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► **To cite this version:**

M. Bouhram, B. Klecker, G. Paschmann, H. Rème, A. Blagau, et al.. Multipoint analysis of the spatio-temporal coherence of dayside O⁺ outflows with Cluster. *Annales Geophysicae*, 2004, 22 (7), pp.2507-2514. hal-00329343

HAL Id: hal-00329343

<https://hal.science/hal-00329343>

Submitted on 18 Jun 2008

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Multipoint analysis of the spatio-temporal coherence of dayside O^+ outflows with Cluster

M. Bouhram¹, B. Klecker¹, G. Paschmann¹, H. Rème², A. Bläggäu^{1,3}, L. Kistler⁴, P. Puhl-Quinn^{1,*}, and J.-A. Sauvaud²

¹Max-Planck-Institut für extraterrestrische Physik, D-85741 Garching, Germany

²CESR-CNRS, BP-4346, F-31028 Toulouse, France

³Space Science Institute, R-76911 Bucharest, Romania

⁴Space Science Center, University of New Hampshire, Durham, NH-03824, USA

*now at Space Science Center, University of New Hampshire, Durham, NH-03824, USA

Received: 30 September 2003 – Revised: 17 March 2004 – Accepted: 14 April 2004 – Published: 14 July 2004

Part of Special Issue “Spatio-temporal analysis and multipoint measurements in space”

Abstract. The spatial distribution of ionospheric ion outflow from the dayside cusp/cleft has previously been studied in great detail with numerous satellite missions, but only statistically. Between July and November 2001, the orbit configuration of the Cluster multi-satellite system close to its perigee (4 Earth radii) allows for delay times between spacecraft of about 4 and 35 min in crossing the cusp/cleft. This enables for the first time to assess the spatial and temporal coherence of O^+ ion outflow on time scales of the order of the satellite time lag. After presenting two contrasting events in detail, O^+ velocities and outflow intensities from three spacecraft, available on 18 events, all with a similar orbit, have been cross-correlated to quantify the degree of coherence in the outflow. The main result from the analysis is that, although dayside outflows are a permanent feature, steady-state conditions are surprisingly never achieved. In particular, a significant variability is found for convection drift and local outflow intensities on small time scales. This variability of local intensities is not found to depend on the total strength of the outflow, which is much more stable and increases with the dynamic solar wind pressure.

Key words. Ionosphere (Ionosphere-magnetosphere interactions) – Magnetospheric physics (Polar cap phenomena)

1 Introduction

Since the discovery of energetic O^+ ions at magnetospheric altitudes by Shelley et al. (1972), many satellite observations consistently demonstrated that the Earth's ionosphere acts as a significant source of magnetospheric plasma (Chappell et al., 1987; Hultqvist et al., 1999). Statistical studies from earlier satellite missions point out that the total mass supply is

of the order of 1 kg s^{-1} (Yau and André, 1997; Cully et al., 2003), while the largest fluxes of heavy ions originate from the dayside cusp and cleft regions (Lockwood et al., 1985; Thelin et al., 1990).

The source of free energy that powers the outflow is a combination of solar UV radiation and solar wind electromechanical energy. Long-term average ion outflow data by the DE-1, Polar and Akebono satellites (Yau et al., 1985, 1988; Peterson et al., 2001; Cully et al., 2003) revealed a good correlation between the total outflow rate and measurements of the solar and geomagnetic activity, as monitored by the daily $F_{10.7}$ and 3h K_p indexes, respectively. On the other hand, numerous case studies reported a good agreement between strong disturbances in the solar wind inputs, such as during the passage of an interplanetary shock associated with a coronal mass ejection, and a dramatic enhancement of the ionospheric outflowing ion fluxes (Moore et al., 1999; Strangeway et al., 2000; Fuselier et al., 2002). Recently, using a large database of ion observations from the Akebono satellite, Cully et al. (2003) found that three solar wind parameters are primarily responsible for controlling ion outflow rates: the solar wind pressure, the solar wind electric field and the variability in the interplanetary magnetic field (σ_{IMF}) in the one hour preceding. However, if the correlation between ion outflow and any set of solar wind and K_p level parameters is statistically well established, it is also low, as reported by Cully et al. (2003). Another recent study by Peterson et al. (2002) points out that when applying such empirical relations to observations with several satellites in shorter time and smaller spatial scales, the outflow rate can deviate enormously, by more than 3 orders of magnitude from the expected average value.

