Solar wind-magnetosphere-ionosphere interactions in the Earth's plasma environment

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The properties of the Earth's coupled magnetosphere-ionosphere system are dominated by its interaction with the solar wind plasma, mediated by magnetic reconnection at the magnetopause interface. As a consequence, Earth's magnetospheric dynamics depend primarily on the concurrent orientation of the interplanetary magnetic field (IMF). In this paper we illustrate current understanding of the system through the results of a number of recent case studies, and highlight remaining issues. The discussion centres on flux transfer events and substorms during intervals of southward IMF, and magnetopause and tail processes during intervals of northward IMF. We emphasise the great diagnostic power of combined *in situ* and remote sensing observations from space and on the ground.

Key index words: Magnetosphere, ionosphere, solar wind interactions

1. INTRODUCTION

Knowledge of the Earth's magnetosphere is of major practical relevance as it is the plasma medium in which a range of applications spacecraft must be designed to operate, used e.g. for communications, navigation, meteorology, and defence. The ionospheric plasma medium is also important in a range of applications, such as HF communications, direction-finding, and 'over-thehorizon' radars. In this paper we briefly review recent progress in understanding the major physical processes which govern the properties of these coupled plasma systems, and some open questions.

The main factor which governs the properties of the near-Earth plasma medium is its interaction with the solar wind plasma, which blows continuously outward from the Sun at speeds ~400 km s^{-1}. The structures to which this interaction gives rise are sketched in figure 1, in which the solar wind blows from left to right. The arrowed lines indicate magnetic field lines, while the dashed lines show important boundaries, namely the bow shock, formed because the solar wind is supersonic in the Earth's frame, and the magnetopause, the boundary of the Earth's magnetic field, inside of which lies the magnetosphere. To a first approximation the magnetosphere deflects the solar wind and frozen-in interplanetary magnetic field (IMF) around the Earth, forming a magnetic cavity which extends ~10 Earth radii ($R_E \approx 6400$ km) upstream from the Earth, determined by pressure balance. However, the diagram also indicates the most important dynamical process occurring in the system, which is that at a 10-20% level the interplanetary flux which is brought up to the magnetopause by the solar wind becomes connected to the Earth's field by magnetic reconnection (Dungey 1961). The reconnection process shown in the figure is that which occurs when a large magnetic shear is present at the subsolar boundary, i.e. when the IMF 'points south'. In this case 'open' flux tubes are formed which connect the Earth's polar regions into interplanetary space. The processes which occur when the IMF points northward will be addressed below. In the situation shown in figure 1, the open tubes produced on the dayside are subsequently carried into the nightside by the solar wind, and are stretched out into a long comet-like tail which extends downstream to distances of ~1000 R_E. Further reconnection in the centre of the tail, as shown, then releases closed flux tubes back towards the Earth and eventually to the dayside, where the process repeats. The consequence is a large-scale cyclical flow in the magnetosphere, and in the polar ionosphere to which it maps, with a typical cycle time of about half a day.

This cyclical flow (the 'Dungey cycle') is also largely deterministic of the plasma populations found inside the magnetosphere, as indicated by the dotted regions in the figure. Plasma of solar wind origin (green dots) gains access to the magnetosphere via open field lines, producing boundary layers inside the magnetopause which extend down to the dayside ionosphere forming the cool (few hundred eV) ‘dayside cusp’ precipitation. On the nightside, this plasma flows downstream in the tail lobes and into the centre of the tail, where it is heated in the reconnection process to form the hot (several keV) plasma sheet population (red dots). Cold plasma (few tens of eV) from the polar ionosphere, consisting of oxygen ions as well as protons (and electrons) (shown by the outer region of blue dots), also flows into the tail and becomes heated to form part of the plasma sheet. Dense cold (few eV) ionospheric plasma is also present in an inner core of flux tubes (inner blue dots), forming the plasmasphere. These inner flux tubes do not take part in Dungey-cycle flow, but instead rotate with the Earth. Geostationary orbit, where many applications spacecraft are placed, is located near this boundary between hot and cold plasma. Since the boundary can move due to IMF-induced modulations of Dungey-cycle flow, a cold dense plasma environment can, at short notice, be replaced by hot tenuous plasma flowing in from the tail. This plasma behaviour makes geostationary orbit a tough environment from a space engineering viewpoint, additional to the effect of penetrating relativisitic electrons from the outer radiation belt, whose fluxes appear to depend instead on the solar wind speed via the power in magnetospheric ULF waves (Mathie and Mann, 2000).

2. FLUX TRANSFER EVENTS

In this section we consider the nature of the primary reconnection process at the dayside magnetopause for large subsolar magnetic shear, which initiates the flow cycle outlined above. Observations of fields and plasma at the magnetopause more than twenty years ago showed that the process is characteristically pulsed on time scales of 5-10 min, forming ‘flux transfer events’ (FTEs) (Haerendel *et al*. 1978; Russell and Elphic 1978). The magnetic signatures of more recent examples, observed by the Cluster 1 spacecraft on 14 February 2001, are shown in figure 2 (Wild *et al*. 2001). Here the spacecraft was located in the post-noon sector at ~14.3 h MLT, and at ~61°

magnetic latitude, and moved outward over the one-hour interval shown from a geocentric distance of 11.3 to 12.2 R_E. The three magnetic components in the upper panels of the figure are in boundary normal co-ordinates (determined from minimum variance analysis of the data), in which N is the outward normal to the magnetopause, and L and M lie in the boundary pointing roughly northward and westward, respectively. Initially the spacecraft was located inside the magnetosphere, but crossed into the magnetosheath (the shocked solar wind downstream of the bow shock) across a boundary layer (the inner edge marked as 'BL') and three magnetopause transitions (marked 'MP'). Both inside the magnetosphere and in the magnetosheath, characteristic bipolar signatures were observed in the B_N field component (marked 'FTE') which are interpreted as being due to bursts of reconnection which produce bulges of open flux propagating over the magnetopause (Southwood *et al*. 1988). Statistical studies show that the occurrence of these signatures is strongly favoured during intervals of large magnetic shear at the subsolar magnetopause (Rijnbeek *et al*. 1984), thus supporting this interpretation.

