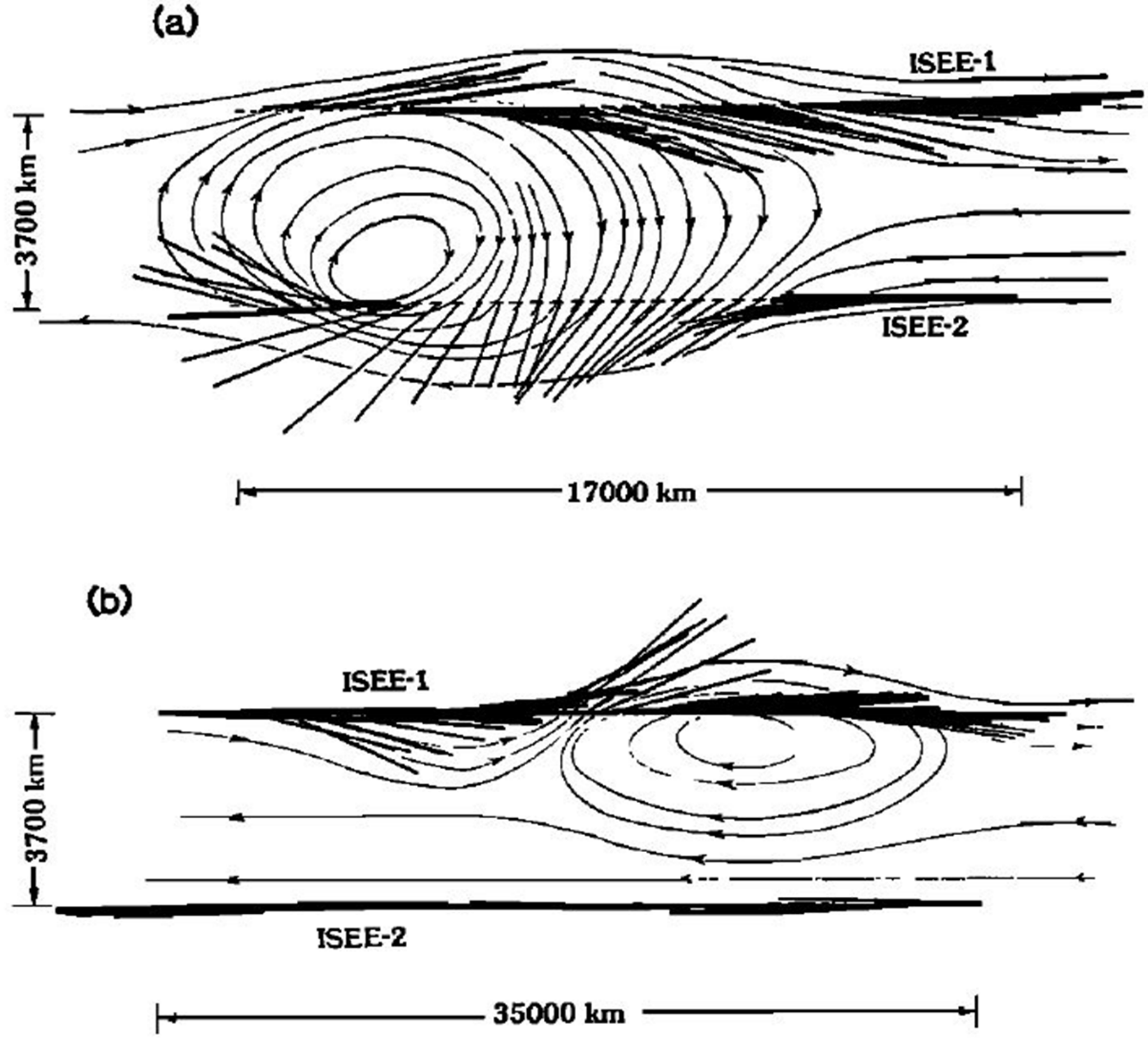
- ***An increase in lobe field is associated with plasma sheet thinning and substorm onset***



A Near-Earth Plasmoid

Lin, N., R. McPherron, M. Kivelson, and R. Walker (1991), Multipoint Reconnection in the Near-Earth Magnetotail: CDAW 6 Observations of Energetic Particles and Magnetic Field, *Journal of Geophysical Research, 96(A11), 19427-19439, doi:10.1029/91JA01952.*

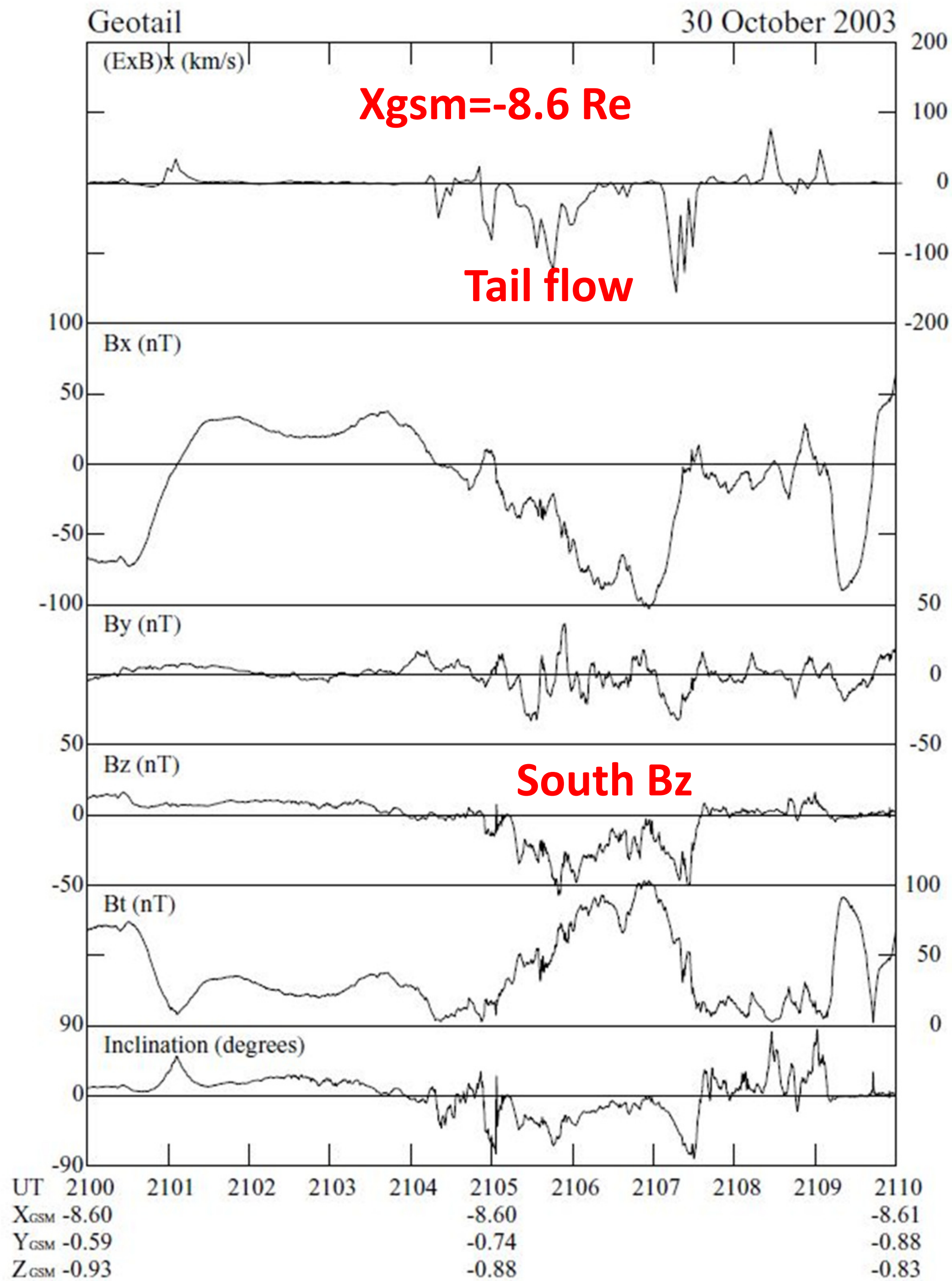
- The CDAW 6 substorm of March 22, 1979 occurred when the two ISEE spacecraft were 15.4 and 14.3 Re behind the Earth at 02 LT
- Negative Bz associated with tailward flow (580 km/s) persisted for 17 m
- This was interpreted as two small plasmoids traveling away from Earth