In the dayside auroral and polar regions, the outflow observed at high altitude is the result of a long chain of processes. In the ionosphere, uploading processes, such as Joule heating caused by the dissipation of the Pedersen currents

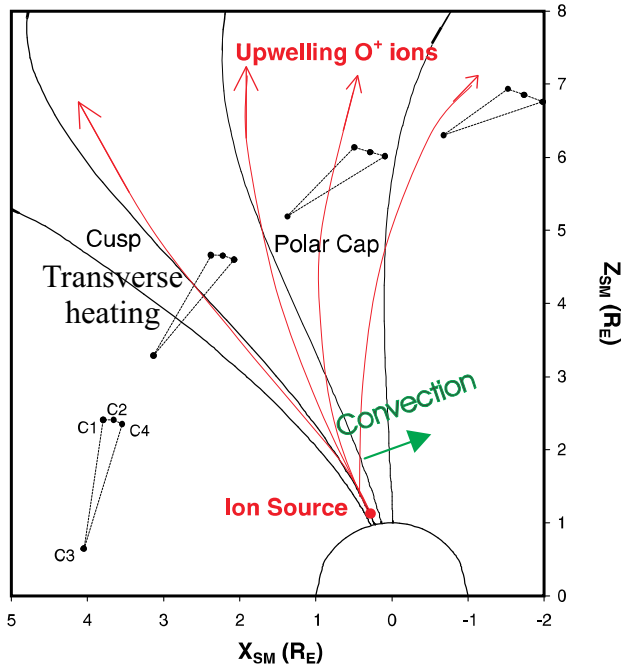


Fig. 1. Drawing of the Cluster orbit configuration in the dayside auroral and polar regions between July and November 2001.

and/or upward acceleration associated with soft electron precipitation (see, for example, Liu et al., 1995), raise the scale height of the ionospheric constituents so that heavy ions can reach higher altitudes where stronger energization mechanisms occur and lead to ion escape from the Earth's gravity. In the dayside cusp/cleft, the most dominant energization mechanism is transverse heating associated with enhancements in the broad-band extremely low-frequency (BBELF) wave activity (Lund et al., 2000). Higher up, ion transport is a combination of upward flow along the magnetospheric field lines via the mirror force and horizontal motion due to the magnetospheric convection, which depends highly on the IMF orientation (Weimer, 1995; Ruohoniemi and Greenwald, 1996). Hence, ions observed at any given point in the high latitude polar cap could originate from different source regions. Since all of these underlying physical processes responsible for non-thermal ion outflow are solar wind dependent, the variability in outflowing ion fluxes and energies can be easily understood as a direct reflection of small temporal and spatial scale processes associated with variations in the solar wind energy input. Unfortunately, since most of the previous studies were done from a single satellite, almost no information is currently available on simultaneous temporal and spatial coherence of ion outflow.

The purpose of this paper is to investigate the spatial and temporal coherence of the ion outflow observed on the Cluster multi-satellite system. The outline of the paper is as follows. In Sect. 2, we describe the instrumentation used in the present study and the satellite configuration. In Sect. 3, we summarize outflowing ion observations for two specific

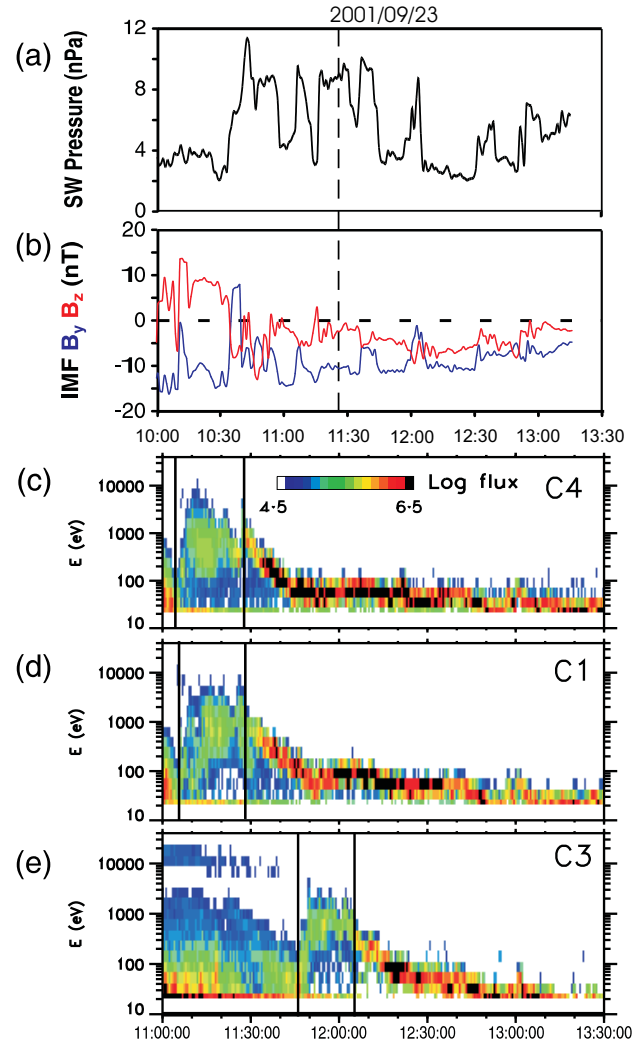


Fig. 2. Overview of an upflowing ion event on 23 September 2001. From top to bottom, (a) time evolution of the solar wind dynamic pressure; (b) time evolution of the IMF B_y (blue) and B_z (red) components; and (c), (d), (e), omnidirectional O⁺ flux measurements in $\text{Log}[\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}]$ aboard C4, C1 and C3, respectively. The dashed vertical line in Fig. 2a indicates the onset of O⁺ observations with Cluster.

events. In Sect. 4, we present the results of a statistical study where we cross correlate satellite data for 18 events in the high-latitude cusp/cleft and dayside polar cap. Finally, a summary of conclusions is given in Sect. 5.

