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Variability in the response time of the high-latitude ionosphere to IMF and solar-wind variations

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Time Delays in Solar Wind-Magnetosphere-Ionosphere Coupling:

- **The time delay for the solar-wind conditions to propagate from the spacecraft to the bow shock**
- **The time delay for the solar-wind conditions to propagate through the magnetosheath to the magnetopause**
- **The time delay for the effects of changes in solar-wind conditions to propagate from the magnetopause to the noon-sector ionosphere (actually, ~1400 MLT)**
- **<u>The time delay for changes in the high-latitude ionospheric convection pattern to first arrive after an initial noon-sector ionospheric response (actually, ~1400 MLT)</u>**
- **The time delay for the high-latitude convection pattern to completely reconfigure after the initial response**

Communication of Large-Scale Electric Field Changes to Different Regions in the Ionosphere:

(1) "Ionospheric convection:" transport of changing electrodynamic conditions at *F*-region convection speeds of ~200 m s^{-1} to 2 km s^{-1} (typically ~500 m s^{-1}) (e.g., polarisation fields associated with conductivity variations; atmospheric dynamo effects; atmospheric gravity waves)

"VERY SLOW MECHANISM"

(2) "The CL92 mechanism:" propagation of reconnection signature at magnetosheath speeds (~100 km s^{-1}) corresponding to propagation around the ionospheric OCB at phase speeds of ~2 km s^{-1} to 10 km s^{-1} (typically ~6 km s^{-1})

"SLOW MECHANISM"

Communication of Large-Scale Electric Field Changes to Different Regions in the Ionosphere:

(3) "Magnetosonic propagation:" Transport of large-scale electric field changes (not transient perturbations) at Alfvénic speeds in the topside *F*-region and inner magnetosphere, e.g., $V_A = B_0/(\mu_0\rho_0)^{1/2} > 820$ km s^{-1}

"FAST MECHANISM"

(4) "Earth-ionosphere wave guide:" Redistribution of large-scale electric potential at near the speed of light (<300,000 km s^{-1}) via spatially and temporally variable wave guides formed by the conducting Earth and ionosphere (e.g., Kikuchi *et al., JGR,* 101, pp. 17,161–17,173, 1996). Analogous to spherical capacitor.

"ULTRA FAST MECHANISM"

Dayside, Nightside, and Balanced Reconnection

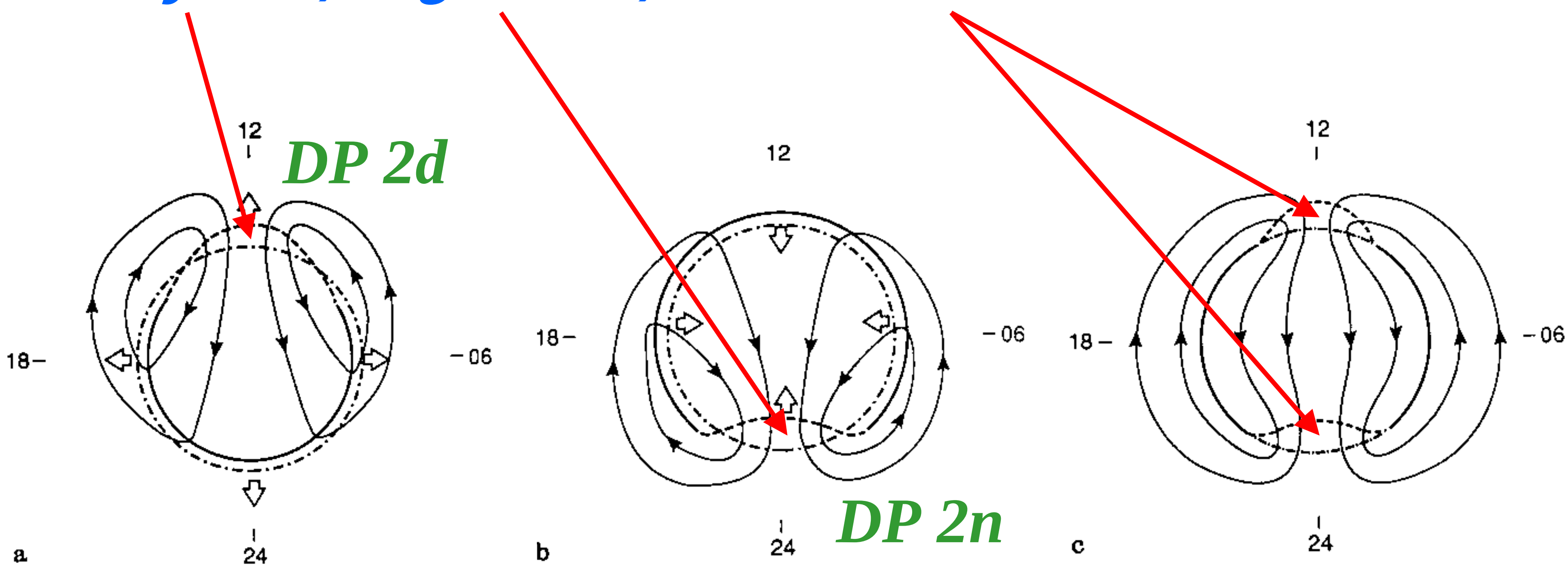


Fig. 8 a–c. Interpretation of the flows driven by **a** steady unbalanced dayside reconnection and **b** steady unbalanced nightside reconnection, previously shown in Fig. 3, in terms of the zero-flow equilibrium boundary picture. In each case the *dashed line* corresponds to the merging gap, the *solid line* to the open-closed field line boundary which moves with the plasma flow, and the *dot-dashed line* to the zero-flow equilibrium boundary which instantaneously contains the same amount of open flux. The *large arrows* indicate the sense of motion of these boundaries. **c** The steady-state flows driven by balanced dayside and nightside reconnection in the same format