Very Near Earth Reconnection!

Nagai, T. (2006), Location of magnetic reconnection in the magnetotail, *Space Science Reviews, 122(1-4), 39-54, doi:10.1007/s11214-006-6216-4.*

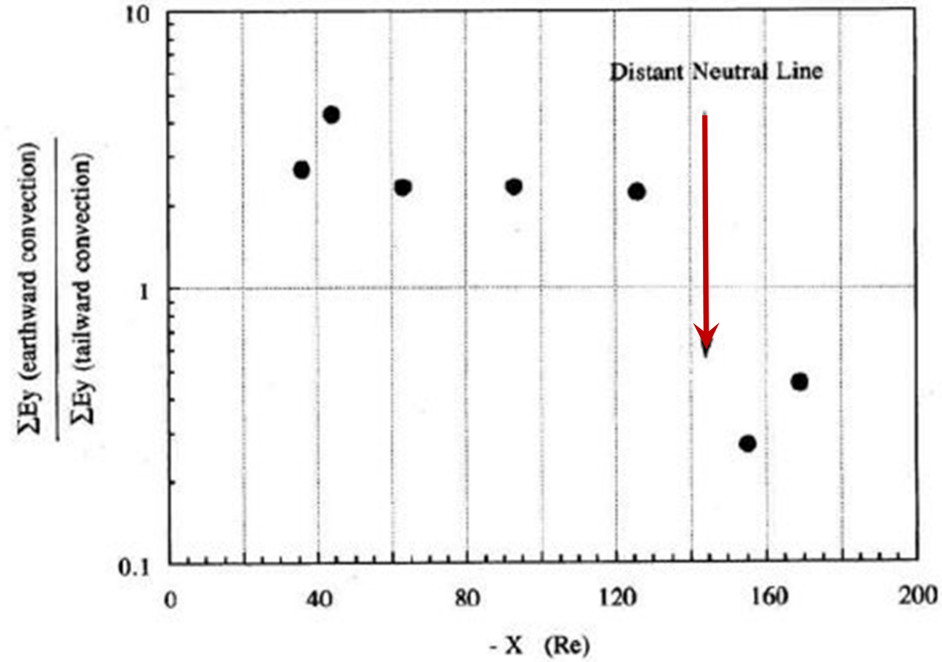
- Nagai reported Geotail signatures of reconnection earthward of X = -8.6 Re when Kp = 9 and Dst = -342 nT

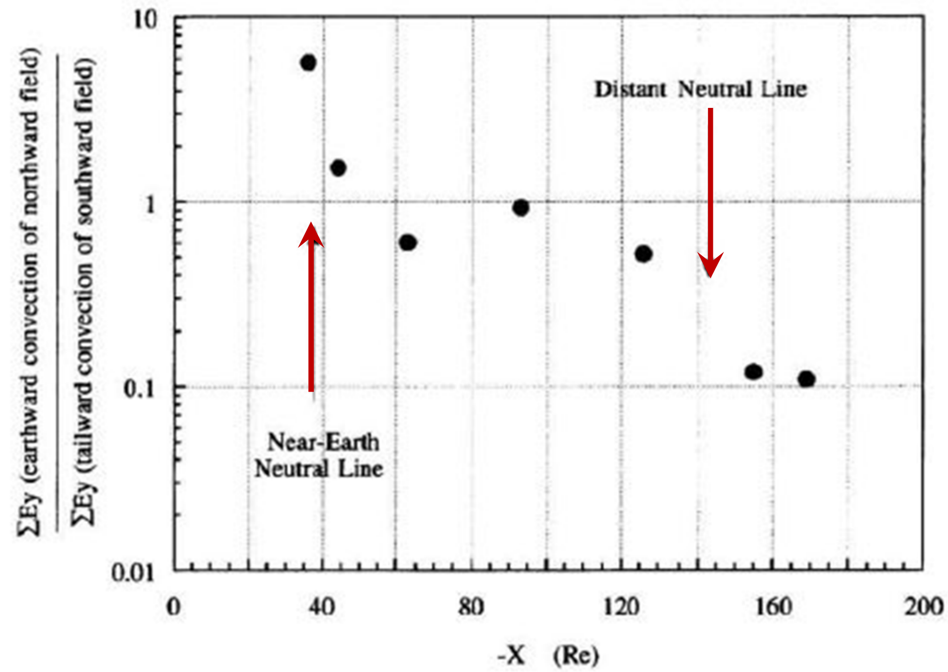


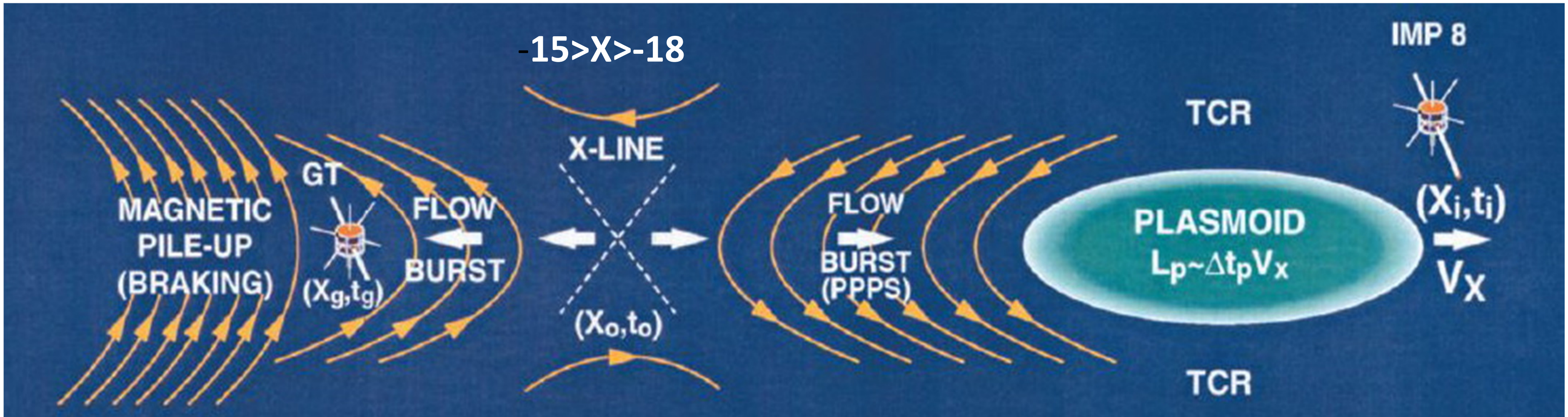
Location of Tail X-lines

Nishida et al., (1996), Magnetotail convection in geomagnetically active times .1. Distance to the neutral lines, *JGG, 48(5-6), 489-501.*

