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Mixed azimuthal scales of flux transfer events

R. C. Fear[1], S. E. Milan[1], E. A. Lucek[2], S. W. H. Cowley[1], A. N. Fazakerley[3]

[1] University of Leicester, UK (r.fear@ion.le.ac.uk)

[2] Imperial College London, UK

[3] Mullard Space Science Laboratory, University College London, UK

Abstract Previous observations have allowed the scale size of flux transfer events (FTEs) to be determined both normal to the magnetopause and in the direction of motion of the FTE, but a key difference between some different models of FTE structure is their azimuthal scale size. Previous ground-based observations of the ionospheric signatures of FTEs indicated that magnetic reconnection can occur coherently over large extents of the magnetopause, but in situ determination of the azimuthal scale size of FTEs has not been possible until recent Cluster magnetopause crossing seasons when the separation of the spacecraft was ~10,000 km. In this paper, we present Cluster observations of flux transfer events from the 27th March 2007, along with observations of the conjugate ionospheric signatures. We highlight two magnetospheric FTEs which were consistent with long X-line FTE models, but note also several FTEs with considerably smaller azimuthal scale.

1. Introduction

Flux transfer events (Russell and Elphic 1978) are the time-varying embodiment of magnetopause reconnection (Dungey 1961). Various attempts have been made in the past to quantify how much flux an FTE transfers into the magnetospheric system (Russell and Elphic 1978, Saunders et al. 1984, Rijnbeek et al. 1984, Milan et al. 2000), but these estimates are dependant on an assumption about the structure that an FTE takes. The original structure proposed was of an azimuthally narrow, elbow-shaped flux tube that crossed the magnetopause through an approximately circular hole (Russell and Elphic 1978), but subsequently other reconnection-based models were proposed which could extend significantly further azimuthally (Lee and Fu 1985, Southwood et al. 1988, Scholer 1988), and therefore could each reconnect more flux.

Therefore, a key difference between some of these models is the azimuthal extent they can allow in comparison with their poleward extent. Since the scale of an FTE both normal to the magnetopause and in its direction of motion (poleward under strongly southward IMF) is typically of order 1-2 R_E (Russell and Elphic 1978, Saunders et al. 1984, Rijnbeek et al. 1984, Owen et al. 2001, Fear et al. 2007), observations from the Cluster spacecraft in their ~10,000 km separation magnetopause crossing seasons (2006 onwards) can provide valuable information about whether the azimuthal scale of FTEs is comparable to or larger than their poleward extent. The first such FTE observations have recently been presented (Fear et al. 2008), but the magnetic shear across the magnetopause was comparatively low (~110°). Whilst it was shown that the flux transfer events observed had a larger azimuthal extent than their poleward extent, the elbow-shaped flux rope model (Russell and Elphic 1978) could not be excluded completely. In this paper, we present a separate case study of flux transfer events observed by Cluster on the 27th March 2007 and their ionospheric signatures. At this time, the magnetic shear across the magnetopause was much closer to 180°, which allows a clearer distinction between some of the models. Magnetic field data are provided at 5 Hz resolution from the Cluster FGM instrument (Balogh et al. 2001), electron data from the Cluster PEACE instrument (Johnstone et al. 1997), and ionospheric observations from the SuperDARN radars (Chisham et al. 2007).

2. Cluster orientation and solar wind conditions

Figure 1 illustrates the location and orientation of the Cluster spacecraft (the tetrahedron has been expanded by a factor of two relative to the location of Cluster 1). In this and all subsequent figures, the Cluster spacecraft are denoted by a consistent colour scale which is shown in the legend. The model magnetopause (dashed line) and bow shock (dash-dot) are derived from the models by Shue et al. (1997) and Peredo et al. (1995), using upstream conditions as model inputs. The spacecraft were at low latitudes in the northern hemisphere, near local noon. Typically for early 2007, the spacecraft were in a flat triangular formation, rather than a good quality tetrahedron, with the surface of the triangle being contained approximately in a plane tangential to the magnetopause surface.

The solar wind conditions are shown in Figure 2, which contains propagated observations from the OMNI database. These data were taken by the Wind spacecraft, which was situated 198 R_E upstream of the Earth, and they have been propagated to the Earth's bow shock using a variable lag time (King and Papitashvili 2005). At 0440 UT, the interplanetary magnetic field (IMF) rotated southward, and the clock angle remained close to 180° until 0550 UT, except for a brief dawnward rotation between 0510 and 0520 UT.