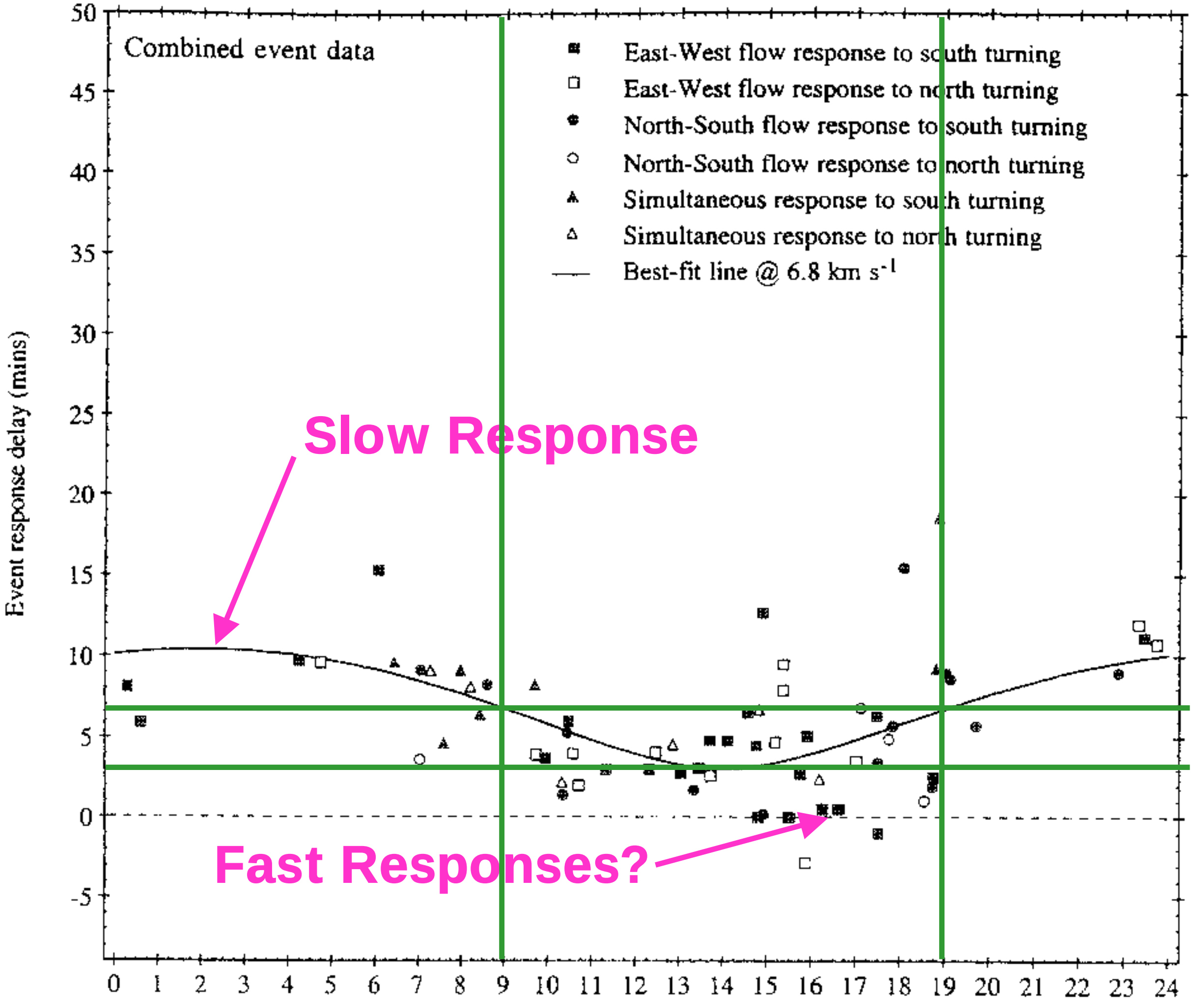
"CL92 Mechanism"

Cowley and Lockwood, *Ann. Geophysicae*, 10, pp. 103–115, 1992

Reports of Finite ("Slow") CL92 Response Times (~10 mins):