- Use Ey = Vx x Bz to calculate rate of flux transport past the Geotail spacecraft and normalize the data
- Calculate total convection in either direction and ratio (top)
- Calculate earthward convection of northward field and tailward convection of southward field and ratio (bottom)
- ***The change in ratio above and below 1.0 indicates average location of x-lines inside 40 Re and about 140 Re***

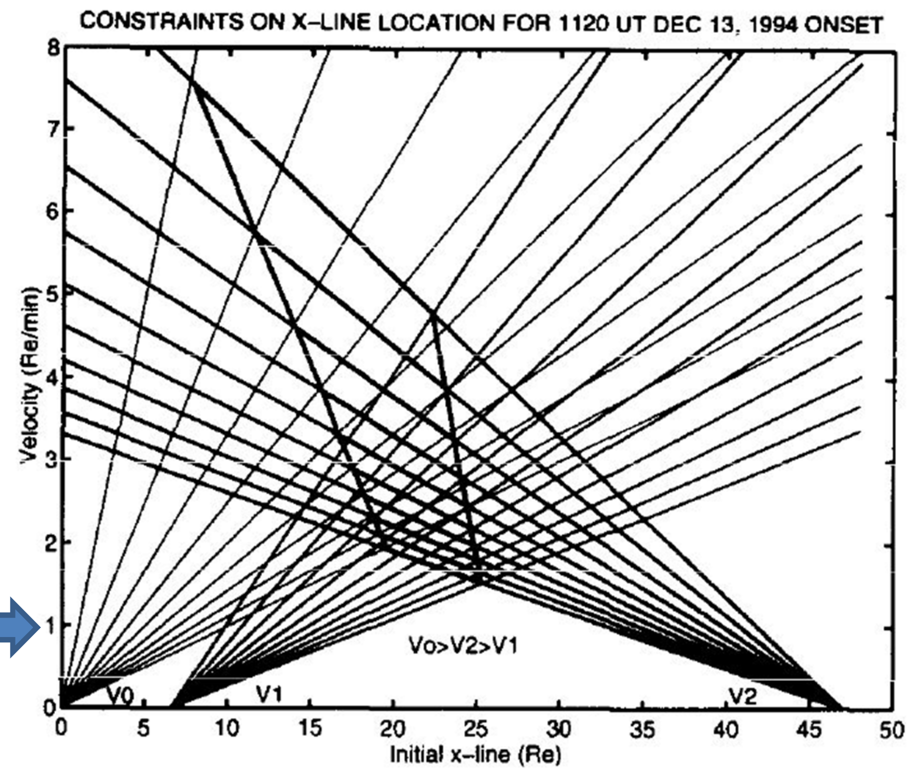






Slavin, J.A., D.H. Fairfield, R.P. Lepping, M. Hesse, A. Ieda, E. Tanskanen, N. &Oslash, stgaard, T. Mukai, T. Nagai, H.J. Singer, and P.R. Sutcliffe (2002), Simultaneous observations of earthward flow bursts and plasmoid ejection during magnetospheric substorms, *Journal of Geophysical Research, 107(A7), doi:10.1029/2000JA003501.*

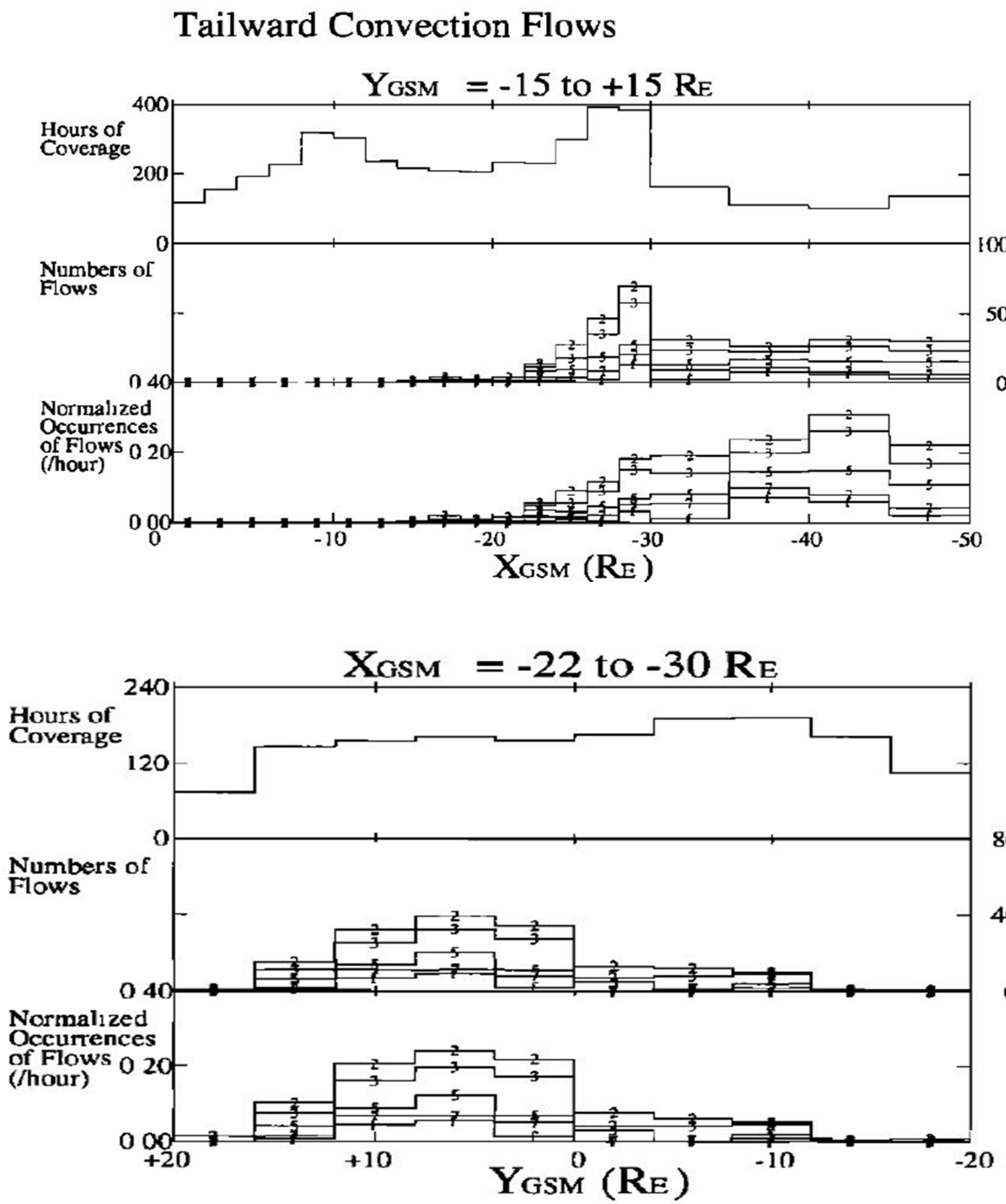
McPherron, R.L., R. Nakamura, S. Kokubun, Y. Kamide, K. Shiokawa, K. Yumoto, T. Mukai, Y. Saito, K. Hayashi, T. Nagai, S. Ables, D.N. Baker, E. Friis-Christensen, B. Fraser, T. Hughes, G. Reeves, and H. Singer (1997), Fields and flows at GEOTAIL during a moderate substorm, *Advances in Space Research, 20(4/5), 923-931.*