We shall present the Cluster data in a boundary normal coordinate system (Russell and Elphic 1978), which was derived as follows. The unit vector normal

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to the magnetopause was derived by carrying out minimum variance analysis (Sonnerup and Cahill 1967) on the Cluster magnetic field data between 0500 and 0512 UT (the Cluster spacecraft all crossed the magnetopause at around 0506 UT). The largest ratio between the intermediate and minimum eigenvalues was observed using Cluster 4 data ($\lambda_{int}/\lambda_{min}$=3.74), so we adopted the minimum eigenvector from the magnetopause crossing made by Cluster 4 as the normal vector [$\mathbf{n}$ = $(0.938, -0.044, 0.342)_{GSE}$]. The azimuthal vector was derived by normalising the cross product of **n** with the Earth's dipole vector [$\mathbf{m}$ = $(-0.174, -0.917, 0.359)_{GSE}$], and the poleward vector completes the right-handed set [$\mathbf{l} = \mathbf{m}\times\mathbf{n}$ = $(-0.298, 0.397, 0.868)_{GSE}$]. The coordinates **n**, **m** and **l** therefore correspond closely to the GSE **x**, -**y** and **z** vectors, as is expected for a low-latitude, near-noon magnetopause crossing.

The Cluster spacecraft separation is shown in these boundary normal coordinates in Figure 3. The spacecraft formed a roughly equilateral triangle in the **l**-**m** plane, with each side of order 8,000 km. The maximum separation of the spacecraft normal to the nominal magnetopause was 1,200 km.

3. Extent of dayside reconnection: Ionospheric signatures

We first investigate the ground-based radar observations of the ionospheric signatures of FTEs to show the azimuthal extent over which magnetopause reconnection was taking place. Ionospheric observations from the Hankasalmi and TIGER coherent scatter radars (part of the SuperDARN network) are shown in Figure 4. The Hankasalmi radar is situated in Finland, and has a field of view that is directed towards magnetic north. TIGER is situated in Tasmania, and its field of view is directed towards magnetic south. The top two panels show a snapshot of the ionospheric velocities from the entire fields of view of these two radars at 0508 UT; each panel is a polar grid of magnetic local time against magnetic latitude with 12^h MLT directed towards the top, and 06^h MLT directed towards the right. Both radars observed strong flows away from the radars (shaded red) in the beams that are directed poleward. TIGER also observed more azimuthal flows toward the radar (blue). Both are consistent with a twin-cell convection pattern.

Time series of these observations are shown in the bottom half of Figure 4. The top two panels show the ionospheric velocities against magnetic latitude (and time). Each panel shows data from one radar beam (beam 15 from Hankasalmi and beam 0 from TIGER). The bottom two panels show the corresponding backscatter power data. Three patches of enhanced backscatter power were observed by each radar, which propagated poleward, and which corresponded to enhanced ionospheric flows. These Poleward Moving Radar Auroral Forms (PMRAFs) are the ionospheric signature of time-varying magnetopause reconnection (Milan et al. 2000 and references therein). The second and third PMRAFs observed by Hankasalmi correspond well with the first and second PMRAFs observed by TIGER.

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The fact that the Hankasalmi and TIGER radars observed PMRAFs in the post- and pre-noon sectors respectively indicates that pulsed reconnection was occurring over a large part of the magnetopause during this interval. As there is a gap in radar coverage around 12^h MLT, it cannot be shown that pulsed reconnection occurred along this entire sector of local time, but we note that the magnetic footprint of the Cluster spacecraft is in this region. As will be shown in the next section, signatures of pulsed reconnection were also observed by Cluster.

4. In situ observations: FTEs and their azimuthal extent

Cluster observations of the flux transfer events before and after the spacecraft crossed the magnetopause are shown in Figures 5 & 6. In each figure, the top two panels show the components of the magnetic field tangential to the magnetopause, followed by the B_N components observed by the four spacecraft, which are ordered by the positions of the spacecraft (equatorward to poleward: C3, C4, C1 and C2). The next panel shows a spectrogram of the electrons observed moving away from the magnetopause by Cluster 2 (0° and 180° pitch angles in Figs. 5 & 6 respectively). The angle between the magnetic field observed by Cluster 3 and the **l** vector (α_{LM}), and the IMF clock angle (θ_{CA}) are shown in the penultimate panel by green and purple traces respectively, and the magnetic field magnitude is shown in the bottom panel.

Before 0504 UT, all four spacecraft were in the magnetosphere, and observed a magnetic field which was almost entirely in the **l** component. At 0504 UT Clusters 2 and 3 crossed the magnetopause, followed by Clusters 1 and 4 at 0508 UT. The magnetosheath magnetic field was largely in the negative **l** direction (α_{LM} = 180°), except between 0515 and 0524 UT when α_{LM} dropped to ~150° (observed in θ_{CA} between 0509 and 0516 UT, and indicating that the IMF lag is too small). Between 0450 and 0524 UT, all four Cluster spacecraft observed bipolar variations of the B_N component which are characteristic signatures of flux transfer events.