- **Lockwood, M., et al.,** Eastward propagation of a plasma convection enhancement following a southward turning of the IMF, *Geophys. Res. Lett.,* **13**, 72–75, 1986
- **Etemadi, A., et al.,** The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF: A high time resolution correlation analysis using EISCAT "POLAR" and *AMPTE UKS* and *IRM* data, *Planet. Space Sci.,* **36**, 471–498, 1988
- **Todd, H., et al.,** Response time of the high-latitude dayside ionosphere to sudden changes in the north-south component of the IMF, *Planet. Space Sci.,* **36**, 1415-1428, 1988
- **Saunders, M. A, et al.,** Dayside ionospheric convection changes in response to long-period interplanetary magnetic field oscillations: determination of the ionospheric phase velocity, *J. Geophys. Res.,* **97**, 19,373–19,380, 1992
- **Lester, M., et al.,** The response of the large scale ionospheric convection pattern to changes in the IMF and substorms: results from the SUNDIAL 1987 campaign, *Ann. Geophysicae,* **11**, 556, 1993
- **Taylor, J. R., et al.,** Ionospheric convection during the magnetic storm of 20-21 March 1990, *Ann.Geophysicae.,* **12**, 1174–1191, 1994
- **Khan, H., and S. W. H. Cowley,** Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data, *Ann. Geophysicae.,* **17**, 1306–1335, 1999

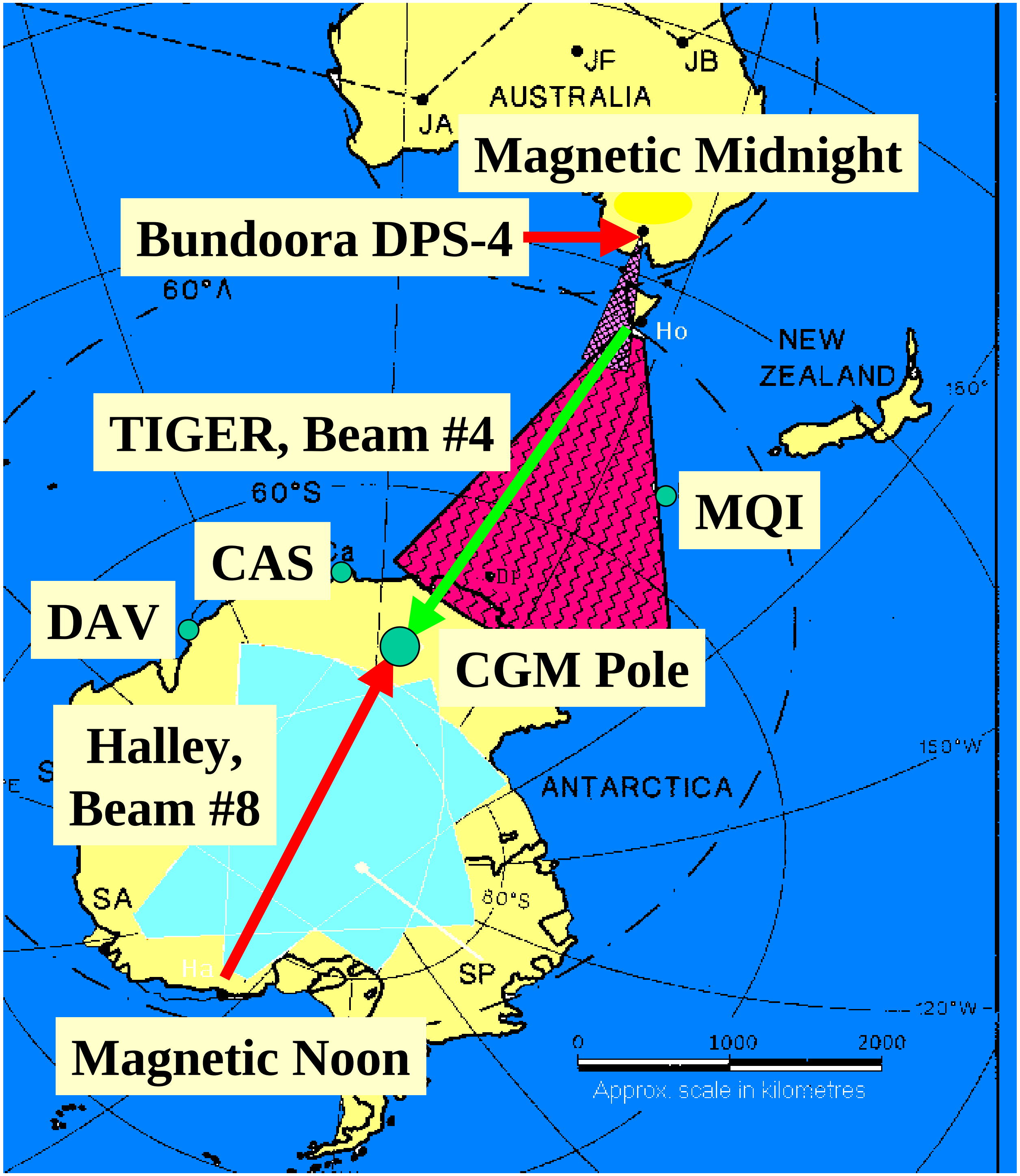
Cross-Correlation Between IMP-8 IMF Data and EISCAT F-Region Flows:



(c)

Khan and Cowley, *Ann. Geophysicae*, **17**, 1306–1335, 1999

Fig. 7. c As for **a**, except that the minimum delay is shown for each event, irrespective of which flow component is involved. *Closed symbols* indicate responses to southward turns of the IMF, while *open symbols* indicate responses to northward turns of the IMF. Responses observed first in the east-west flow component are shown by *squares*, while those observed first in the north-south component are shown by *circles*. If both components responded simultaneously the symbol is plotted as a *triangle*. These data have been least-squares fit to the same simple theoretical model as in Fig. 5c, shown by the *solid line*. In this case the best-fit epicentre of information propagation was also found to lie at 1400 MLT, while the expansion phase speed was found to be 6.8 km s^{-1}