Location of Tail Reconnection

Nagai and Machida (2013)

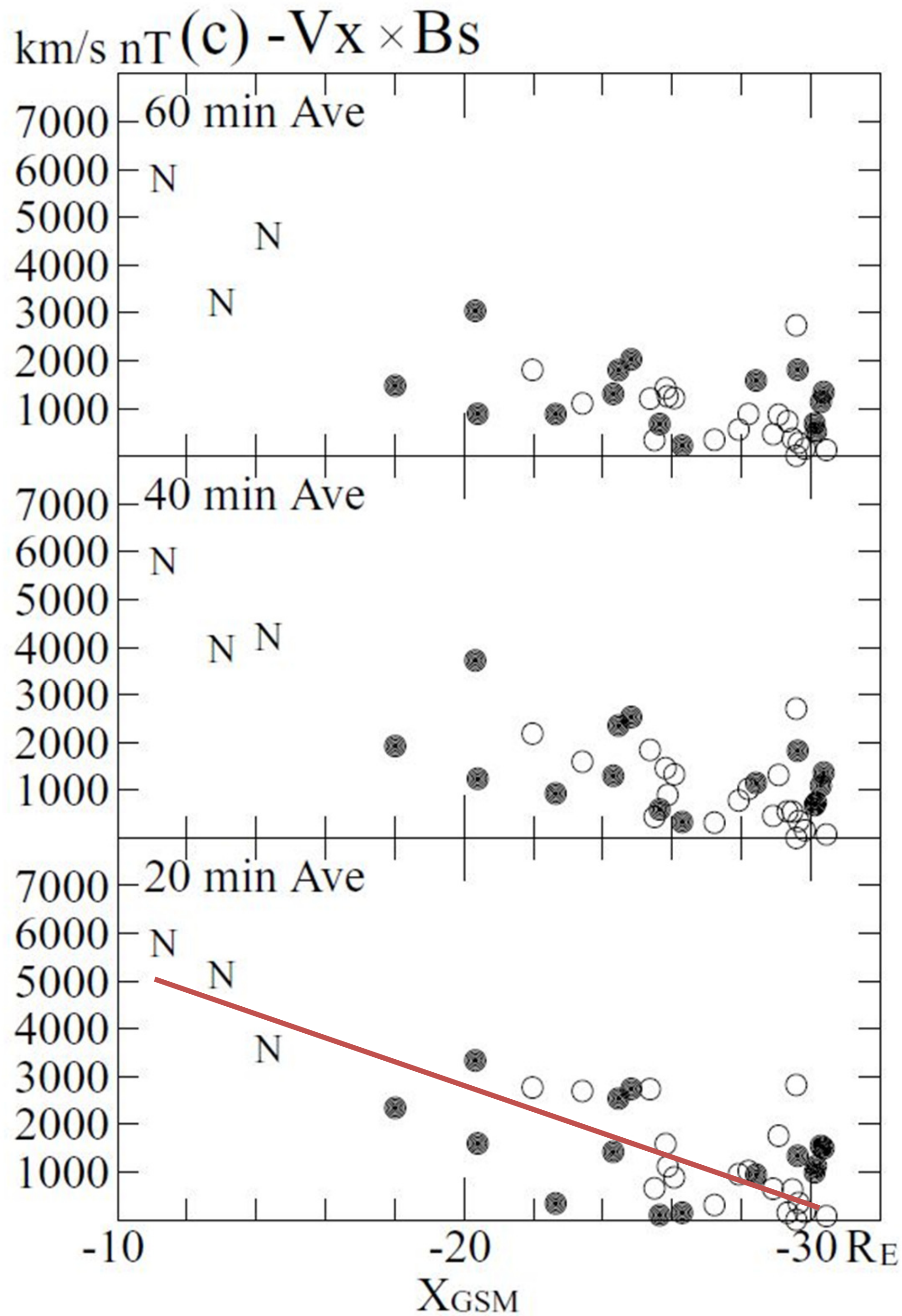
- Geotail observed tailward flows from reconnection tailward of X_{GSM}= -20 Re
- Most of the tailward flows occurred up to 10 Re west of midnight
- The rate of tailward flows was about 4.8 per day



