A tailward moving current sheet normal magnetic field front followed by an earthward moving dipolarization front

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The plot

On 3 October 2005 Cluster and ground magnetometers observed a substorm onset propagating from the **inner** to **outer** plasma sheet.

Cluster in the near-Earth plasma sheet, detected a sudden enhancement of B_Z — quickly followed by a series of **tailward-moving** flux ropes.

~5 min later, another B_Z enhancement propagated rapidly **earthward**.

Between those two B_Z enhancements, there was a significant removal of magnetic flux.

The flux removal caused the magnetotail to stretch globally so that the thinnest part was **tailward** of Cluster.

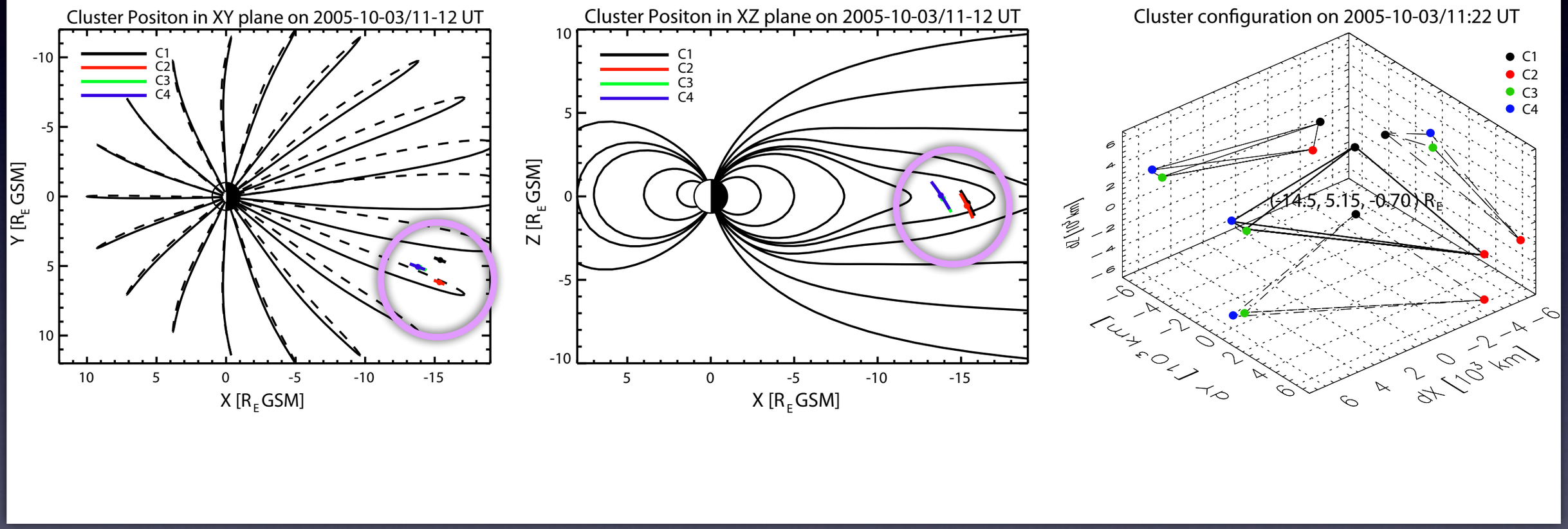
The thinned current sheet facilitated magnetic reconnection that quickly generated an earthward moving dipolarization front.

Ground magnetograms show two-step bay enhancements. The positive bay associated with the first B_Z enhancement shows that the substorm onset signatures propagated from the **inner** to the **outer** plasma sheet.

The more intense bay features associated with the later dipolarization front reflect the **earthward** motion of that second front.

This event suggests that a “current disruption” originated in the near-Earth current sheet and propagated tailward, causing reconnection that led to a substorm.

Location of Cluster



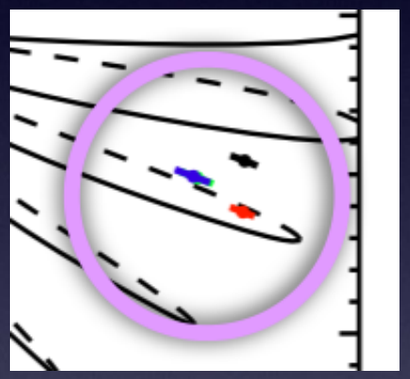
Location of the four Cluster spacecraft during 1100–1200 UT on 3 October 2005; in the GSM (left) XY and (middle) XZ planes, superposed over magnetic field lines (Tsyganenko, 1995 model). (right) The spacecraft configuration and separation at 1122 UT. The barycenter of the 4 Cluster spacecraft is at (−14.5, 5.15, −0.70) Earth radii (R_E) (GSM).