RCP: "Z_Tiger_99" (Written by "Kevin," Halley Base)

Halley Beam Sequence:
0, 8, 1, 8, 2, 8, 3, 8, 4, …

TIGER Beam Sequence:
15, 4, 14, 4, 13 , 4, 12, …

Halley Beam #8:
MLT ≈ UT – 02 h 46 m

TIGER Beam #4:
MLT ≈ UT + 10 h 25 m

Bundoora DPS-4:
MLT ≈ UT + 10 h 18 m

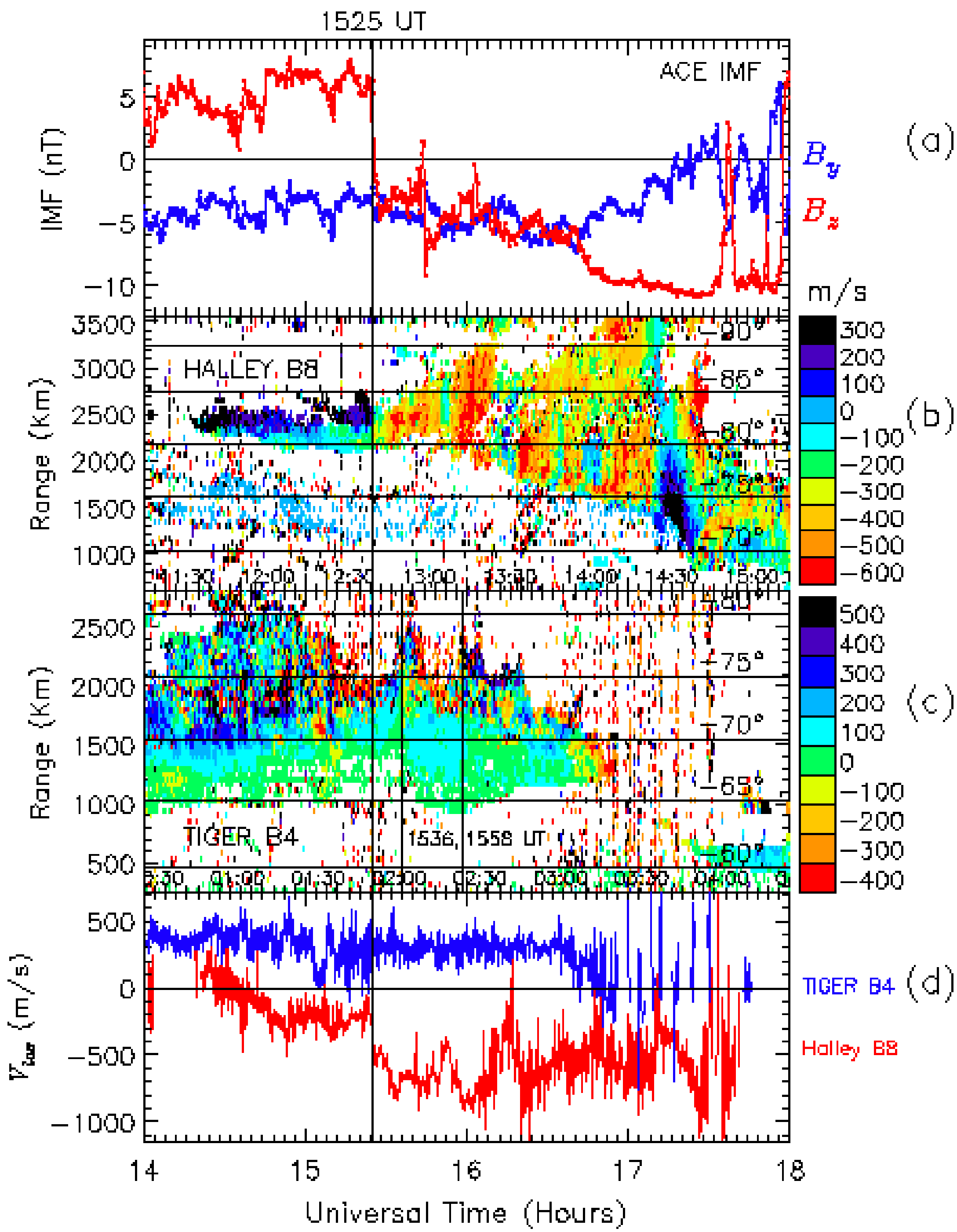
1st April, 2000

(a) ACE IMF B_y (blue) and B_z (red)