If they are produced by reconnection, FTEs should also be accompanied by pulsed flow in the dayside magnetosphere and ionosphere, and pulsed precipitation in the dayside cusp. It has been found that both these effects are characteristic of intervals of large subsolar magnetic shear (Lockwood et al. 1989; Pinnock et al. 1995; Sandholt et al. 1990), though simultaneously-observed events in space and in the ionosphere remain a rarity (Elphic et al. 1990; Neudegg et al. 2000), mainly for logistical reasons. The lower panels of figure 2 show simultaneous data from beam 3 of the CUTLASS Finland HF radar, obtained in the cusp ionosphere near the estimated Cluster magnetic footprint. The upper of these panels shows the backscatter power, the middle panel the line-of-sight Doppler velocity, and the lower panel the mean Doppler velocity in the latitude band defined by the dashed lines in the middle panel, which encompassed the latitude of the footprint of Cluster. It can be seen that pulses in both the backscatter power and Doppler velocity occur in synchronism with the FTEs observed by Cluster, the latter directly implying input of momentum into the magnetosphere. Several of these pulses also appear to act as sources for poleward-moving features in the radar backscatter, which occur commonly in cusp radar data (e.g. Provan and Yeoman 1999). Similar poleward-moving forms are also commonly observed in dayside auroral data, and an example from another interval is shown in figure 3 (Sandholt *et al*. 1999). Here we show meridian-scanning photometer (MSP) data from Ny Ålesund (Svalbard), obtained in the post-noon sector on 30 November 1997, specifically for the oxygen red line emission (630 nm), which typically is excited at ~250 km altitude by low-energy (tens to hundreds of eV) electrons. In common with the radar data, a pulsed band of precipitation is present (which drifts slowly equatorward in this case following a southward turn of the IMF), in which the pulses are associated with transient auroral forms which propagate poleward.

It is clearly difficult to determine the geometry and propagation of FTEs either from single spacecraft *in situ* data at the magnetopause, or from local measurements on the ground. Progress using *in situ* data requires multi-spacecraft observations, work on which is currently opening up via newly available four-spacecraft data from the Cluster mission. In addition, important clues can also be obtained from 'global' ground-based observations of the aurora and radar backscatter. Results from the first published study of the latter nature are shown in figure 4 (Milan *et al*. 2000). Here we show four successive images of the UV aurora obtained at 3 min intervals on 26 August 1998 by the UVI instrument on the Polar spacecraft, projected onto a magnetic grid with noon at the top and dusk to the left. In the first image, a kink is visible in the auroral band at ~1430 MLT and ~72° latitude. This evolves into an eastward-propagating bifurcation in the second image, which has reached ~1630 MLT in the third image, and ~1800 MLT in the fourth (where a further event is also starting to form nearer to noon). It seems clear that these auroral effects and the transients observed in the MSP data shown in figure 3 are related phenomena, and indicate that (in the present case during an interval of positive IMF B_y), the transients start in the post-noon sector, and propagate eastward over ~6 h of MLT in ~10 min. The coloured pixels overlaid on the auroral data show the regions of radar backscatter observed simultaneously by the CUTLASS Finland radar. The data plotted in the pixels represent the line-of-sight Doppler velocity. It can be seen that 'poleward-moving radar auroral forms' are observed, co-located with the UV auroras, in which the Doppler velocity indicates the presence of strong westward flows (consistent with the field tension effects expected for positive IMF B_y). These data are interpreted as representing the response to individual 'FTE' bursts of reconnection, which are thus envisaged to propagate wave-like on the magnetopause from near noon to the magnetospheric flanks over intervals of ~10 min or more. The UV aurora is excited by the precipitation of accelerated electrons in regions of upward field-aligned current, while the radar backscatter results from ionospheric irregularities which grow in the structured ionosphere produced by the precipitation and flow (Davies *et al*. 2001). Patches of related backscatter have been tracked in their motion across the polar cap over several tens of minutes (McWilliams *et al*. 2001). Results such as these are currently in the process of elucidating the dynamics of the dayside magnetopause for large subsolar magnetic shear, and substantial future progress is anticipated from co-ordinated measurements with Cluster. However, the underlying reason for the pulsed nature of FTEs has yet to be determined.

3. SUBSTORMS

During intervals of large subsolar magnetic shear at the dayside magnetopause, the open flux produced is transported to the nightside by the solar wind, and the magnetic flux in the tail lobes increases. This growth lasts typically for 30-50 min before the tail becomes unstable, and rapid reconnection begins within the near-Earth dusk side plasma sheet, at down-tail distances of 20-30 R_E (Nagai *et al*. 1998). As a consequence, much of the pre-existing plasma sheet is pinched off from Earth in this sector, forming a plasmoid which propagates tailward out of the magnetosphere at speeds of 500-1000 km s^{-1}, as sketched schematically in figure 1. Earthward of the reconnection region, the newly closed field lines collapse towards the Earth, compressing and heating the tail plasma, and causing bright auroras at the feet of the field lines. Such events are called substorms, which are another feature characteristic of intervals of (or just following) southward IMF.