Electric Field in Tail for Tailward Flow Events

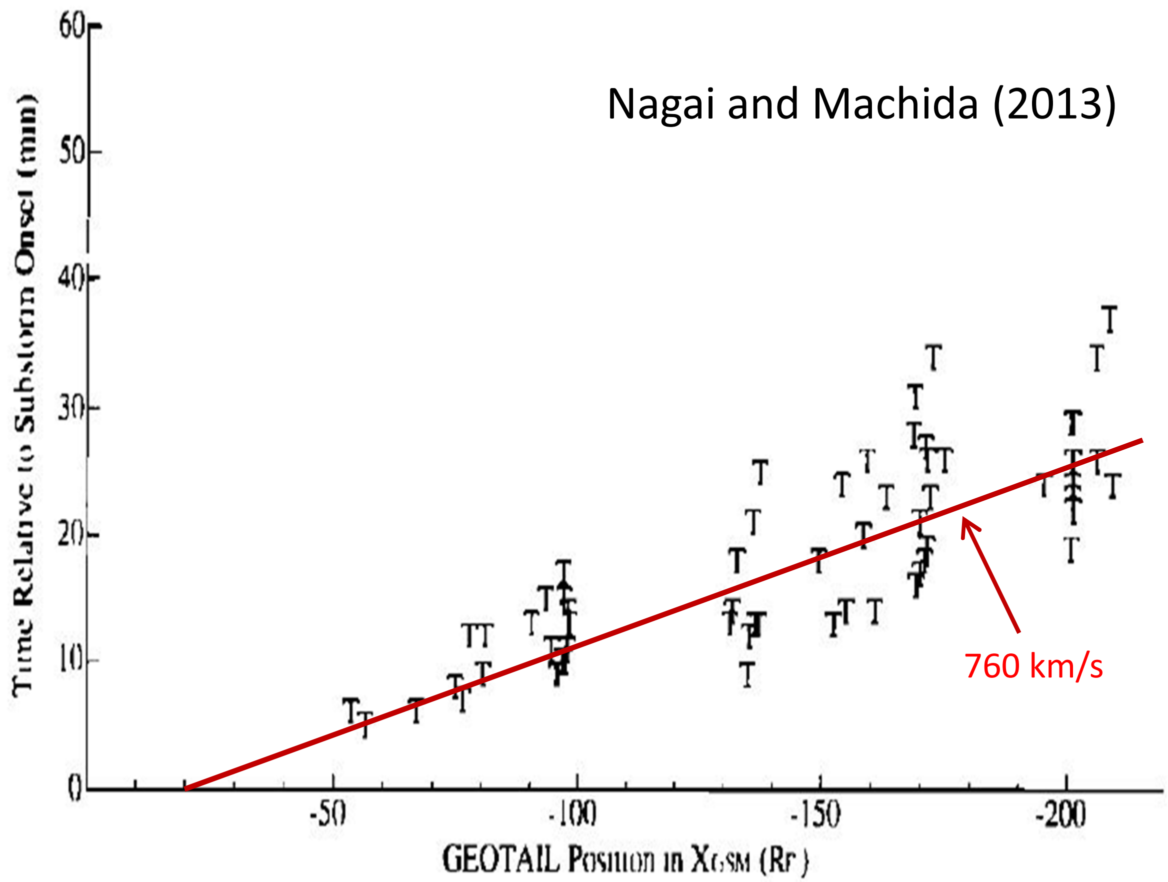
Nagai, T. (2006), Location of magnetic reconnection in the magnetotail, Space Science Reviews, 122(1-4), 39-54, doi:10.1007/s11214-006-6216-4.

- The electric field in the tail as a function of the locations at which tailward flows were observed by Geotail
- There exists a definite trend with near-Earth reconnection events being associated with stronger E field in the tail



Plasmoid Delay Relative to Midlatitude Onset

- The 43 selected substorms had a positive bay at mid-latitudes and auroral electrojet activity in the auroral zone while Geotail in tail
- Onset is start of midlatitude positive bay
- ***The plasmoids start at about -20 Re and move tailward at 760 km/s***

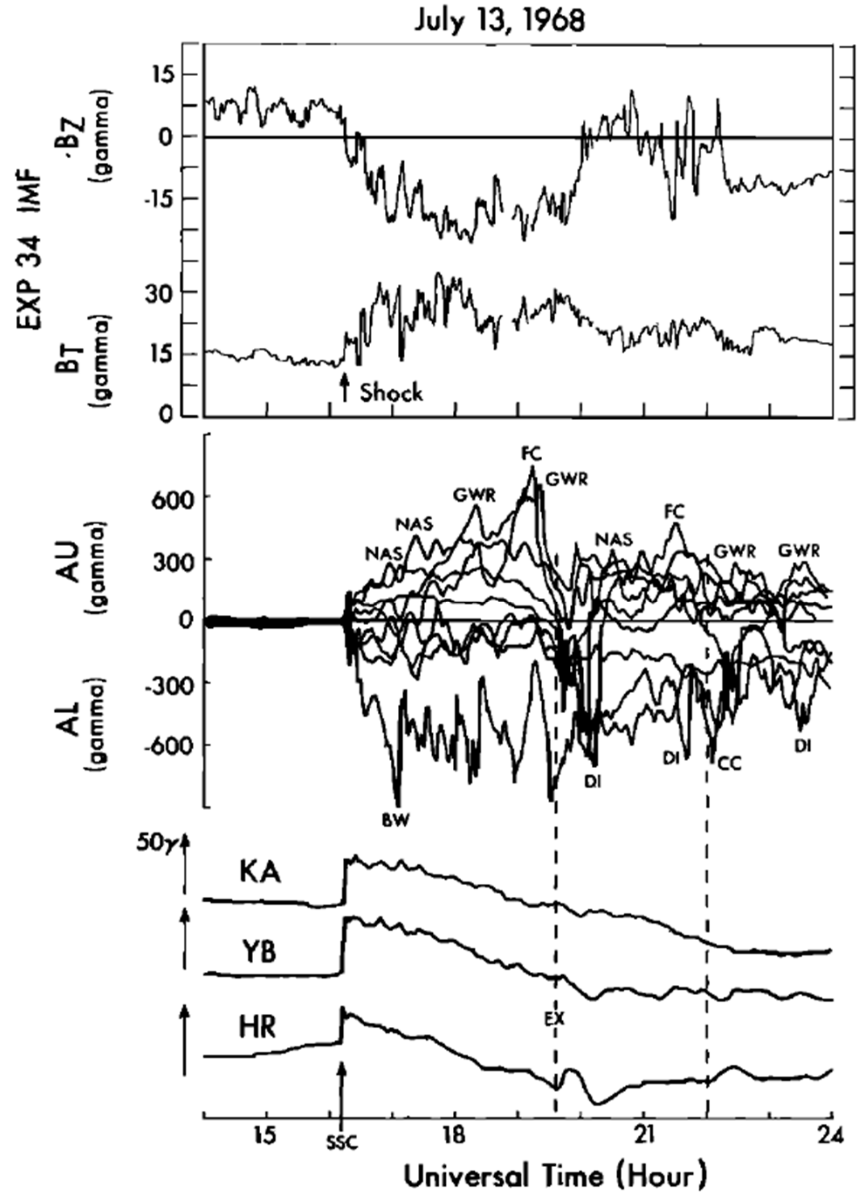


Shock Trigger of Substorm Activity

Kokubun, S., R. McPherron, and C. Russell (1977), Triggering of Substorms by Solar Wind Discontinuities, *Journal of Geophysical Research, 82(1), 74-86, doi:10.1029/JA082i001p00074.*

- 43% of the ssc's and si's were followed by negative bays
- Probability of trigger depends on the amplitude of the ssc and the level of preceding AE
- IMF Bz southward for at least 30 minutes before ssc