(b) Halley Beam 8 LOS Doppler velocity

(c) TIGER Beam 4 LOS Doppler velocity

(d) Halley Beam 8 (red) and TIGER Beam 4 (blue) LOS Doppler velocity



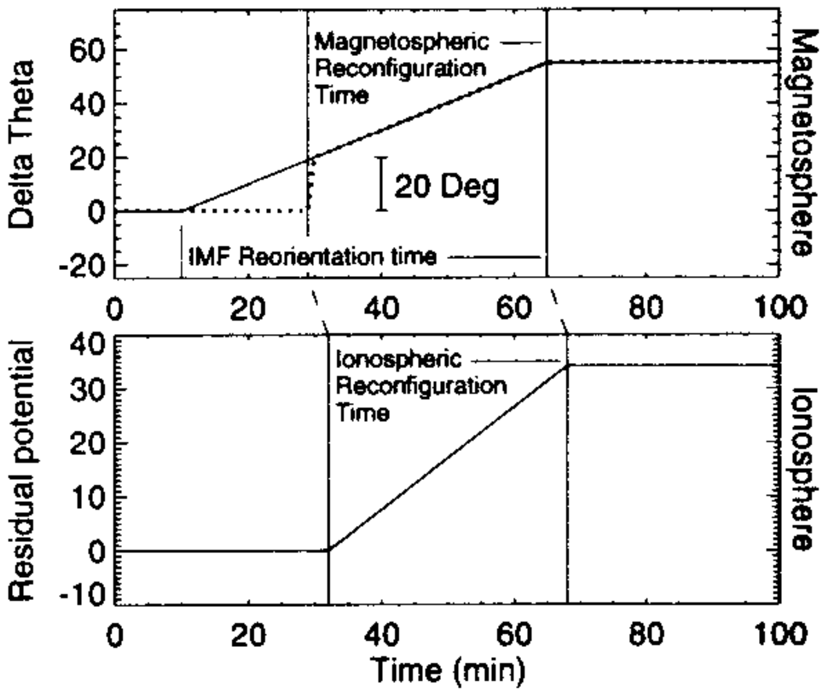
Reports of "Fast" (and "Ultra Fast?") Response Times (~0–2 mins):

- **<u>Kikuchi, T., et al.,</u> Direct penetration of the polar electric field to the equator during a *DP 2* event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, *J. Geophys. Res.,* 101, 17,161–17,173, 1996**
- **<u>Ridley, A. J., et al.,</u> A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique, *J. Geophys. Res.,* 103, 4023–4039, 1998**
- **<u>Ruohoniemi, J. M., and R. A. Greenwald,</u> The response of the high-latitude convection to a sudden southward IMF turning, *Geophys. Res. Lett.,* 25, 2913–2916, 1998**
- **<u>Shepherd, S. G., et al.,</u> A possible explanation for rapid, large-scale ionospheric responses to southward turnings of the IMF, *Geophys. Res. Lett.,* 26, 3197–3200, 1999**
- **<u>Watanabe, M., et al.,</u> The ionospheric response to interplanetary magnetic field variations: Evidence for rapid global change and the role of preconditioning in the magnetosphere, *J. Geophys. Res.,* 105, 22,955–22,977, 2000**
- **<u>Murr, D. L., and W. J. Hughes,</u> Reconfiguration timescales of ionospheric convection, *Geophys. Res. Lett.,* 28, 2145–2148, 2001**
- **<u>Ruohoniemi, J. M., et al.,</u> The response of the high-latitude ionosphere to IMF variations, *J. Atmos. Solar-Terr. Phys.,* 64, 159–171, 2002**

The AMIE Technique, Linear Reconfiguration Times, and Fast Ionospheric Response Times

<u>Ridley *et al.*,</u> ***J. Geophys. Res.*, 102, 14,563–14,579, 1997**

<u>Ridley *et al.*,</u> ***J. Geophys. Res.*, 102, 4023–4039, 1998**



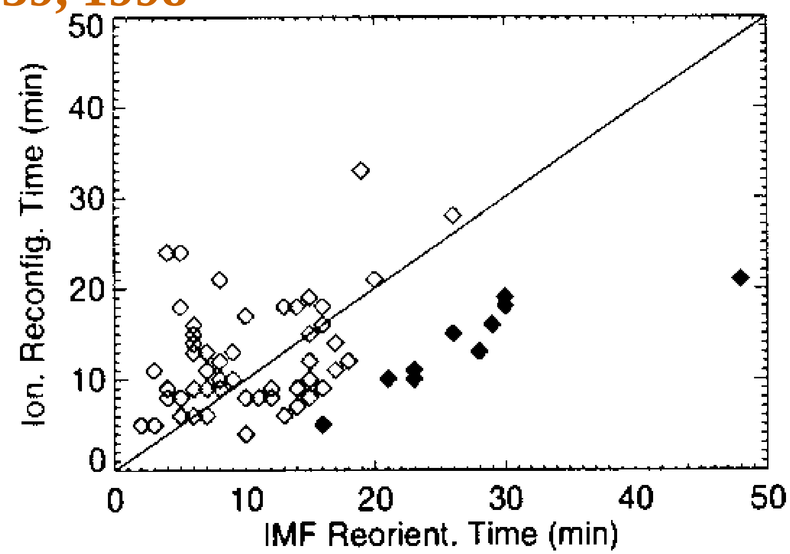


Figure 20. Amount of time the ionosphere took to reconfigure versus amount of time the IMF took to reorient. The solid line represents an equal amount of time. The black solid diamonds are events in which the ionosphere took significantly less time (over 10 min less) to reconfigure than the