The region of bright nightside auroras which occurs during a substorm is called the ‘substorm auroral bulge’ and within it large westward-directed currents flow (a few million amps), which close via field-aligned currents at its eastward and westward ends. These currents produce large (few hundred nT) southward-directed perturbation magnetic fields on the ground in the region underneath the bulge (the induced line voltages associated with which are a matter of serious concern for power distribution companies). These currents are not driven by large electric fields, however, but are rather associated with very large electrical conductivities produced in the bulge ionosphere by the precipitating auroral electrons. Instead, the electric field is found to be strongly suppressed within the bulge, corresponding to a suppression of the plasma velocity (related to the electric field by $\boldsymbol{V} = (\boldsymbol{E} \times \boldsymbol{B}) / B^2$, where $\boldsymbol{B}$ is the magnetic field) (e.g. Yeoman *et al*. 2000; Khan *et al*. 2001). To date, the electrodynamic origin of this suppression and its coupling with the magnetosphere have yet to be determined, whether it is associated, for example, with enhanced ion-neutral frictional drag which is communicated to the magnetosphere, or whether it might involve large-scale ionosphere-magnetosphere decoupling by field-aligned voltages.

On the other hand, tail reconnection contributes to the Dungey cycle by closing open flux tubes in the lobes and returning them to Earth, so we would expect it to excite magnetospheric flow. Indeed, localised nightside flow intensifications are known to occur during all phases of the substorm cycle in association with localised ‘poleward boundary intensifications’ of the auroras and ‘bursty bulk flows’ in the tail, taken to be the signatures of azimuthally localised bursts of tail reconnection (e.g. Watanabe *et al*. 1998). Substorms should produce similar effects but on a larger scale, and very recently detailed flow observations by the SuperDARN HF radar array during a small high-latitude substorm have revealed clear evidence for excitation of large-scale nightside flow (Grocott *et al*. 2001). Figure 5 shows a plot of radar flow vectors (black) and inferred streamlines of the ionospheric plasma flow for a 2 min interval occurring ~10 min after substorm expansion onset. These have been superposed on a simultaneous UV auroral image obtained by the VIS camera on the Polar spacecraft (blue). The red vectors also show magnetic perturbation vectors, which have been rotated anti-clockwise by 90° such that they point in the direction of the flow if they are produced wholly by an overhead Hall current. It can be seen that the flow is of twin-vortex form, with anti-sunward flow over the polar cap and return sunward flow at lower latitudes, typical of the Dungey cycle, but where the flow vectors tend to be deflected around the brightest part of the auroral bulge in the midnight sector. The few flow vectors observed within the latter tend to be small, in accordance with the flow suppression mentioned above. Overall, the voltage associated with the flow, equal to 67 kV during the interval shown, increased from ~40 kV prior to onset, to a peak of ~80 kV after ~15 min, and then declined to ~35 kV over ~10 min of recovery. Flow excitations during larger substorms have also been reported by Sandholt *et al.* (2001).

4. THE MAGNETOSPHERE FOR NORTHWARD IMF

While FTEs and substorms are the primary characteristics of the magnetosphere for large subsolar magnetic shear, the properties of the magnetosphere for low subsolar magnetic shear are more subtle and less well determined. Observations of dayside auroras (such as those shown in figure 3) suggest that open flux production does not switch off entirely until the ‘clock’ angle of the IMF (the angle in the Y-Z plane relative to north) decreases to become less than ~45° (e.g. Sandholt *et al.* 1998). The magnetosphere thus remains weakly driven by open flux production when the IMF is northward but dominated by the B_y component. An interesting question then concerns whether substorms, perhaps weak or more infrequent, occur under such circumstances. This has recently been investigated by Grocott and Cowley (2001) who examined magnetometer and radar flow data during extended (several hour) intervals of northward but B_y-dominated IMF. They found that weak B_y-asymmetric flow was continuously present in the ionosphere, interspersed every hour or so by strong surges of nightside flow lasting a few tens of minutes. Examples of the former and latter types of flow are shown on the left and right sides of figure 6, respectively, in a similar format to figure 5. These two observation intervals were separated by 30 min under similar interplanetary field conditions. No large ground magnetic perturbations characteristic of substorms were observed, including during the flow surges, indicating that the ionospheric conductivity was not significantly enhanced by auroral precipitation (no auroral data is available in these cases). However, the flow surges do appear to be associated with contractions of the polar cap, and hence with open flux destruction by tail reconnection. The reconnection is presumably confined to the more distant tail, rather than occurring near-Earth as during substorms.

In addition to the reduction of open flux production as the IMF turns northward, the dayside reconnection sites migrate to higher latitudes and begin to encompass reconnection with previously opened flux in the tail lobes. When a significant B_y component is still present, this 'lobe reconnection' appears to involve one lobe only for a given field line, so that the amount of open flux in the system does not change, only the mapping of the open field lines to the magnetosheath. The dynamical consequence is that the open flux is 'stirred' into B_y-dependent vortical motion by field tension effects on the 'new' open field lines. However, when the IMF is closely northward (the limits not yet having been precisely determined), lobe reconnection appears to be able to occur in both northern and southern hemispheres for given flux tubes, at least sequentially. This process then removes open flux from the tail, and adds new closed field lines to the dayside. The characteristic magnetospheric feature of this process is boundary layer plasmas adjacent to the magnetopause which have continuous properties across the boundary between open and closed field lines. Characteristic features in the dayside auroras are shown in figure 7, which shows 630 nm MSP data from Ny Ålesund in the same format as figure 3, during an interval in which the IMF clock angle was typically less than ~20° (Sandholt et al. 2000). It can be seen that during the early part of the interval the band of precipitation grew substantially in thickness via a series of 'steps' at the poleward border. This is interpreted as being due to a sequence of discrete two-lobe reconnection events which appended new closed flux tubes to the dayside magnetopause. Weak 'reversed' flow cells were observed, as expected, in simultaneous radar data.