We identify five FTEs which were clearly observed by all four spacecraft, which are indicated by vertical purple lines in Figures 5 & 6. Two of these FTEs (at 04:56 and 05:22 UT) exhibited signatures at C3 & C4 that were not clearly bipolar, but they are similar enough to the other signatures observed for us to regard them as 'irregular' polarity FTEs (Rijnbeek et al. 1984). In each case, the FTE was observed first by C3 & C4 (simultaneously), then by C1 & C2 (at approximately the same time as each other, but 30-60s after C3). This order indicates a northward motion which is consistent with the 'standard' polarity of the B_N signatures that was observed whenever the polarity was clear (e.g. Rijnbeek et al. 1984). Since the Cluster tetrahedron had little extent in the **n** dimension, we cannot obtain a reliable three-dimensional velocity for these two FTEs by conventional multi-spacecraft timing analysis (Harvey 2000). Therefore, we use the time delays between the FTEs being observed at Cluster 4 (which we take as a reference space-

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craft) and Clusters 1 and 2 to obtain the FTE velocities in the **l-m** plane (which does contain large spacecraft separations as shown in Figure 3). The results are shown in Table 1. The two magnetospheric FTEs were observed to move at speeds of 257 and 197 km s^{-1}, in a largely poleward direction. Such a direction of motion is expected from the fact that there are no significant azimuthal forces exerted on the reconnected flux tubes by either the magnetic tension in the reconnected field lines or the magnetosheath flow.

Unfortunately, neither of these FTEs exhibited plasma signatures at any of the spacecraft (i.e. the draping region alone was observed). We therefore take the “characteristic time” (the time difference between the positive and negative peaks of B_N, as defined by Kawano et al. 1992) as a proxy for the duration of the FTE. These two FTEs had characteristic times of 26 and 29s respectively; these correspond to poleward extents of 6,700 and 5,700 km respectively, which is smaller than the 8,500 km azimuthal separation of Clusters 1 and 2. Consequently, it appears that these two FTEs have a larger azimuthal than poleward extent; in such conditions of high magnetic shear this is more consistent with extended X-line models of FTEs (e.g. Lee and Fu 1985, Southwood et al. 1988, Scholer 1988).

However, there are some interesting differences between spacecraft in some other FTEs which were observed, and which are indicated by green arrows in Figure 5. At 0455 UT an FTE was observed at Clusters 1, 3 and 4 (most clearly at Cluster 1). However, no B_N signature is evident at Cluster 2. Considering that Cluster 2 was nearer the magnetopause than Cluster 1 and crossed the magnetopause before Cluster 1 (see Figures 3 and 6), this implies that the azimuthal extent of this FTE is more limited. The dearth of FTEs at Cluster 1 between 0458 and 0502 UT could be explained by the fact that Cluster 1 is the furthest spacecraft from the magnetopause, but considering the size of the FTEs observed by Cluster 2 at 0459 and 0502 UT, and the fact that the separation between Clusters 1 and 2 normal to the magnetopause is only 1200 km, it is perhaps more likely that these are also more azimuthally-limited features. Finally, between 0502 and 0504 UT, Cluster 2 observed three FTEs whilst Cluster 1 only observed a single event.

The magnetosheath observations are shown in Figure 6. The three FTEs identified at all four spacecraft are again indicated by purple lines. All three occurred during the interval where the magnetosheath magnetic field rotated dawnward (α_{LM}, penultimate panel), caused by the rotation in the lagged IMF clock angle observed a few minutes before. The electron signature observed at 0514 UT was not clearly distinct from that of the previous FTE, but distinct electron signatures were observed for the other two FTEs, most clearly in the antiparallel pitch angle bin at Cluster 2. Three distinct electron energy enhancements were observed during the course of the 0518 FTE; the time from the beginning of the first enhancement to the end of the last was 60s. A single electron signature was observed at 0523 UT, which lasted 67s. Multiplying these durations by the speeds reported in Table 1 gives poleward scale sizes of 8,200 and 10,000 km respectively (these two FTEs had a lower speed than those observed before the magnetopause crossing).

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Prior to 0515 UT, the rate at which FTEs were observed was higher, due at least in part to the proximity of the spacecraft to the magnetopause. It is therefore harder to link specific FTEs at different spacecraft with a high degree of certainty. However it is again clear that there are significant differences between Clusters 1 and 2, separated predominantly in the azimuthal direction. We highlight two FTEs in Figure 6 which were observed by a subset of the spacecraft (both indicated by a green arrow). Clusters 3, 4 and 2 observed a clear FTE at 0513 UT, which was not observed by Cluster 1, despite the fact that this spacecraft was now the closest to the magnetopause. Cluster 1 alone observed a clear FTE at 0516 UT; recalling again that the maximum separation of the spacecraft normal to the magnetopause was only 1200 km, this also suggests a spatially-limited structure.