Two enhancements of B_z

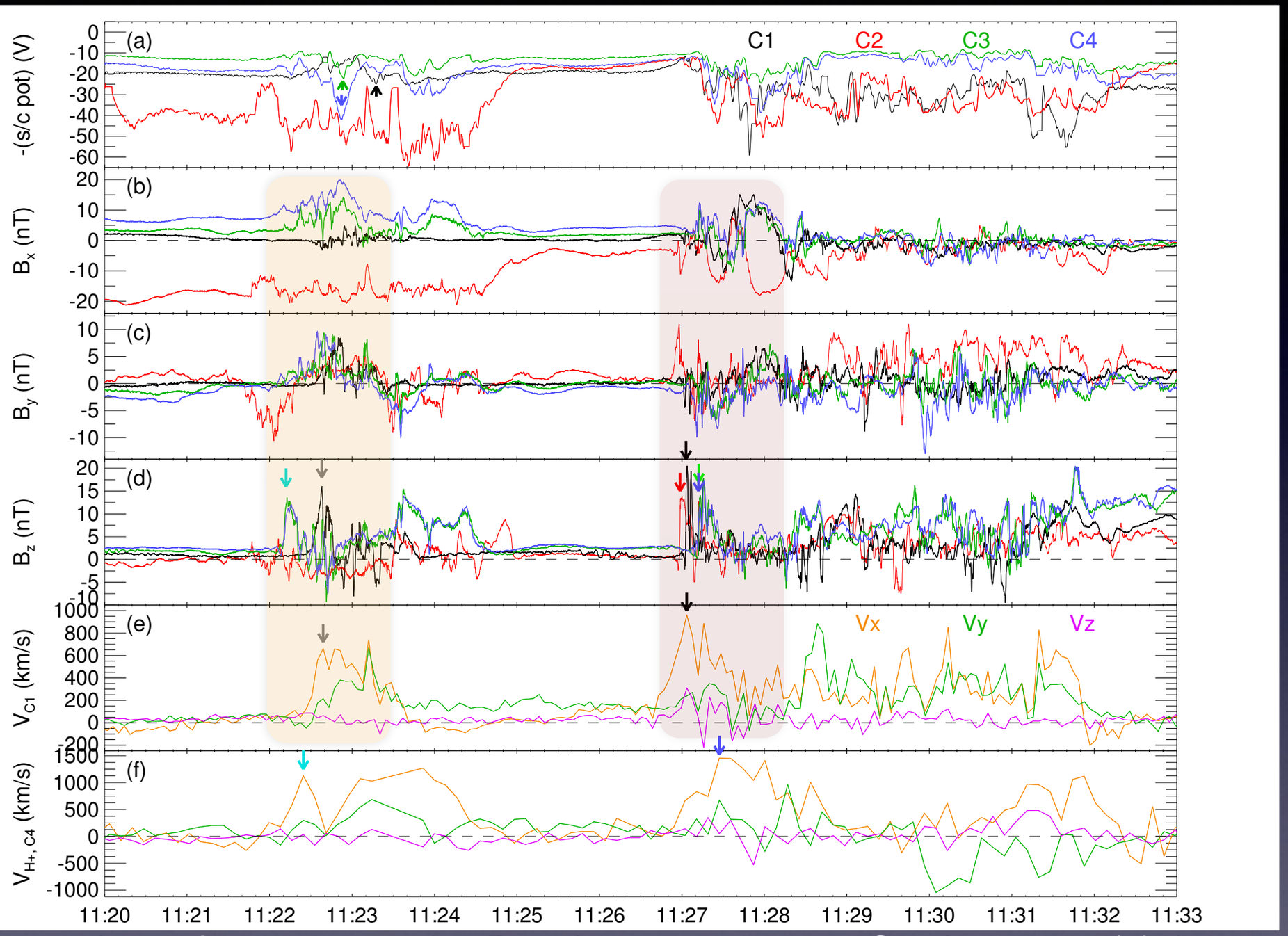
The 1st event is moving tailward, from C3/ C4 to C1:

"Density"

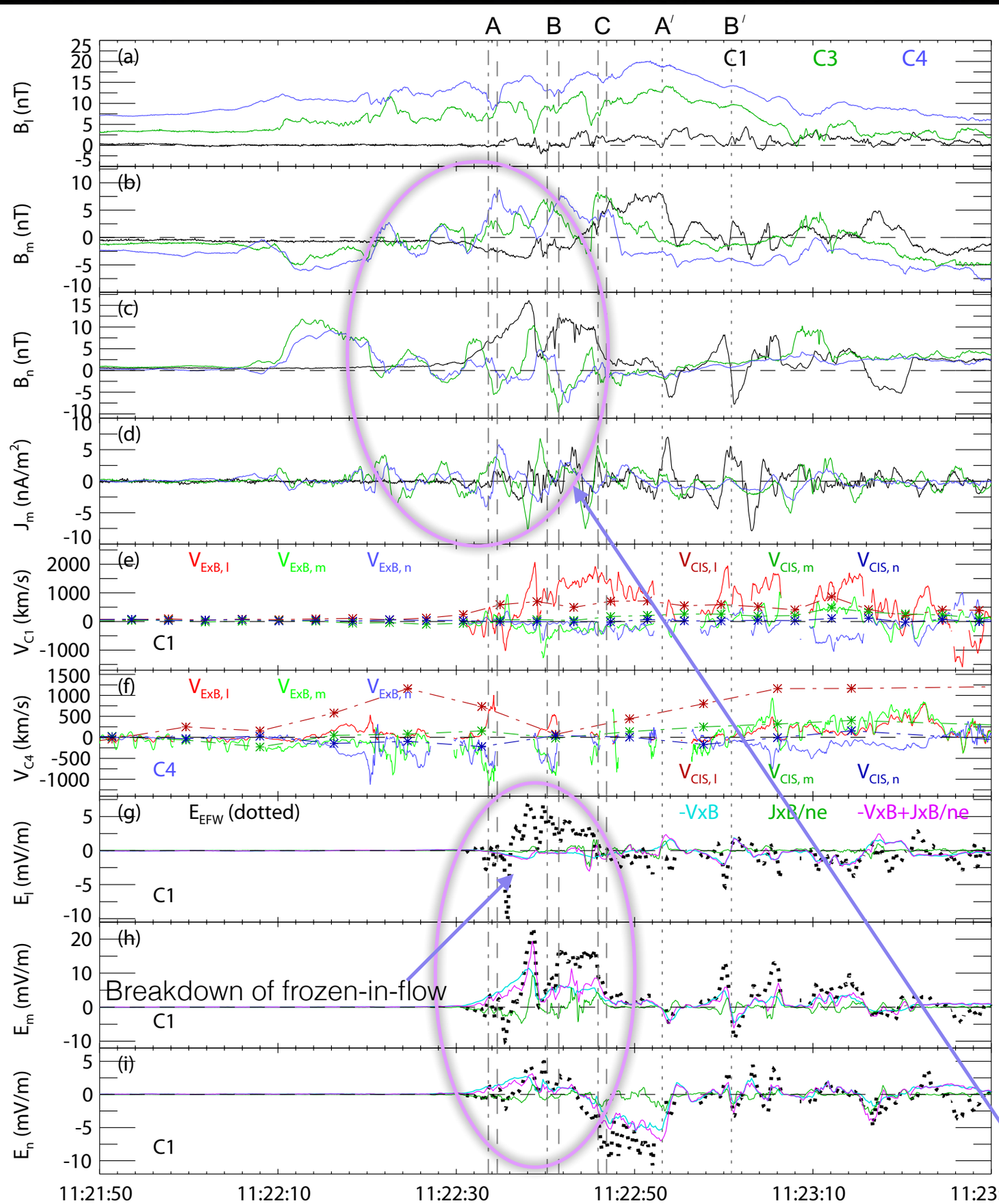
The increase in B_x indicates a thinning current sheet.