5. SUMMARY

The Earth’s coupled magnetosphere-ionosphere is a complex plasma system whose dynamics are driven principally by the solar wind via magnetic reconnection at the boundary. As such, the system responds strongly to the direction of the IMF, and is typically in a state of change as the IMF direction changes. Research over the past ~25 years has succeeded in establishing much of the morphology and characteristic behaviours of the system, but major questions remain to be answered, such as why magnetopause reconnection is characteristically pulsed, and what determines the location and onset of the tail reconnection region during substorms. While many of the initial fundamental discoveries were made using either space-based data alone (e.g. the existence of FTEs), or ground-based data alone (e.g. the existence of substorms), future progress requires a more holistic approach, requiring co-ordinated multi-point space- and ground-based observations, combined with theory and modelling. In addition, a full understanding of the solar-terrestrial environment also requires co-ordinated studies of the solar and heliospheric drivers of magnetospheric and ionospheric activity, as well as studies of the latter’s consequences in the upper, middle and lower atmosphere, topics which are addressed elsewhere in these proceedings.

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FIGURE CAPTIONS

FIGURE 1. Cut through the noon-midnight meridian plane showing the principal features of the Earth’s plasma environment. The solid lines with arrows show magnetic field lines, while the dashed lines show the bow shock and magnetopause as marked. The coloured dots show the principal plasma populations originating in the solar wind (green) and the Earth’s ionosphere (blue). Both plasma sources contribute to the hot plasma sheet population located at the centre plane of the tail (red). [After Cowley 1993]

FIGURE 2. Combined Cluster-CUTLASS radar measurements obtained on 14 February 2001. The top three panels show Cluster magnetometer data in boundary normal co-ordinates. The bottom three panels show power and Doppler velocity measurements from beam 3 of the CUTLASS HF radar. Vertical dashed lines indicate the principal flux transfer events (marked ‘FTE’), magnetopause transitions (‘MP’), and the inner edge of the magnetopause boundary layer observed in the Cluster data. [Adapted from Wild *et al*. 2001]

FIGURE 3. Meridian scanning photometer observations of the dayside cusp emission obtained from Ny Ålesund (Svalbard) on 30 November 1997. Colour-coded contours of 630 nm emission intensity are plotted versus zenith angle (degrees) and time (UT). For magnetic local time, add ~3 h. The photometer scans in the magnetic meridian, with north at the top, zenith at the centre, and south at the bottom. [From Sandholt *et al*. 1999]

FIGURE 4. Four successive images of the UV aurora obtained at 3 min intervals on 26 August 1998 by the UVI instrument on the Polar spacecraft are shown in the grey pixels, on which are superposed CUTLASS Finland observations of Doppler velocity as indicated by the colour scale on the right. The field-of-view of the radar is indicated by the dashed-line wedge. The noon meridian

is the vertical line at upper right in each plot, while the dusk meridian is the horizontal line at lower left. The dashed circles indicate magnetic latitude at steps of 10° from the pole. [From Milan *et al*. 2000]

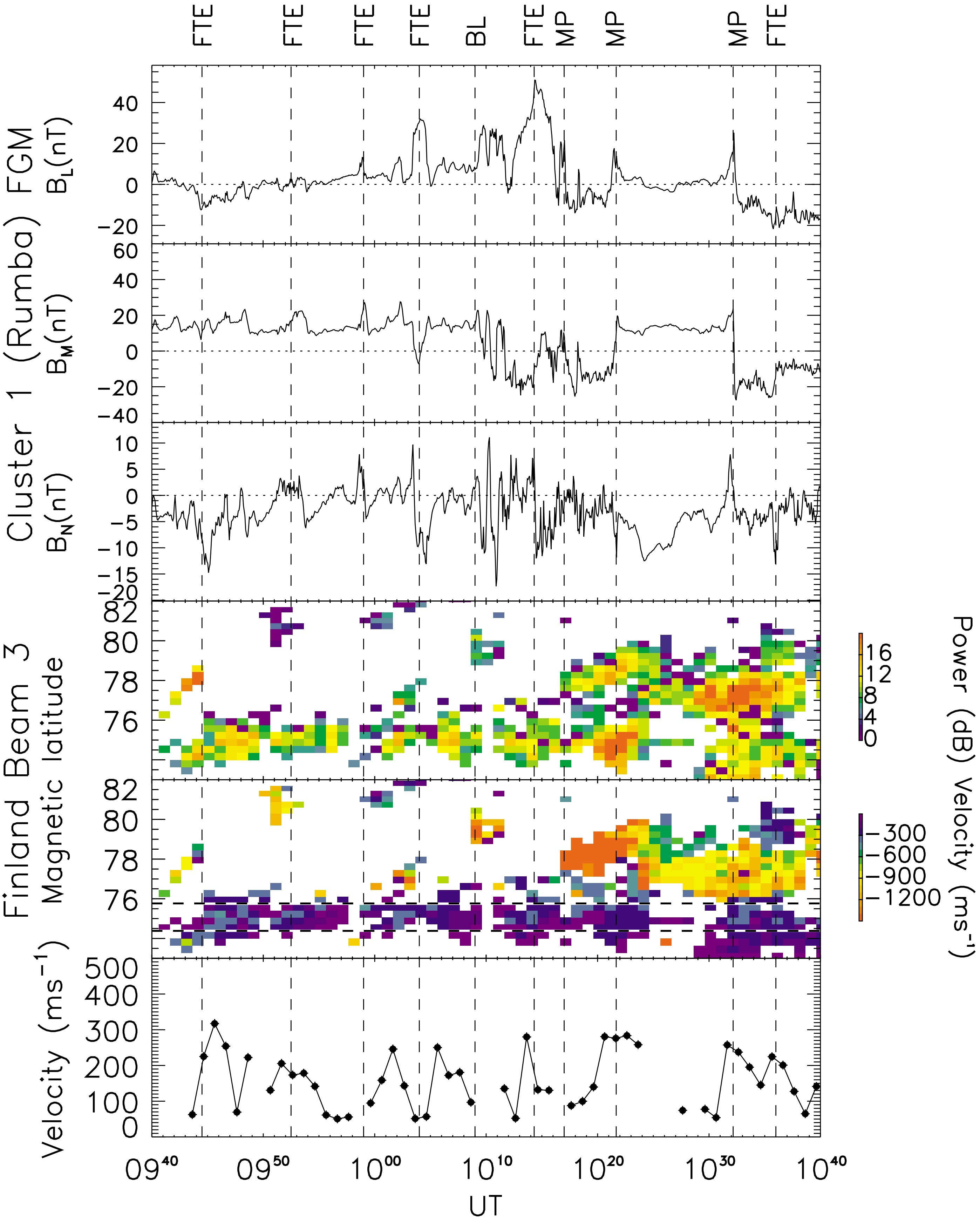
FIGURE 5. Plasma streamlines and flow vectors derived from SuperDARN radar measurements on 2 December 1999 (black) are shown projected onto a geomagnetic grid and are superposed on a UV auroral image obtained from the Polar VIS camera (blue). The red vectors are magnetic disturbance vectors which have been rotated anti-clockwise by 90° into the direction of the flow, assuming that they are due wholly to overhead Hall currents. The auroral intensities are indicated by the scale on the right hand side, while the scale for the flow and magnetic vectors is shown at upper left. The logo at lower right indicates the concurrent direction and strength of the IMF in the Y-Z plane. The time given at upper centre represents the centre time of the 32.5 s integration interval of the UV image, while the interval shown in brackets is the 2-min interval of the radar scan, which contains this centre time. [From Grocott *et al*. 2001]