5. Summary

We have presented ground- and space-based observations of flux transfer events during an interval when the IMF clock angle was near 180° and Cluster was near magnetic noon. The ionospheric observations indicate that pulsed magnetic reconnection occurred over a large part of the dayside magnetopause. Some FTEs were observed at all four spacecraft indicating that they extended azimuthally by at least 8,500 km. In some cases, this is larger than their observed poleward scale size, consistent with long X-line models of FTE formation. However, there are also significant differences in FTE observation on these azimuthal scales, implying that FTEs can also occur more patchily. These FTEs could be explained by any of the models.

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Fig. 1. The location and orientation of the Cluster spacecraft tetrahedron at 04:50 UT on the 27th March 2007. The tetrahedron has been expanded by a factor of two relative to Cluster 1.

Fig. 2. OMNI lagged solar wind conditions. From top: the IMF GSM components and magnitude, the magnitude of the IMF clock angle (expressed between 0° and 180°) and the solar wind dynamic pressure.

Fig. 3. The orientation of the Cluster tetrahedron, relative to Cluster 3, in boundary normal coordinates at 05:15 UT on the 27th March 2007.

Fig. 4. Ionospheric signatures of flux transfer events on the 27th March 2007. Top: 2D snapshots of the fast flows observed by the Hankasalmi radar (northern hemisphere, left) and the TIGER radar (southern hemisphere, right). The green asterisk in each panel denotes the footprint of Cluster 3. Bottom: Time series of data from individual beams of these two radars. The top two panels show the ionospheric flow velocities deduced from the radar backscatter, and the bottom two panels show the backscatter power. Poleward moving features are observed in both hemispheres (PMRAFs).

Fig. 5. Magnetospheric FTEs observed by Cluster. From top: The magnetic field components observed by the four Cluster spacecraft, a spectrogram of 0° pitch angle electrons, the angle between the magnetic field observed by Cluster 3 and the vector **l** (green trace) and IMF clock angle (purple), and the magnetic field strength.

Fig. 6. Magnetosheath FTEs observed by Cluster. The spectrogram shows 180° pitch angle electrons; the format is otherwise the same as Figure 5.

Time (UT)	dt_{41} (s)	dt_{42} (s)	$\|\mathbf{v}\|$ (km s^{-1})	$\hat{\mathbf{v}}_{LM}$	Angle to **l**
04:54:20	15.8	32.4	257	(0.932, 0.363)	21°
04:56:20	37.8	32.6	197	(0.959, -0.285)	16°
05:14:40	18.2	18.8	393	(0.990, -0.140)	8°
05:17:52	27.4	61.4	168	(0.950, 0.312)	18°
05:22:31	59.0	61.6	122	(0.991, -0.132)	8°

Table 1. 2D FTE velocities determined from three-spacecraft timing.