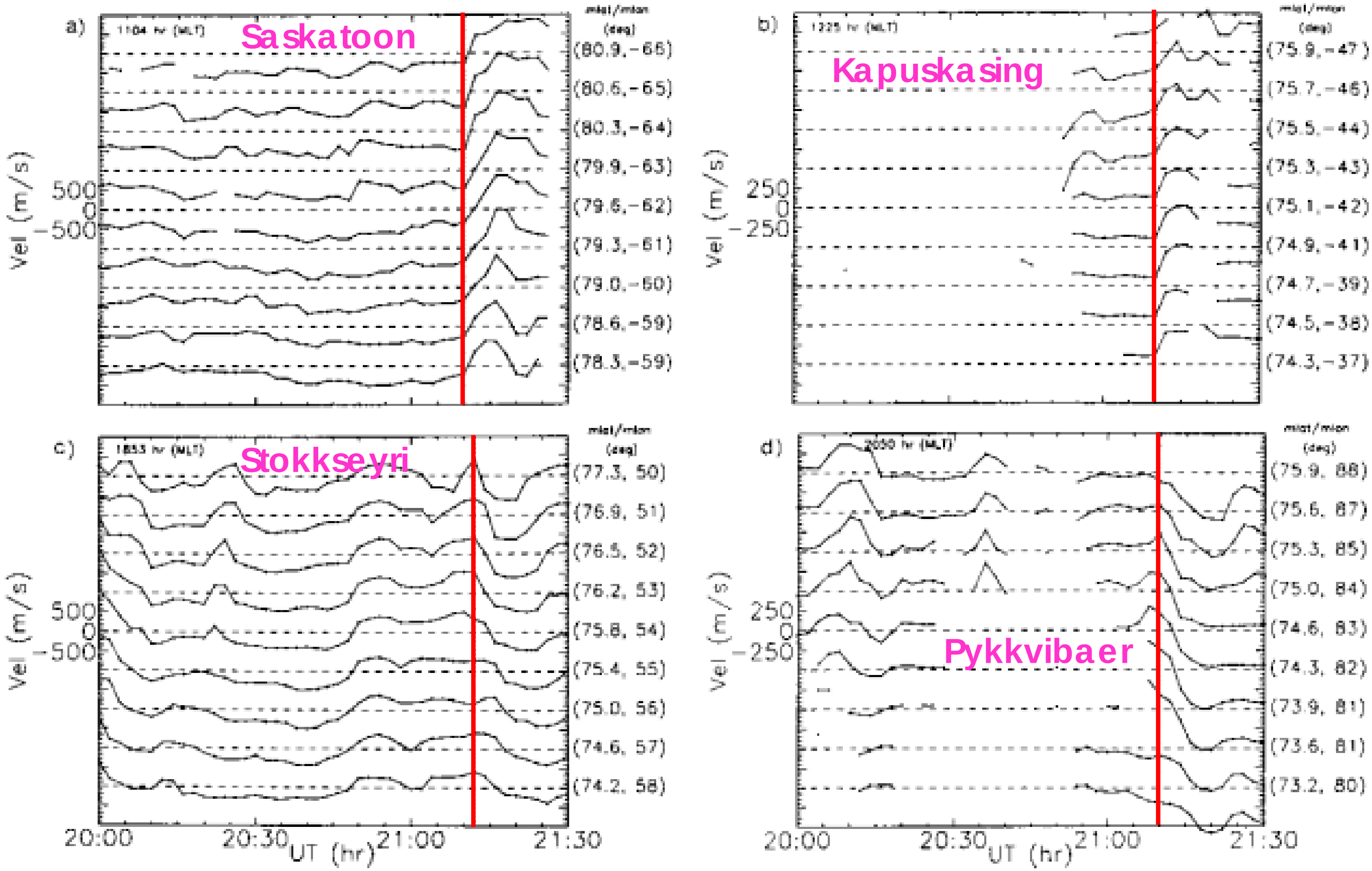
<u>Lockwood, M., and S. W. H. Cowley,</u> **Comment on "A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique" by A. J. Ridley et al., *J. Geophys. Res.*, 104, 4387–4391, 1999**

<u>Ridley, A. J., *et al.*,</u> **Reply, *J. Geophys. Res.*, 104, 4393–4396, 1999**