FIGURE 6. SuperDARN radar data for two 2 min intervals on 2 December 1999 are shown projected onto a magnetic grid in a similar format to figure 5. The simultaneous direction of the IMF is indicated by the logo in the lower right hand corner of each plot. The difference between the maximum and minimum ionospheric potentials associated with the flow are given at lower left. [From Grocott and Cowley 2001]

FIGURE 7. Meridian scanning photometer observations of the dayside cusp emission obtained from Ny Ålesund (Svalbard) on 16 December 1998. The format is the same as for figure 3. [From Sandholt et al. 2000]

SHORT TITLE

Earth’s plasma environment



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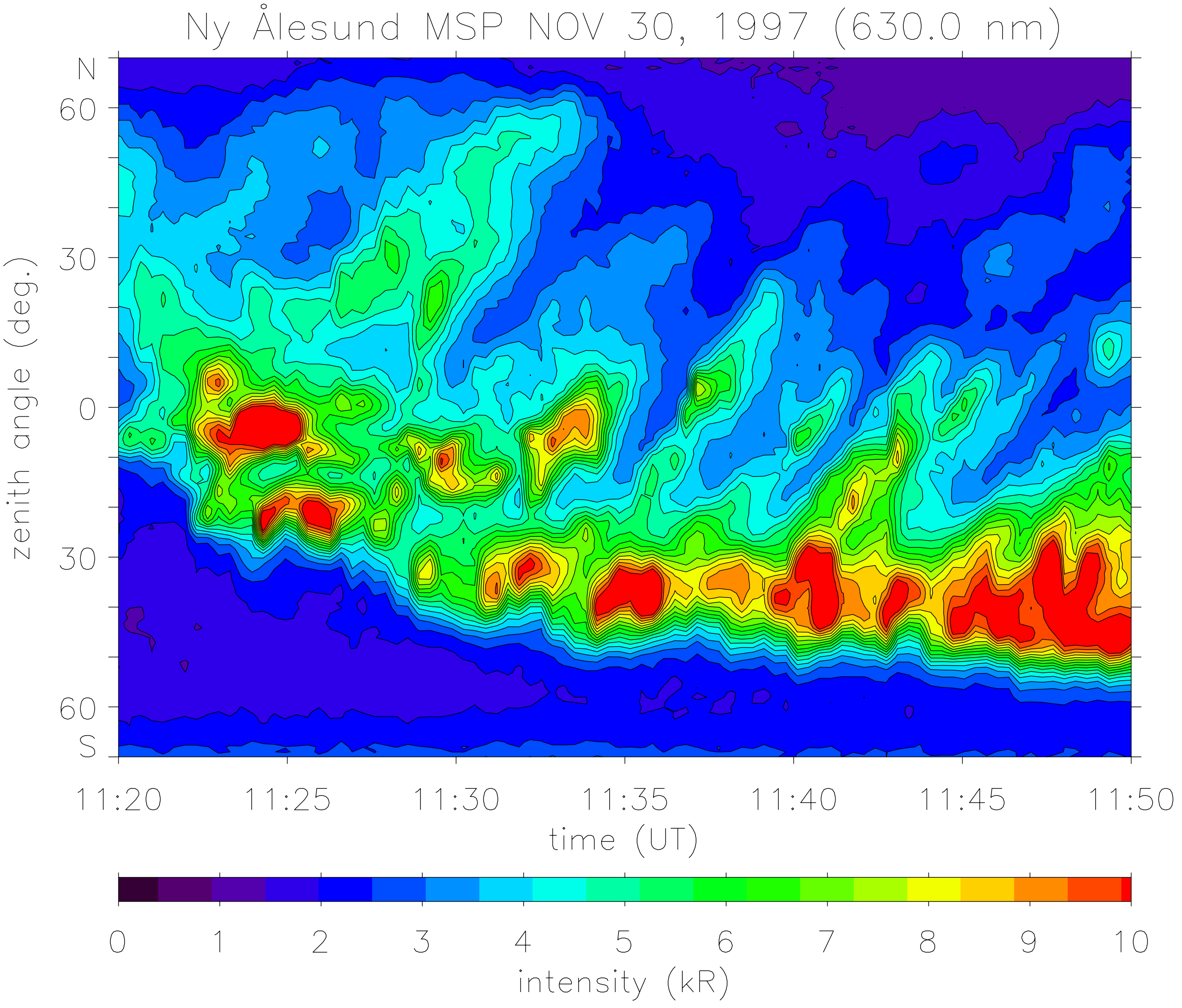
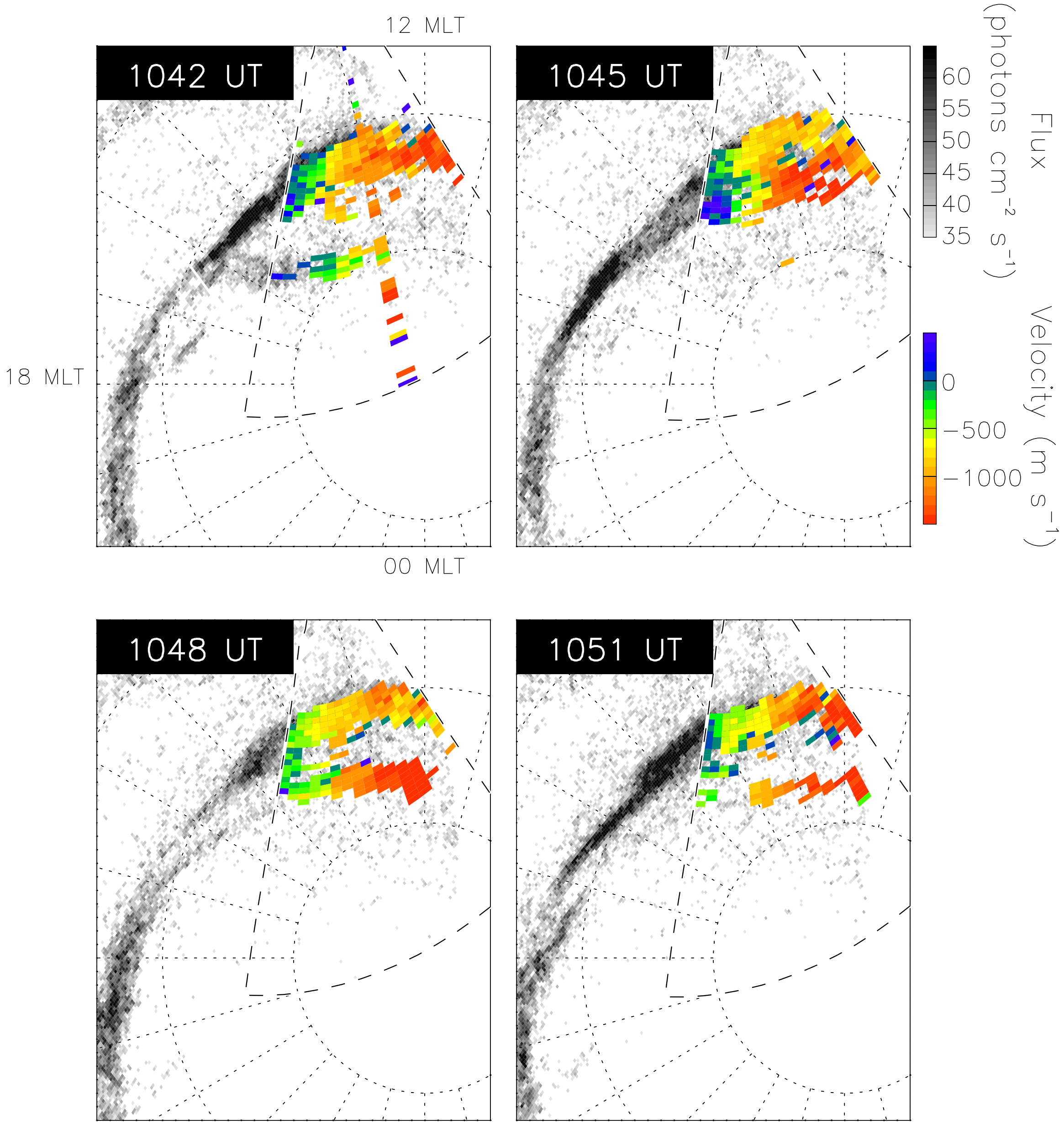
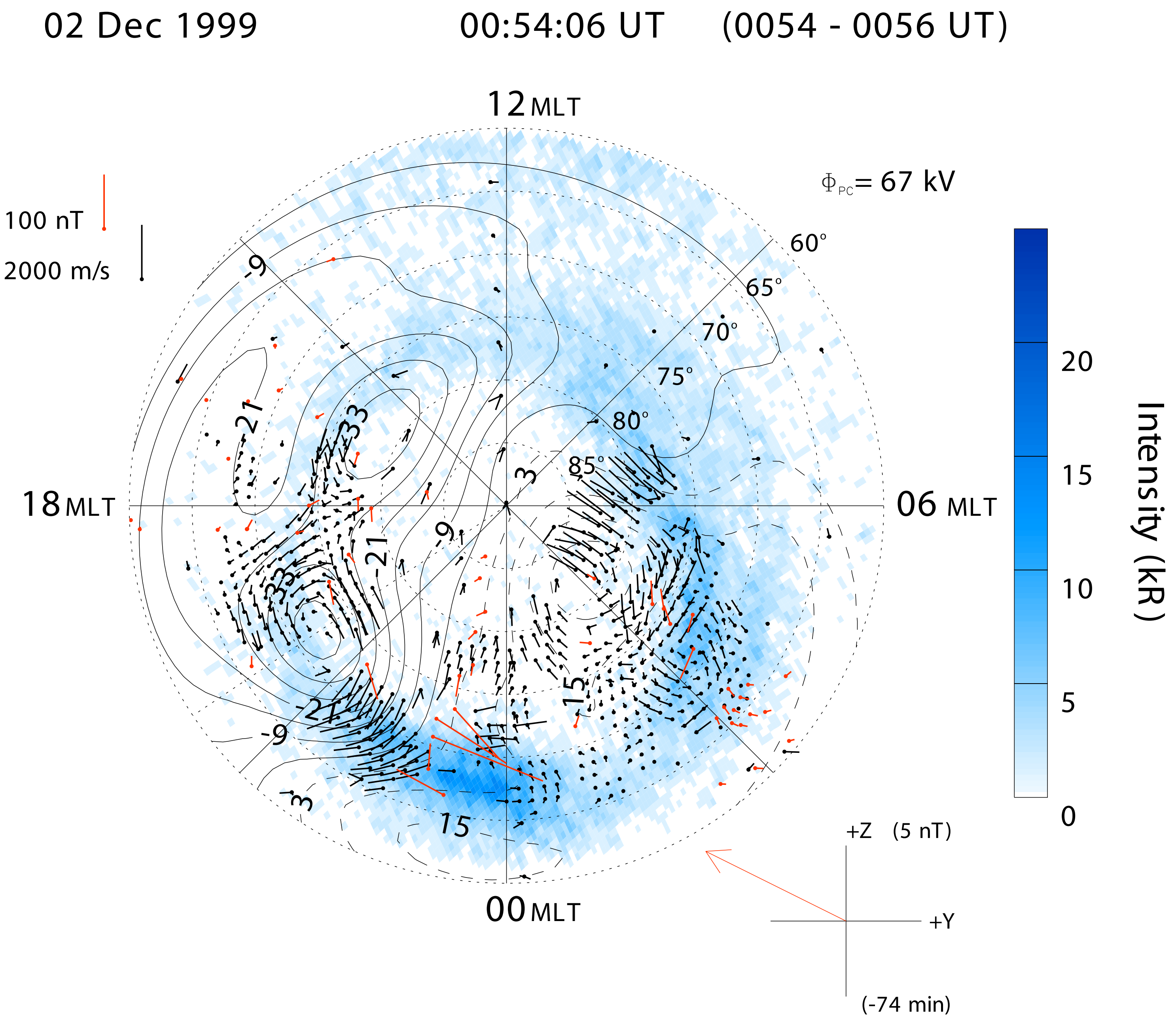
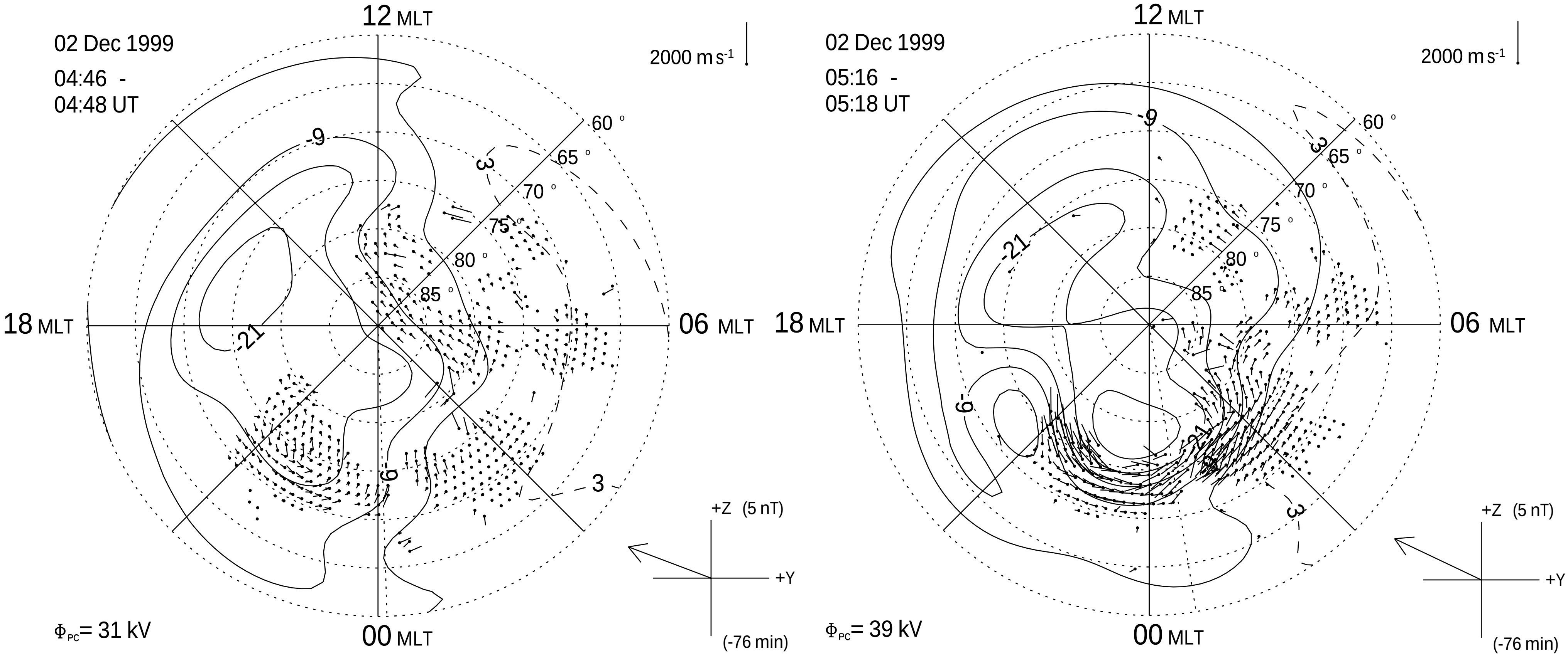
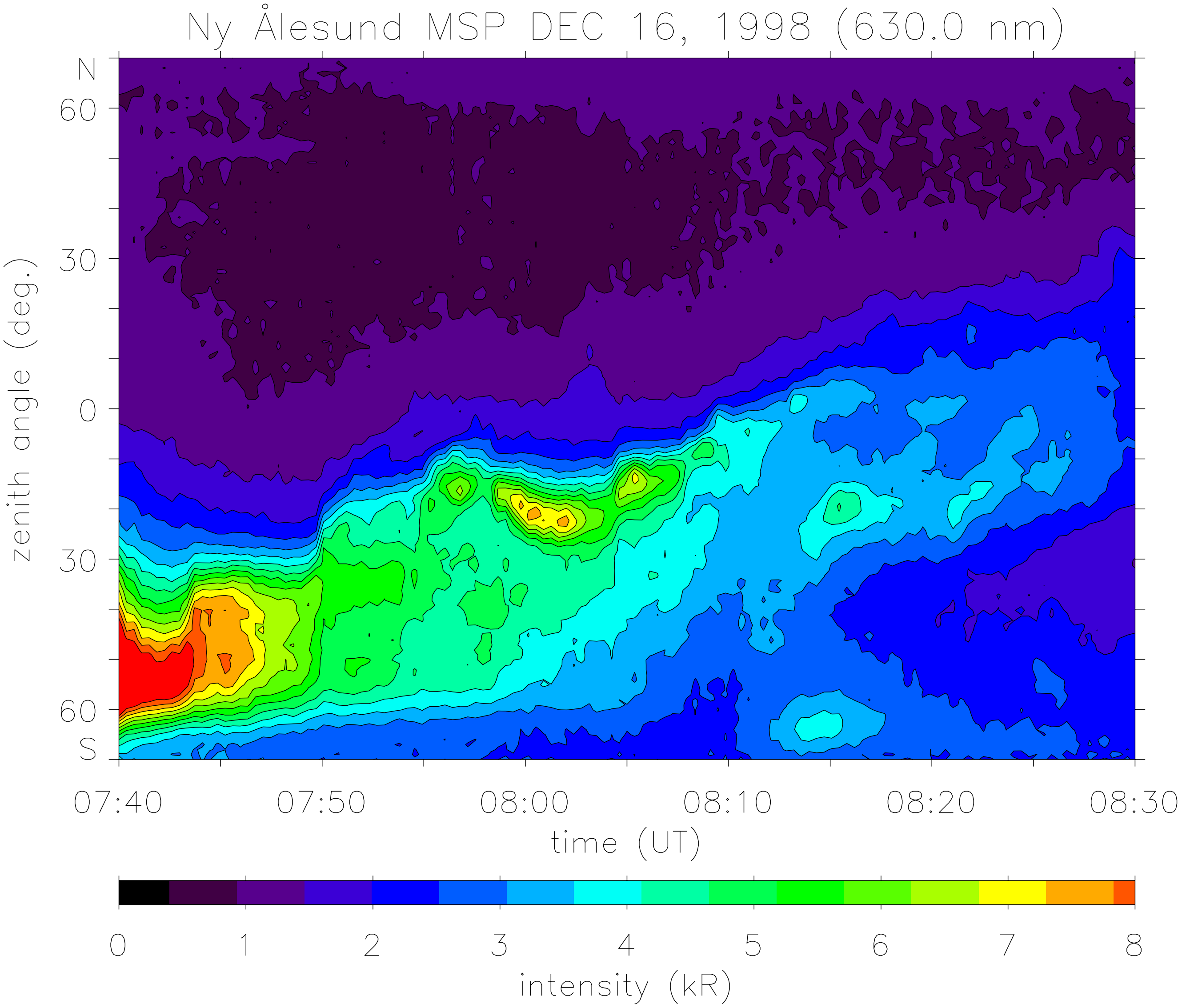
0
09⁴⁰
09⁵⁰
10⁰⁰
10¹⁰
10²⁰
10³⁰
10⁴⁰
UT