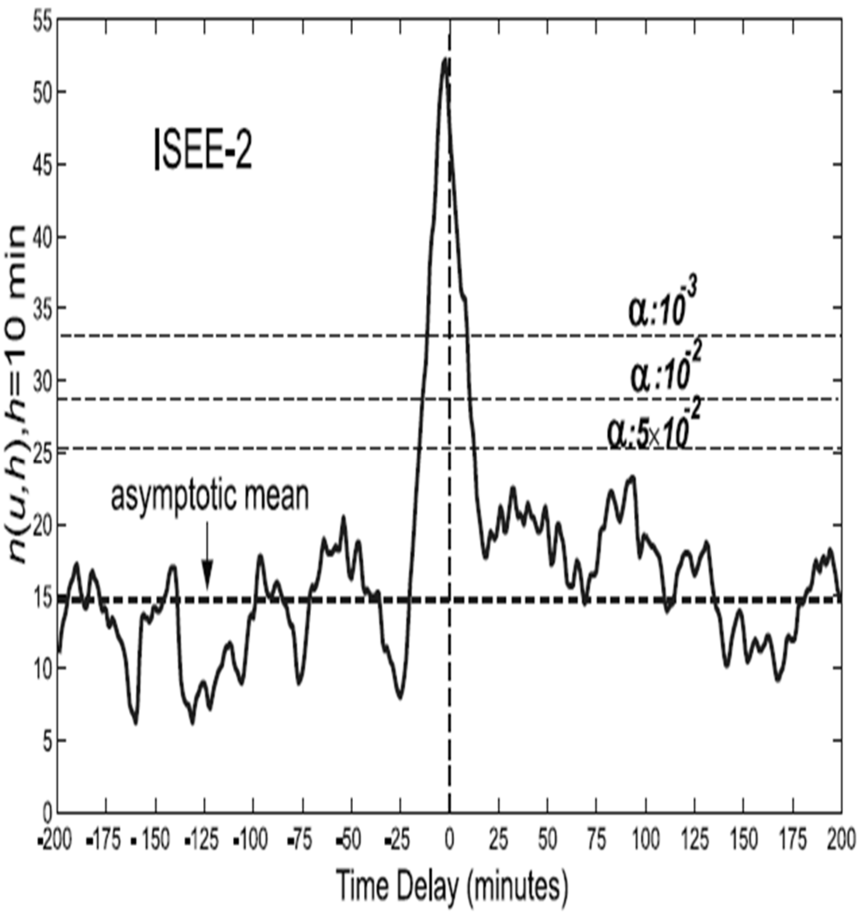
- ***It seems likely that the compression of the magnetosphere accelerates intrinsic processes in the magnetosphere which lead to the substorm occurrence***

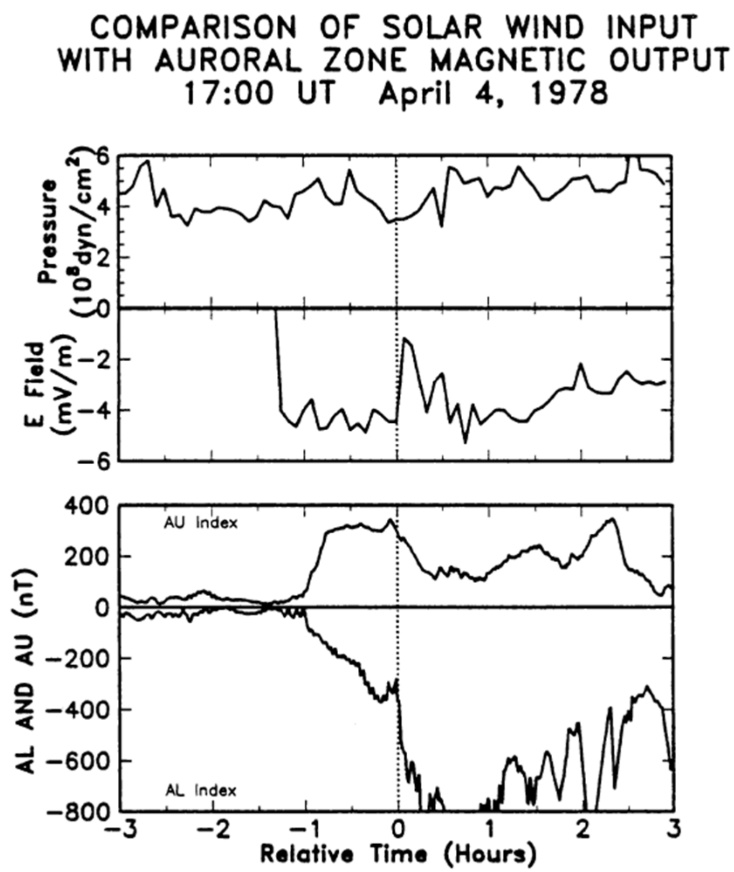


IMF Trigger of Substorm Onset

Hsu, T., and R.L. McPherron (2002), An evaluation of the statistical significance of the association between northward turnings of the interplanetary magnetic field and substorm expansion onsets, Journal of Geophysical Research, 107(A11), SMP 31-1-SMP 31-15, doi:10.1029/2000JA000125.

McPherron, R.L., T. Terasawa, and A. Nishida (1986), Solar wind triggering of substorm expansion onset, *Journal of Geomagnetism and Geoelectricity, 38(11), 1089-1108, doi:10.5636/jgg.38.1089.*