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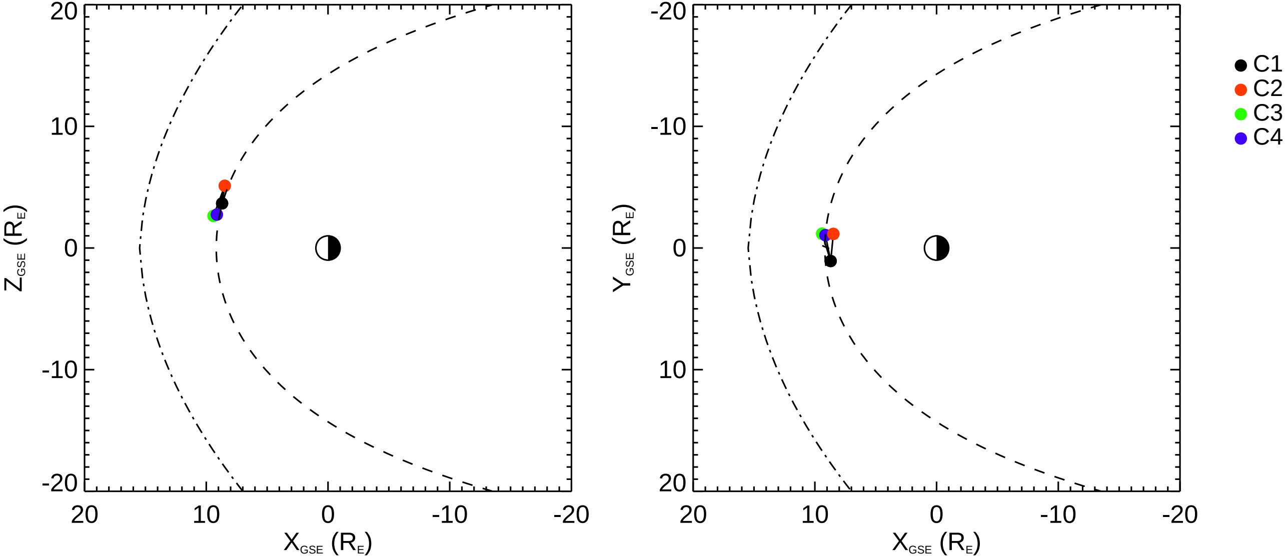
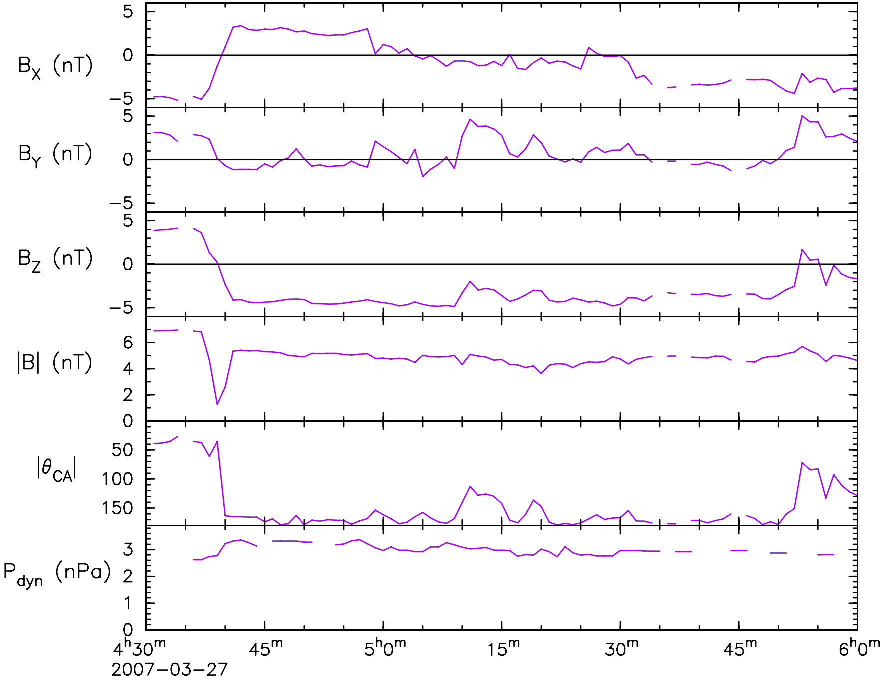