At 11:27 a 2nd event is observed moving earthward (C2,C1,C4,C3)



Cluster observations of two consecutive B_z enhancements on 3 October 2005: (a) the negative of the spacecraft potential ($\propto$ electron density); the magnetic field: (b) B_x ,(c) B_y, and (d) B_z; (e,f) the ion bulk flow, V_x (orange), V_y (green), and V_z (magenta) measured at C1 and C4, assuming that the majority is H^+ ions). At ~11:21 the current sheet thickness is ~proton gyroradius.

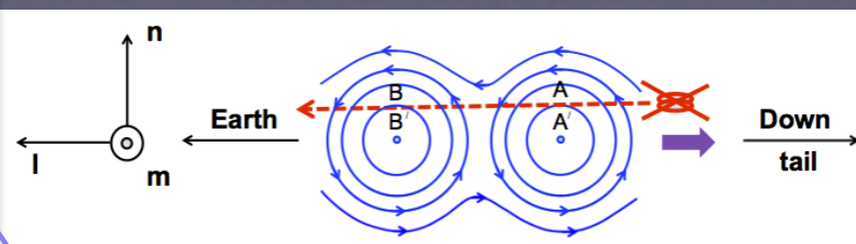


View of the first B_z enhancement (current sheet normal coordinates):

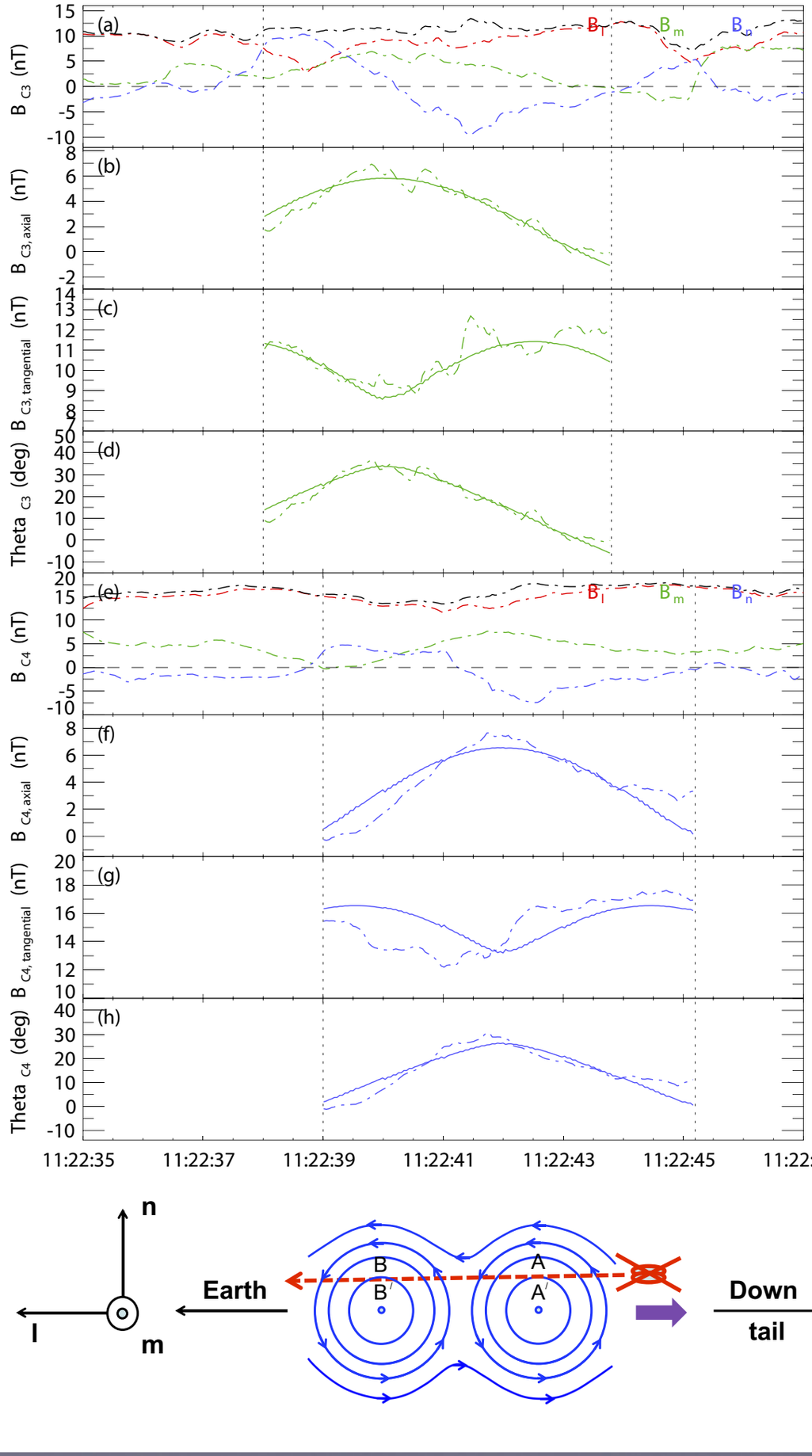
(a–c): B_l,B_m,B_n
(d) current along $\hat{m}$
(e,f) plasma velocity at C1 and C4
(g–i) E_l,E_m,E_n at C1