Ny Ålesund MSP NOV 30, 1997 (630.0 nm)
zenith angle (deg.)
N
60
30
0
30
60
S
11:20
11:25
11:30
11:35
11:40
11:45
11:50
time (UT)
0
1
2
3
4
5
6
7
8
9
10
intensity (kR)


12 MLT
18 MLT
00 MLT
1042 UT
1045 UT
1048 UT
1051 UT
Flux (photons cm^{-2} s^{-1})
60
55
50
45
40
35
Velocity (m s^{-1})
0
−500
−1000


02 Dec 1999
00:54:06 UT
(0054 - 0056 UT)
12 MLT
18 MLT
06 MLT
00 MLT
100 nT
2000 m/s
Φ_{PC}= 67 kV
60°
65°
70°
75°
80°
85°
-9
-21
-33
-27
-3
3
9
15
+Z (5 nT)
+Y
(-74 min)
Intensity (kR)
0
5
10
15
20


12 MLT
02 Dec 1999
04:46 -
04:48 UT
2000 m s-1
60 °
65 °
70 °
75 °
80 °
85 °
-9
-3
-21
18 MLT
06 MLT
-9
3
+Z (5 nT)
+Y
(-76 min)
ΦPC= 31 kV
00 MLT
12 MLT
02 Dec 1999
05:16 -
05:18 UT
2000 m s-1
60 °
65 °
70 °
75 °
80 °
85 °
-9
-3
-21
18 MLT
06 MLT
-9
-21
-3
+Z (5 nT)
+Y
(-76 min)
ΦPC= 39 kV
00 MLT



Ny Ålesund MSP DEC 16, 1998 (630.0 nm)