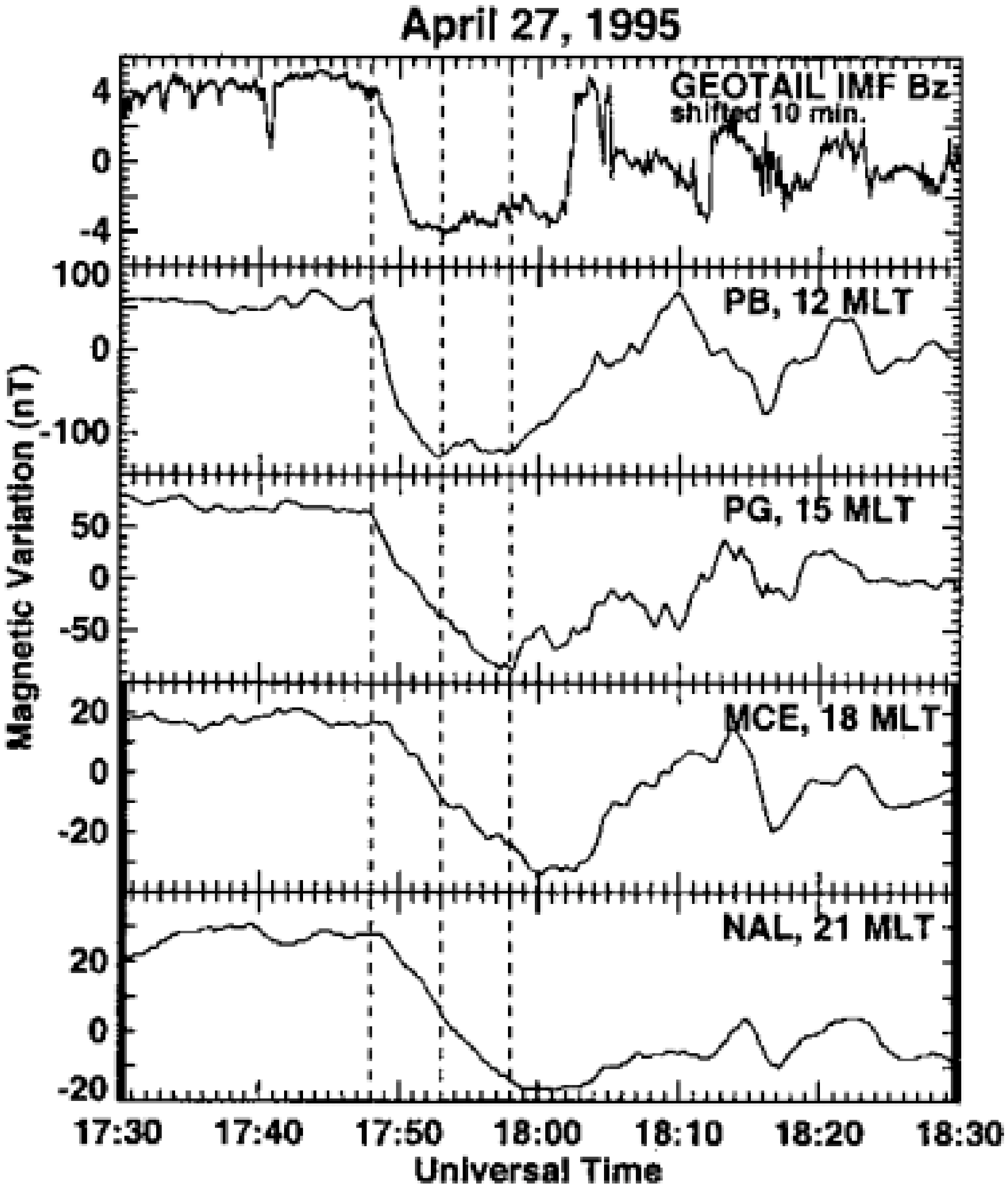
SuperDARN Observations of Fast ("Rapid") Ionospheric Response Times

<u>Ruohoniemi and Greenwald,</u> ***Geophys. Res. Lett.,*** **25, 2913–2916, 1998**

<u>Shepherd *et al.*,</u> ***Geophys Res. Lett.,*** **26, 3197–3200, 1999**



Ground-Based Magnetometer Observations of Fast ("Rapid") Ionospheric Response Times