CIS plasma velocities compared with the frozen-in flows (e,f)
(3g–3i) show contributions of the convection term (cyan) and the Hall term (green), and compare the sum of the two terms (magenta) to the measured E field (black dots).

Dotted, dash-dot, and dashed vertical lines for C1, C3, C4, represent changes in sign of B_n + to – during tailward passage of the flux ropes.



Flux rope crossings—note sign changes of B_n

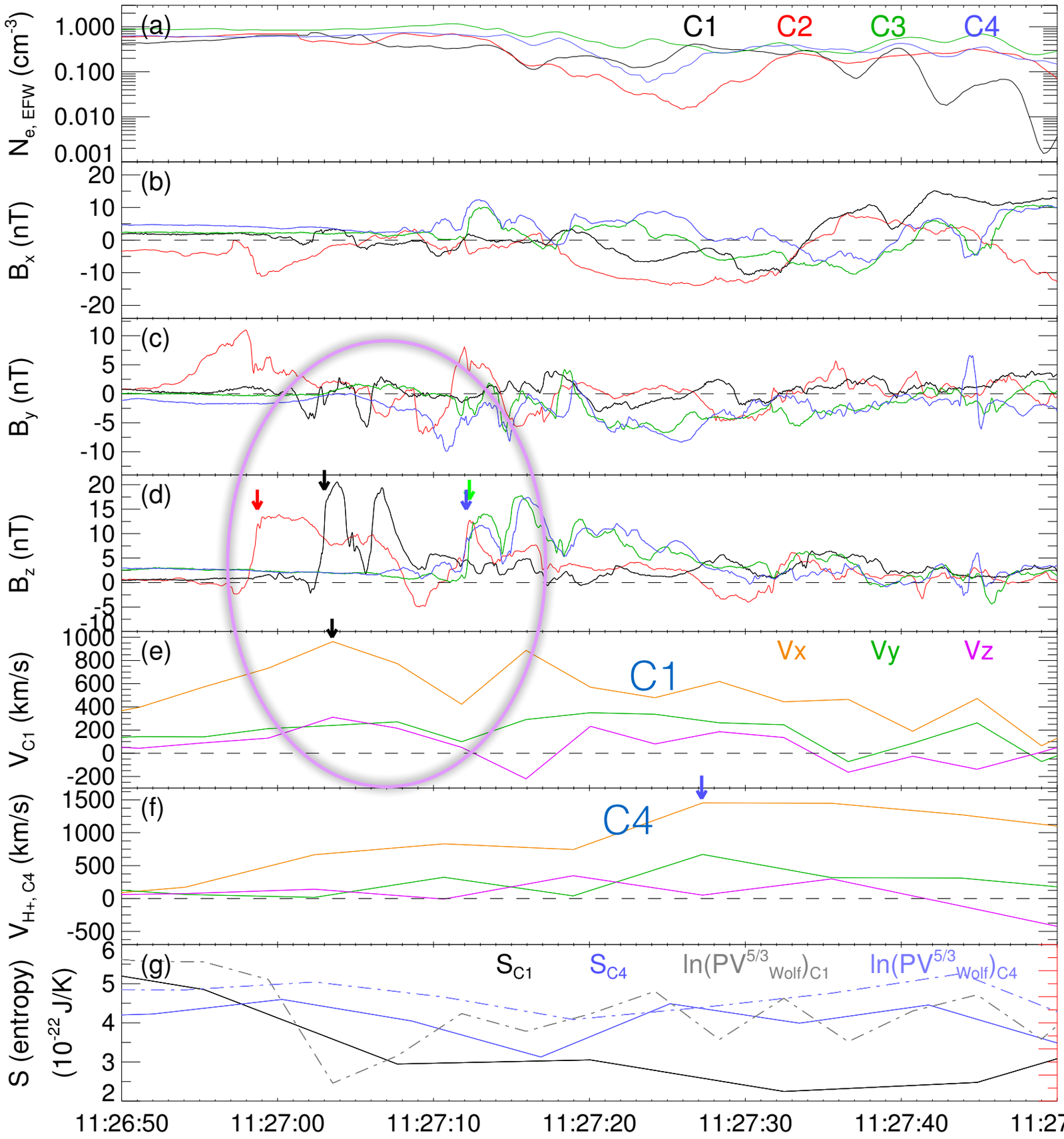


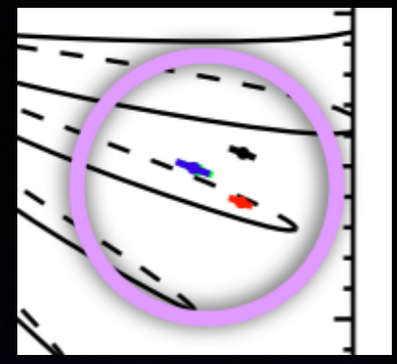
Single period of the series of bipolar-B_n structures.