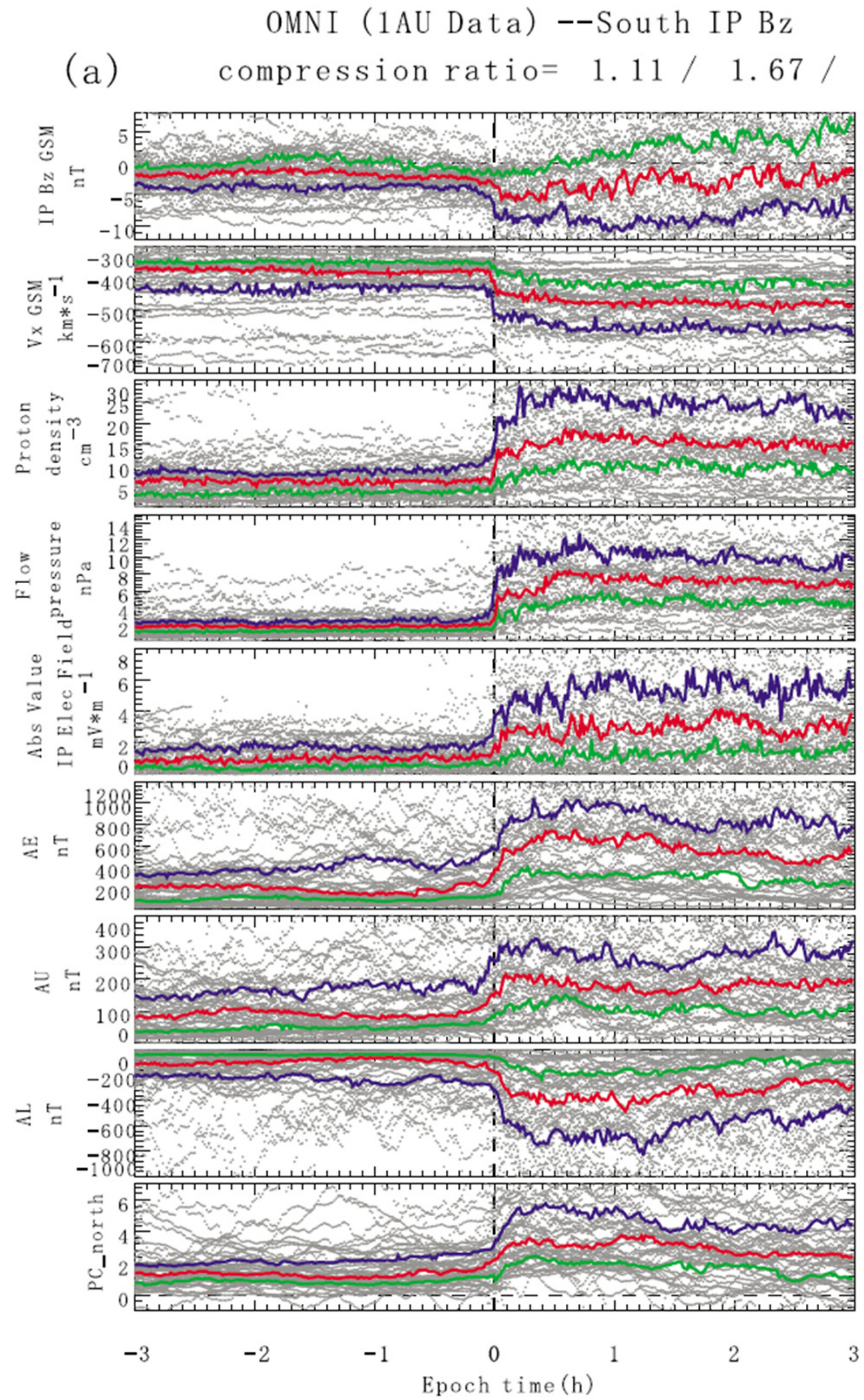




Evidence That Conductivity Affects Substorm Occurrence

Wang, H., H. Luhr (2007), Seasonal-longitudinal variation of substorm occurrence frequency: Evidence for ionospheric control, *Geophys. Res. Lett., 34(7), 1-4, doi:10.1029/2007GL029423.*

- 2760 substorm onsets in the northern hemisphere and 1432 in the southern hemisphere observed by the FUV on IMAGE
- around December solstice UT noon-time and around June solstice UT night times are more favorable for substorms by a factor of 2
- The sum of Pedersen conductances of both hemispheres caused by solar illumination in the nightside auroral regions can account for the S/L dependence.

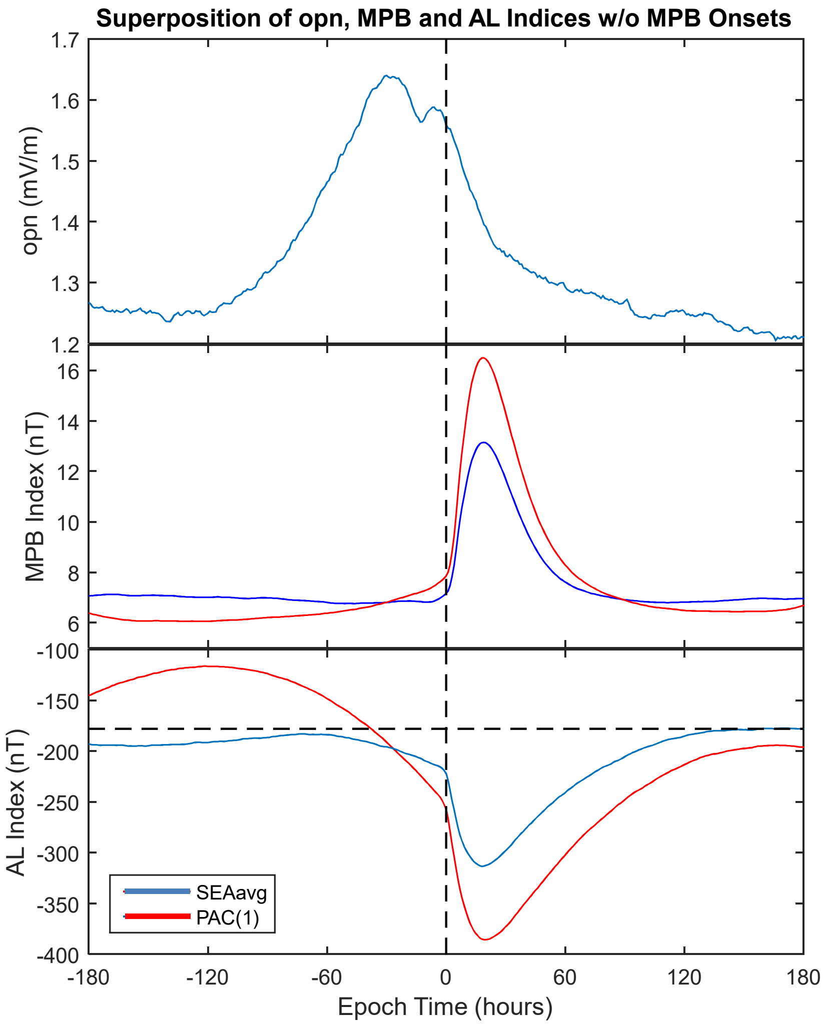


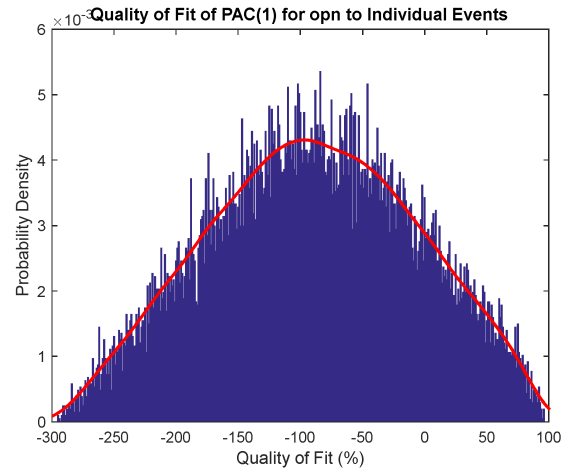
Some Recent Papers on Substorm Triggers

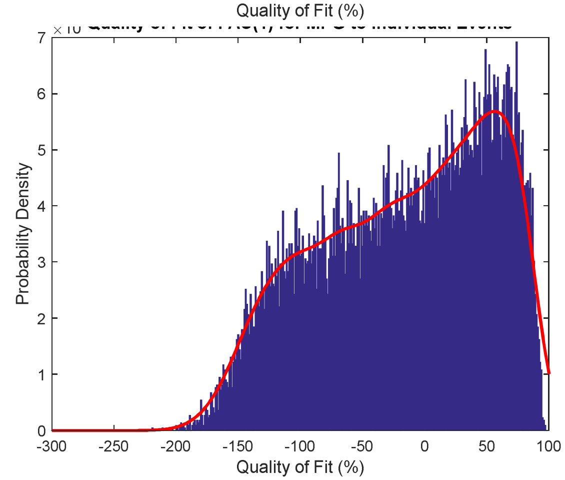
- Fluctuations in flow direction during northward IMF cause vertical (Z) pressure fluctuations and trigger reconnection
- Strict Lyons' criteria give only 17% and 22% triggered, but relaxed criteria suggest 50%, and events with large injections 60%
- Analysis of 106 IP shocks shows that southward Bz before leads in 46% of cases to enhanced AE
- Northward-turning structures in the IMF, while sometimes coinciding with the initial phase of individual substorms, are not required to trigger the magnetospheric instability of a substorm
- In satellite auroral images we have found a distinct season/longitude (S/L) dependence of substorm occurrence frequencies equally valid for both hemispheres. The ionospheric conductivity seems to have a significant influence on the trigger level of an onset.