<u>Murr and Hughes,</u> *Geophys. Res. Lett.*, **28**, 2145–2148, 2001

Pelly Bay (PB):
12 MLT, 78.6°Λ

Pangnirtung(PG):
15 MLT, 75.2° Λ

MAGIC East (MCE):
18 MLT, 75.5°Λ

Ny Alesund (NAL):
21 MLT, 76.1°Λ

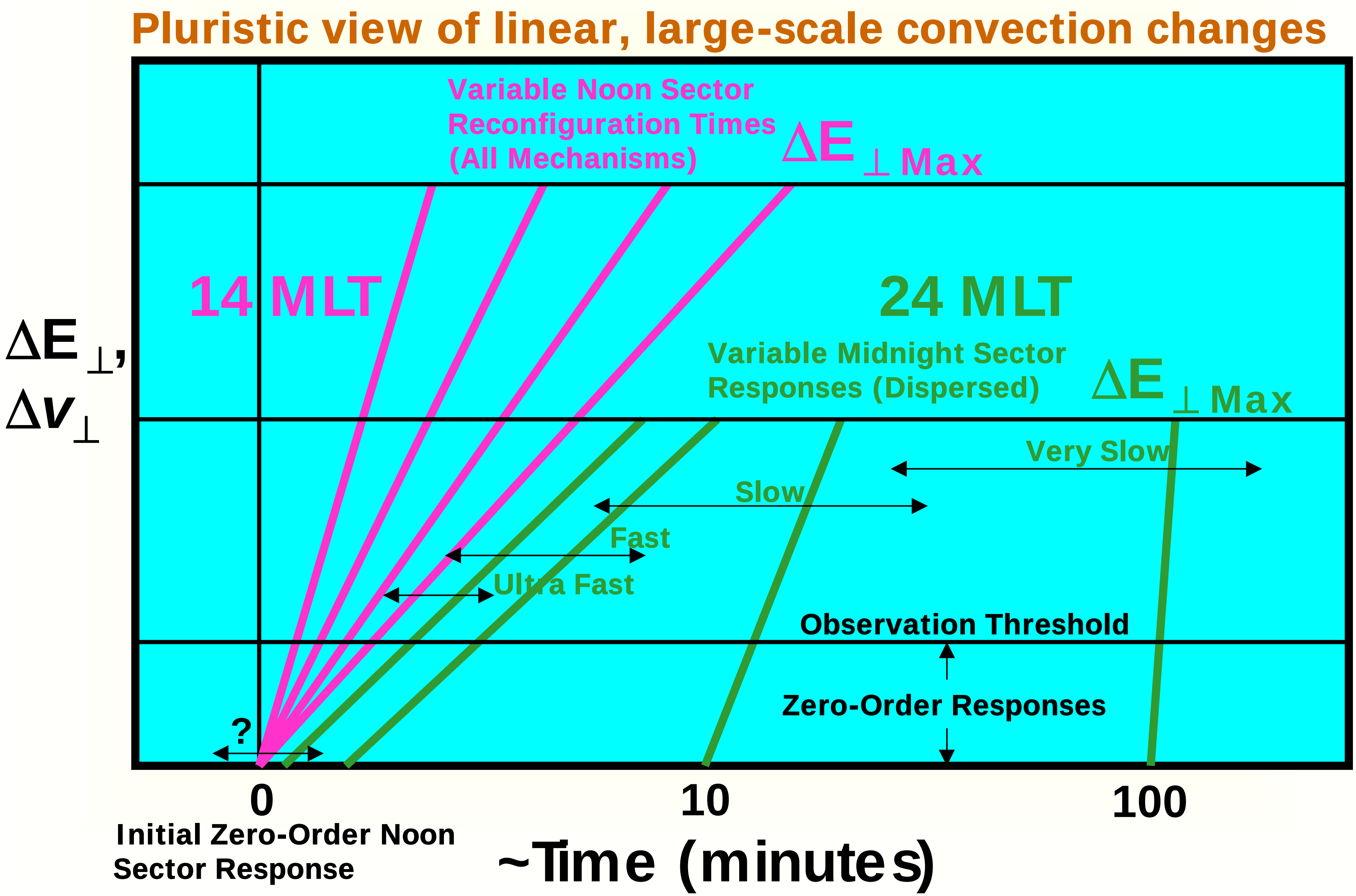
Difficulties with Fast ("Rapid") Response Time Measurements:

- **The deduction of an observed response time should not be based upon theoretical expectations or modeling of the data. It should be obvious in "raw data."**
- **HF radars are extremely sensitive instruments, recording very complex data sets revealing a plethora of unexplained geophysical transients, or "noise." Hence:**

  (1) There is a degree of subjectivity involved in interpret-ing the data, and to some extent, people will see what they want to see (e.g., the canals of Mars).

  (2) Strictly, a large-scale ionospheric convection change has not occurred until the observable exceeds twice the standard deviation of the geophysical "noise."
- **Magnetometers respond to magnetic perturbations integrated over the full celestial sphere. Hence they are sensitive to near-vertical ionospheric Hall currents, distant ionospheric and magnetospheric currents, and currents induced inside the Earth and sea.**

Reconciling the Observation of Slow to Rapid Response Times:



Reconciling the Observation of Slow to Rapid Response Times:

- **A synthesis of the very slow, slow, fast, and ultra fast mechanisms may be optimum for explaining the diversity of observations.**
- **Different mechanisms may operate concurrently, with their relative importance changing with geophysical conditions, e.g.:**

  (1) The slow, dominant ionospheric responses may be explained by the "classical" CL92 mechanism, especially in nightside regions with low ionospheric conductivity. ← Highly variable!

  (2) The ultra fast redistribution of ionospheric electric potential (e.g., Kikuchi *et al.*, 1996) may be confined to continuous regions of large ionospheric conductivity.

- **Field-line draping (Shepherd *et al.*, 1999) and the relative extent and location of the reconnection *X*-line (e.g., Chisham *et al.*, 2000), may explain some of the observations of nearly simultaneous dayside responses.**
- **All of these processes are highly variable!!!**
- **Lastly, there are ideas/mechanisms we are yet to invent/discover.**

Some Final Important Questions:

- Do different mechanisms play a role in communicating large-scale convection changes, and to what extent and under what conditions?
- What are the relative occurrence rates and relative amplitudes of convection changes associated with different mechanisms, and how do they change with geophysical conditions?
- Can the observed response times be sorted according to solar-wind conditions including the IMF, and especially according to ionospheric conductivity and its spatial continuity?
- Do the contributions from different mechanisms add “in phase?”
- Does the magnetospheric convection always drive the ionospheric convection, or can the ionospheric convection drive the magnetospheric convection?

Some Final Important Questions:

- **Do convection changes occur on the dayside after changes occur on the nightside (i.e., when dayside merging relaxes, and reconnection in the tail dominates)?**
- **Can measurements made with the four Cluster II spacecraft reveal the passage of step-like changes in magnetospheric electric fields propagating at Alfvénic or near light speed?**
- **Can we develop robust techniques to reliably identify persistent, large-scale convection changes against the background of instrumental noise and geophysical transients?**
- **Can we devise experiments to negate any of the proposed mechanisms for communicating convection changes?**