Measured B-fields (dot-dashed curves) are fit to force-free flux rope model (solid curves) for (a–d) C3 and (e–h) C4.

Axial (4b,4f); tangential (4c,4g) components, and angle (4d,4h) made by the axial component to the total magnetic strength (90○ ⇒ the core of the flux rope).

Bottom:
Cluster's crossing of multiple tailward moving flux ropes. Timings as the spacecraft pass closest to the center of the flux ropes are marked A,B for C3 and C4, and A′,B′ for C1, corresponding B_n sign changes.





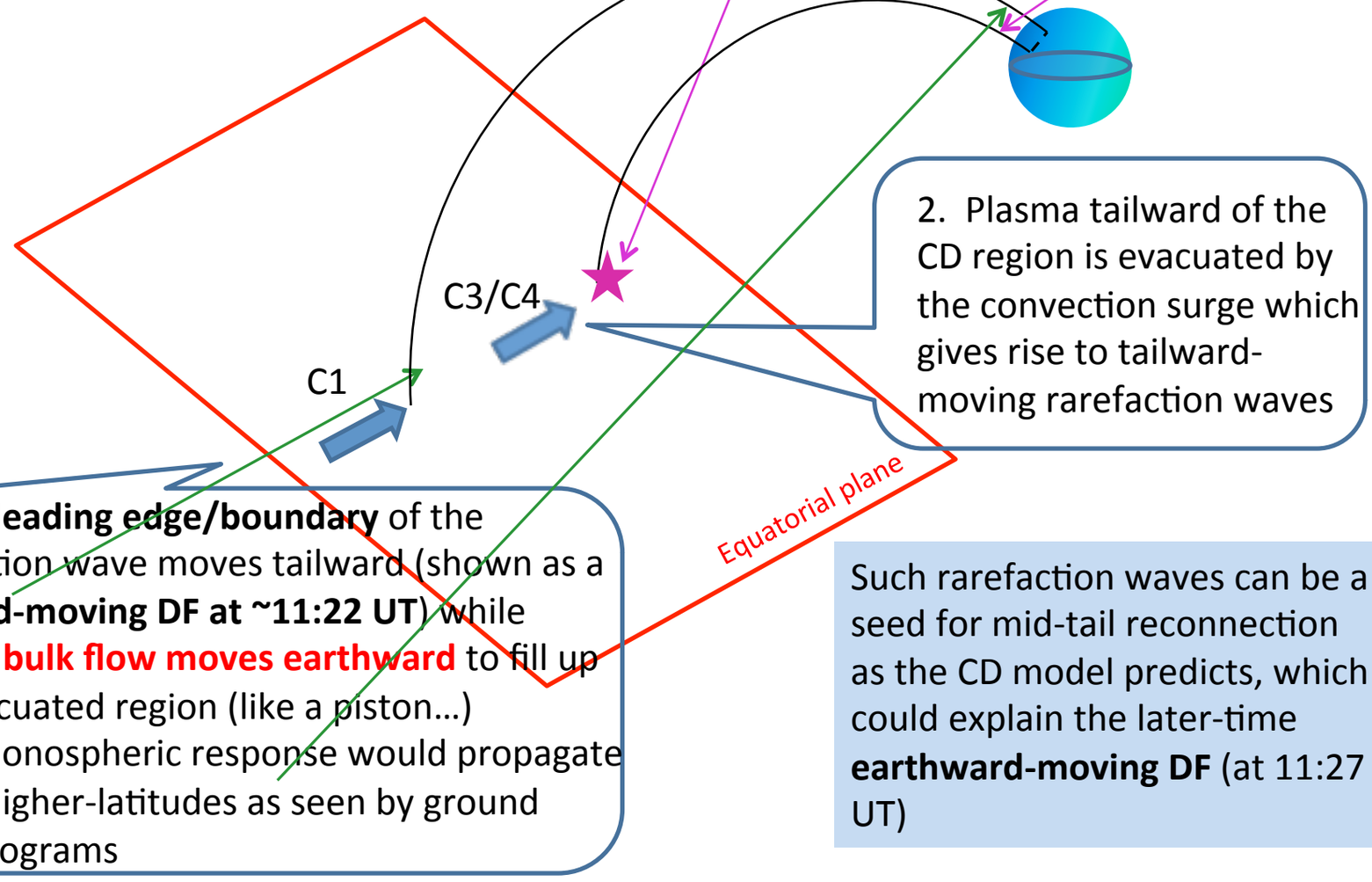
The earthward 2nd event:

Detailed profiles of:
(a) electron density,
(b–d) magnetic field
(e) plasma velocity from C1
(f) plasma velocity from C4
(g) entropy calculated from the ion distribution function (solid black and blue lines for C1 and C4, respectively), or, the flux tube entropy parameter, dash-dotted grey and light blue lines for C1 and C4).

The velocity (determined by the 4 spacecraft is ~540 km/s earthward)

Is this the first *in-situ* observation of rarefaction waves associated with substorm onset?

1. If a current disruption (CD) [Lui, 1999] or some other instability occurred in the near-Earth plasma sheet, then the low-latitude magnetograms would see the signature ~~before the high-latitude ones~~.

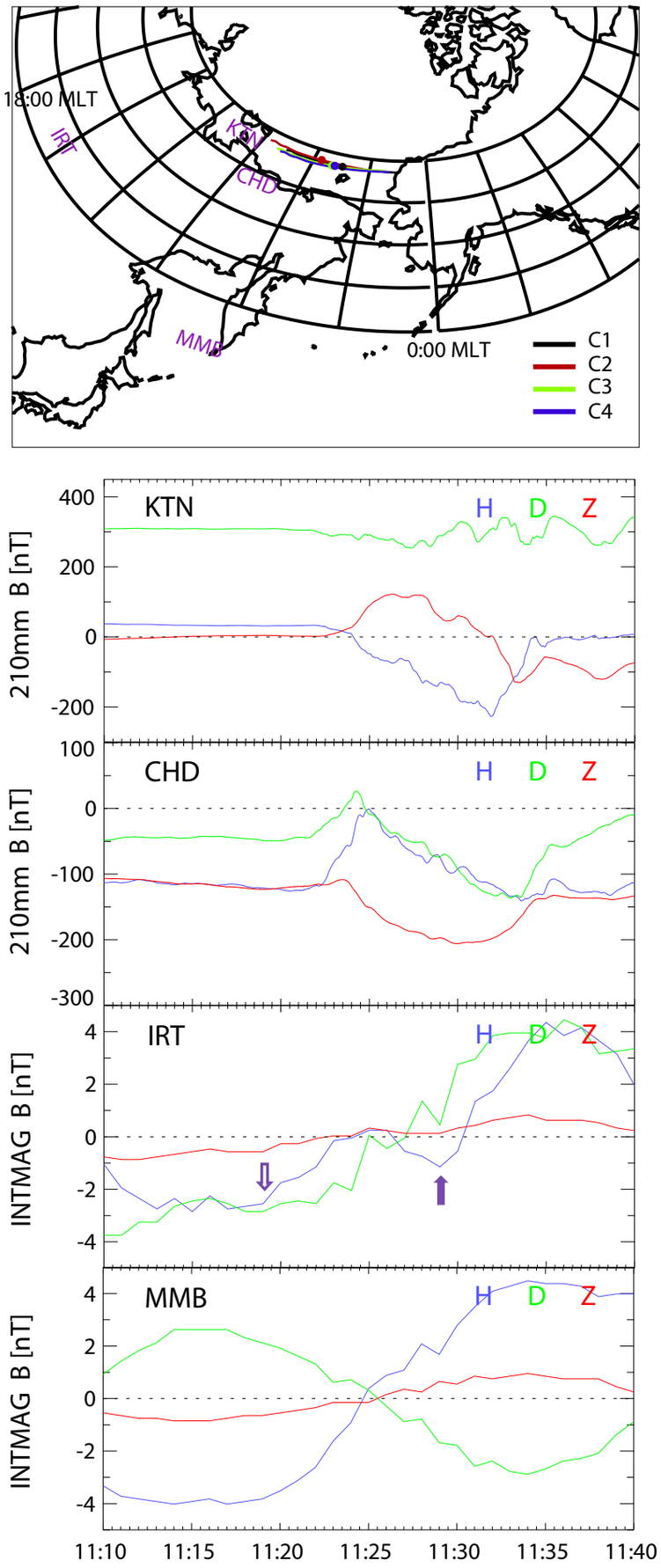


2. Plasma tailward of the CD region is evacuated by the convection surge which gives rise to tailward-moving rarefaction waves

3. The **leading edge/boundary** of the rarefaction wave moves tailward (shown as a **tailward-moving DF at ~11:22 UT**) while **plasma bulk flow moves earthward** to fill up the evacuated region (like a piston…)
=> The ionospheric response would propagate to the higher-latitudes as seen by ground magnetograms

Such rarefaction waves can be a seed for mid-tail reconnection as the CD model predicts, which could explain the later-time **earthward-moving DF** (at 11:27 UT)

Ground magnetograms



(top) Ground magnetograms from KTN, CHD, IRT, and MMB—located around the meridian of Cluster's foot points.

There was probably an electrojet somewhere between KTN and CHD

The magnetograms indicate that a positive bay (variations in the H-component) started at lower latitudes (MMB), i.e., before CHD and KTN along the longitude of the Cluster's footprint during the event.

Discussion

Two consecutive B_z enhancements were observed—separated by ~5 min.

The first (and subsequent tailward moving flux ropes) propagated tailward and did not seem to be associated with reconnection.