20
10
0
-10
-20
Z_GSE (R_E)
X_GSE (R_E)
-20
-10
0
10
20
Y_GSE (R_E)
X_GSE (R_E)
C1
C2
C3
C4



B_X (nT)
B_Y (nT)
B_Z (nT)
|B| (nT)
$|\theta_{CA}|$
P_{dyn} (nPa)
5
0
−5
6
4
2
50
100
150
3
1
4^h30^m
45^m
5^h0^m
15^m
30^m
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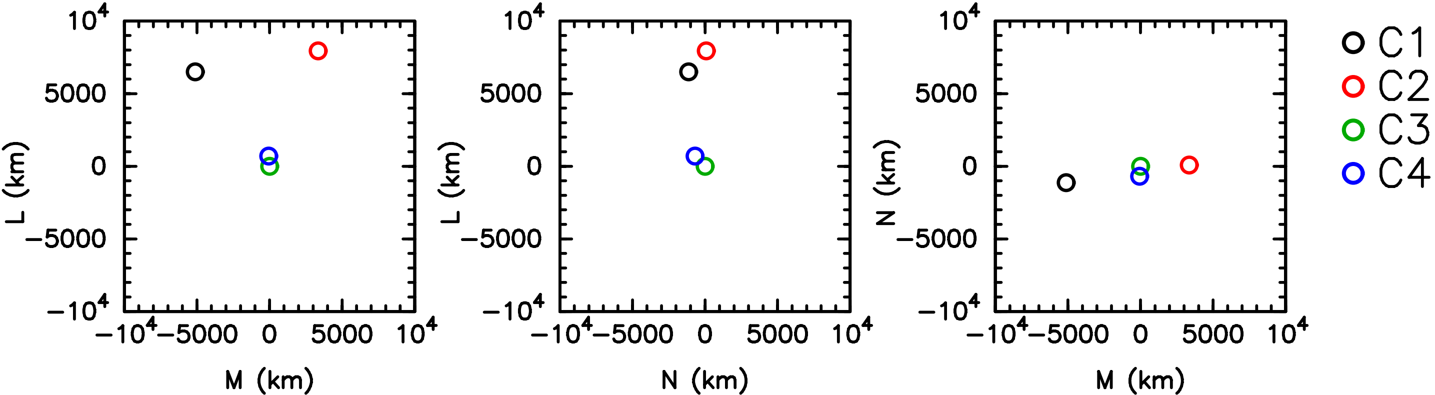
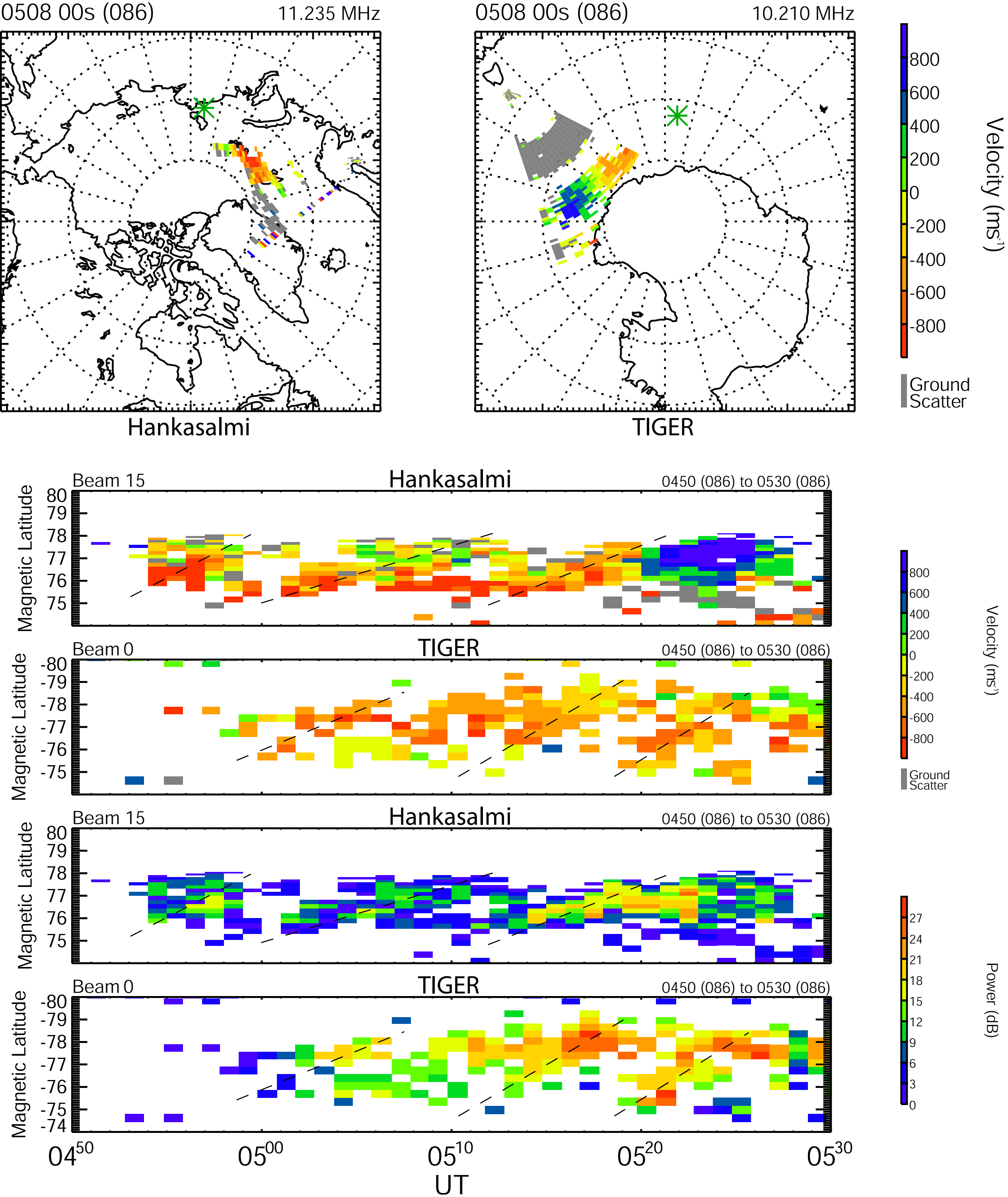
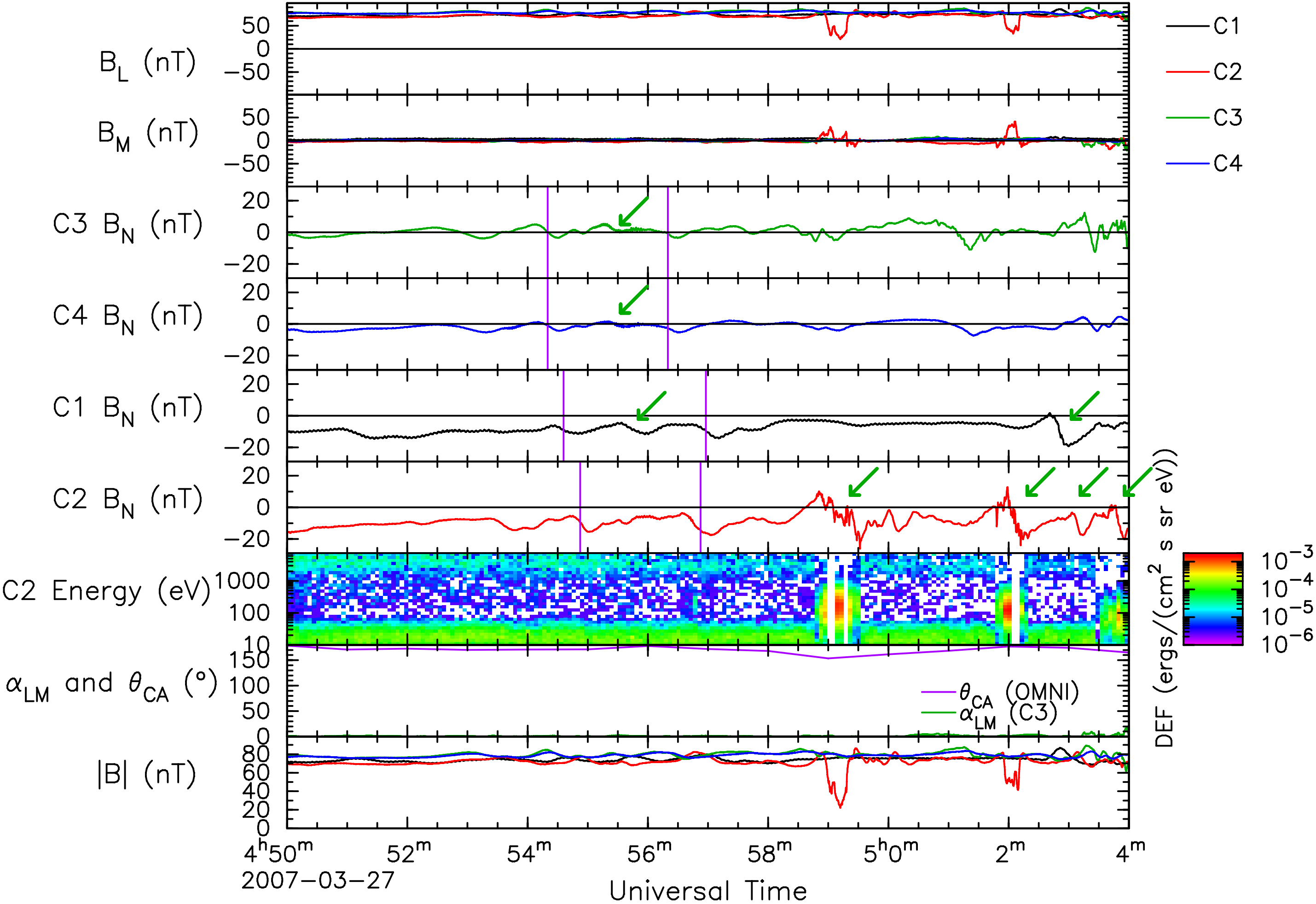
2007−03−27