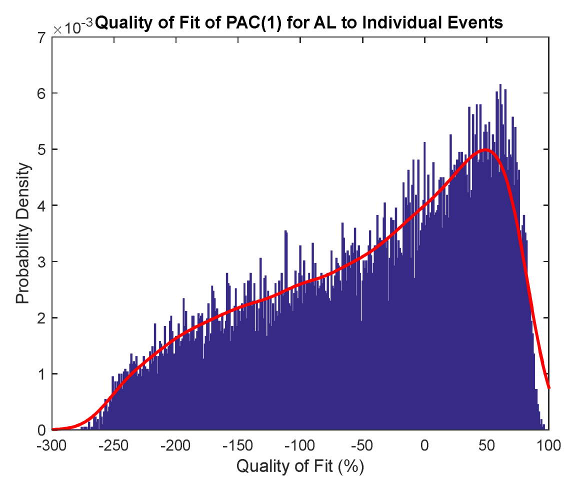
- Voeroes, Z. et al. (2014), Windsock memory COnditioned RAM (CO-RAM) pressure effect: Forced reconnection in the Earth's magnetotail, *JGR-Space Physics, 119(8), 10.1002/2014ja019857.*
- Gallardo-Lacourt (2012), External triggering of substorms identified using modern optical versus geosynchronous particle data, Annales Geophysicae, 30(4), 667-673, doi:10.5194/angeo-30-667-2012.
- Yue, C. (2010), Geomagnetic activity triggered by interplanetary shocks, *JGR-Space Physics, 115, 13, doi:10.1029/2010ja015356.*
- Wild, J.A. (2009), On the triggering of auroral substorms by northward turnings of the interplanetary magnetic field, Annales Geophysicae, 27(9), 3559-35703570, doi:10.5194/angeo-27-3559-2009.
- Wang, H., H. L&#252, and hr (2007), Seasonal-longitudinal variation of substorm occurrence frequency: Evidence for ionospheric control, *Geophys. Res. Lett., 34(7), 1-4, doi:10.1029/2007GL029423.*

Characteristic Variations of opn input, MPB index, and AL index w/o MPB Onset









Compare the principal component variations of three variables to all 22,000 events and calculate quality of agreement

The driver waveforms do not look much like the principal component

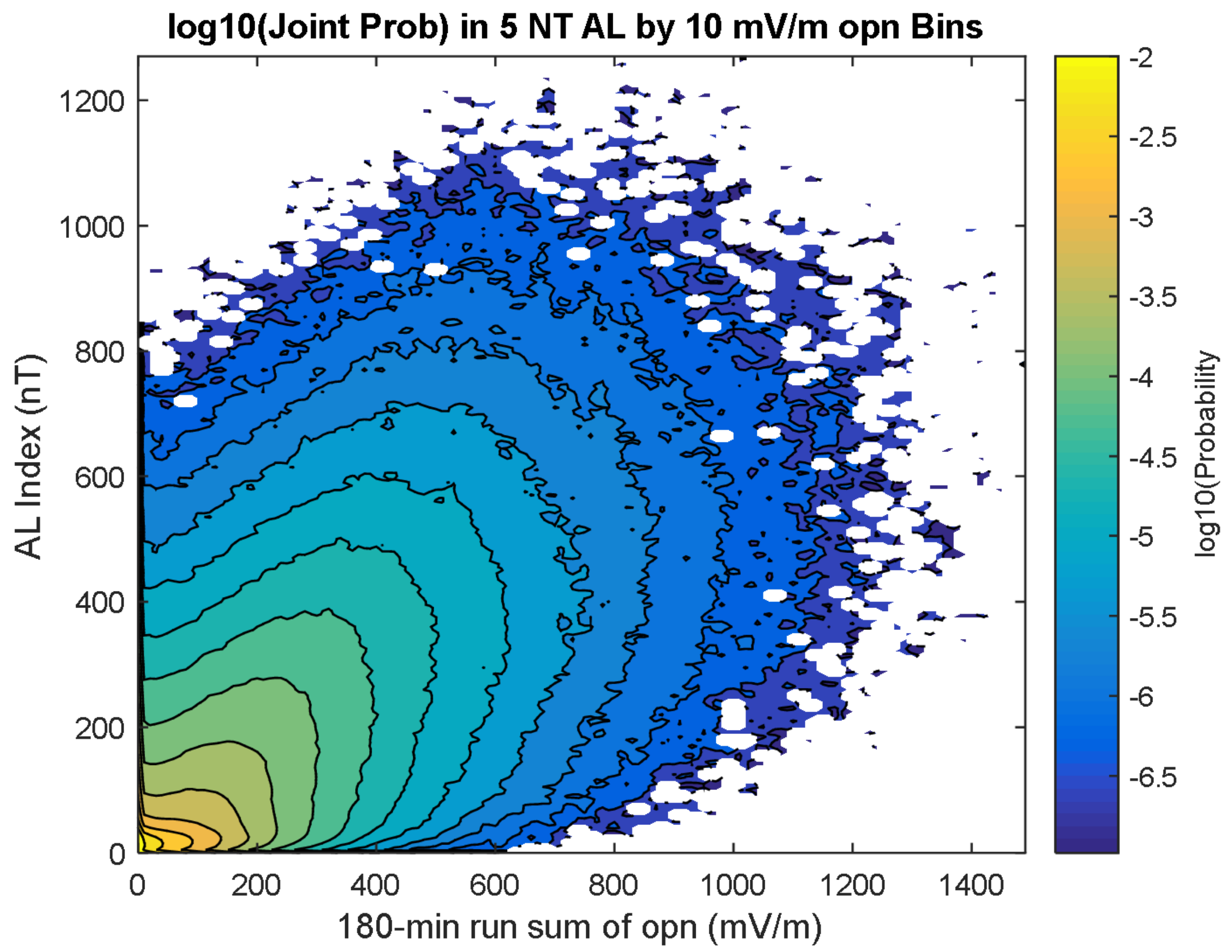
MPB and AL are much closer with a substantial number in agreement

Unanswered Questions about Tail Reconnection

- Why does it normally take ~60 minutes for tail reconnection to begin after a southward turning of the IMF?
- Why is the duration of a substorm about 3 hours?
- Why does tail reconnection usually occur beyond 20 Re behind the Earth?
- Why does tail reconnection normally occur 0-10 Re towards dusk?
- When does tail reconnection begin relative to auroral expansion onset?
- Is there any cause of fast flows other than localized reconnection?
- Why are fast earthward flows structured as bursty bulk flows (BBF)?
- Does every BBF correspond to a tailward moving plasmoid?
- Why do BBFs have a quasi-periodic repetition of 20 minutes?
- Is every Pi 2 pulsation burst caused by a BBF?
- How many BBFs and plasmoids occur during a typical substorm?

Relation of AL to Preceding Integral of Driver

- The AL index depends on the integral of the coupling function (opn) preceding the measured value
- In this diagram the bins are 5 nT in AL and 10 mV/m in integrated opn coupling function



Miyashita, Y. et al. (2009), A state-of-the-art picture of substorm-associated evolution of the near-Earth magnetotail obtained from superposed epoch analysis, *Journal of Geophysical Research-Space Physics, 114, doi:10.1029/2008ja013225.*