The second event propagated rapidly earthward; consistent with reconnection tailward of Cluster.

Between the two B_z enhancements, the current sheet showed a reduction in magnetic flux, indicating that there was a significant removal of flux from the near-Earth plasma sheet outward to the distant tail, thereby leading to stretching and thinning of the current sheet

The thinning and stretching led to magnetic reconnection that quickly generated a rapid earthward propagating dipolarization front associated with a large decrease in plasma density and flux tube entropy.

That these two events were causally linked is consistent with the ground magnetogram signatures.

Conclusions

Cluster and ground-based magnetometers observed a substorm onset propagating outward from the inner plasma sheet.

The spacecraft observed a thin current sheet and a series of tailward moving flux ropes (~5 min apart).

Between the two B_z enhancements, the current sheet thinned.

Magnetic flux removal caused the magnetotail to stretch; the thinnest region was tailward of Cluster. Magnetic reconnection followed and generated a rapid earthward-moving dipolarization front.

The 2nd B_z enhancement was a typical dipolarization front propagating rapidly earthward at ~542.5 km/s.

Ground magnetograms showed two-step positive bay enhancements; one 3 min before the initial B_z enhancement and the second 2 min after the second dipolarization front.

A positive bay associated with the first B_z enhancement was seen at low latitudes first, implying that the substorm signatures first propagated from inner to outer plasma sheet.

Intense negative and positive bay features associated with the second B_z enhancement formed northward of the ground magnetometer and propagated to lower latitudes—consistent with earthward motion of the second DF.

This event suggests that current disruption originating in the near-Earth current sheet caused DF to propagate tailward triggering midtail reconnection and a subsequent strong substorm.