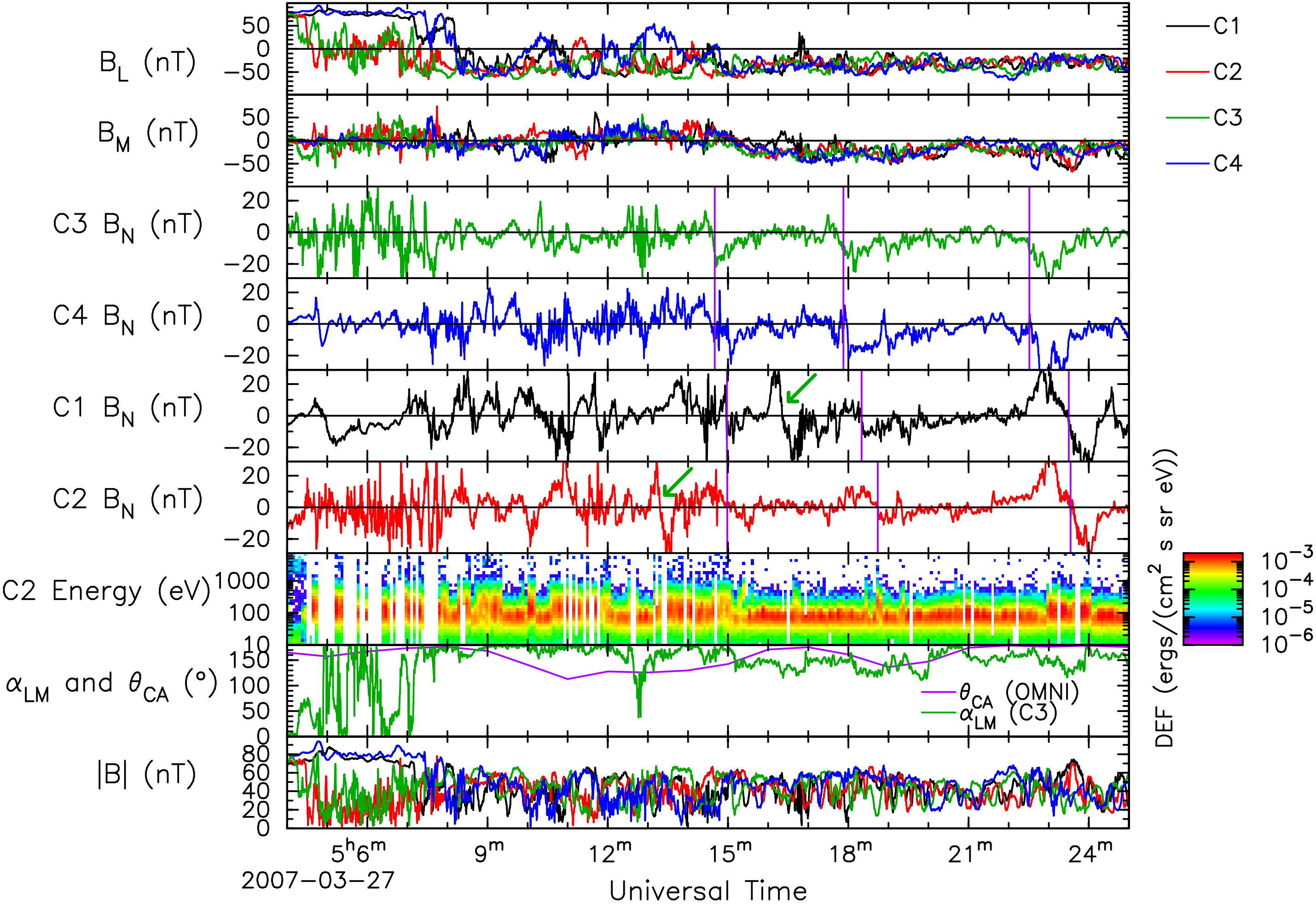
L (km)
M (km)
N (km)
N (km)
M (km)
L (km)
C1
C2
C3
C4



0508 00s (086)
11.235 MHz
0508 00s (086)
10.210 MHz
Hankasalmi
TIGER
Velocity (ms-1)
800
600
400
200
0
-200
-400
-600
-800
Ground Scatter
Beam 15
Hankasalmi
0450 (086) to 0530 (086)
Magnetic Latitude
Beam 0
TIGER
0450 (086) to 0530 (086)
Beam 15
Hankasalmi
0450 (086) to 0530 (086)
Beam 0
TIGER
0450 (086) to 0530 (086)
Power (dB)
0450
0500
0510
0520
0530
UT



C1
C2
C3
C4
B_L (nT)
B_M (nT)
C3 B_N (nT)
C4 B_N (nT)
C1 B_N (nT)
C2 B_N (nT)
C2 Energy (eV)
α_LM and θ_CA (°)
θ_CA (OMNI)
α_LM (C3)
|B| (nT)
DEF (ergs/(cm^2 s sr eV))
4^h50^m
52^m
54^m
56^m
58^m
5^h0^m
2^m
4^m
2007-03-27
Universal Time



C1
C2
C3
C4
B_L (nT)
B_M (nT)
C3 B_N (nT)
C4 B_N (nT)
C1 B_N (nT)
C2 B_N (nT)
C2 Energy (eV)
α_{LM} and θ_{CA} (°)
|B| (nT)
θ_{CA} (OMNI)
α_{LM} (C3)
DEF (ergs/(cm^2 s sr eV))
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5^h6^m
9^m
12^m
15^m
18^m
21^m
24^m
2007-03-27
Universal Time