2 Cluster configuration and instrumentation

The four identical Cluster satellites have an elliptical orbit ($4.0 \times 19.6 R_E$) with an inclination of 90° . Between July and November 2001, the Cluster fleet crossed the mid-altitude dayside cusp and polar cap regions close to their perigee with a large separation distance, as schematically shown in Fig. 1. Here, C4 is the leading satellite and C2, C1 and C3 are lagged with respect to C4 by about 2, 4 and 35 min, respectively.

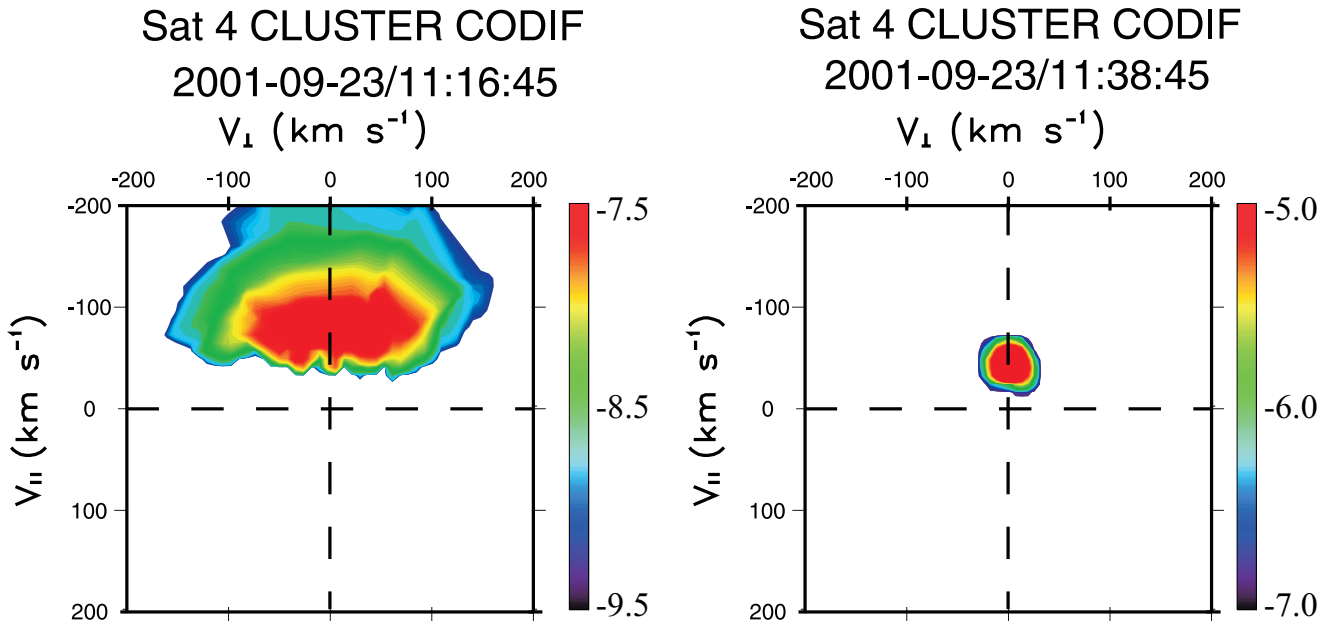


Fig. 3. Two-dimensional cuts in the V_{\perp} - V_{\parallel} plane of oxygen velocity distributions in $\text{Log}[\text{cm}^{-3} \text{km}^{-3} \text{s}^3]$ measured by C4 at 11:16:45 UT (left) and 11:38:45 UT (right) on 23 September 2001.

Three-dimensional (3-D) distributions of upflowing O⁺ ions were measured every spin period (4 s) over the energy range from 20 eV up to 40 keV by the COMposition and DIstribution Function (CODIF) analyser (Rème et al., 2001) aboard three satellites, C1, C3, and C4. In this study, in-flight convection measurements are available from the Electron Drift Instrument (EDI) (Paschmann et al., 2001) with a temporal resolution of 1 s aboard three satellites, C1, C2 and C3. Aboard C4, the convection drift may be inferred from O⁺ ion distributions measured by CODIF.

3 Examples of events

3.1 23 September 2001 case

Figure 2 shows an overview of solar wind parameters and O⁺ data on 23 September 2001. IMF and solar wind bulk parameters are available from the Advanced Composition Explorer (ACE), which is located in an orbit around the libration point L1, upstream of the magnetosphere ($\sim 220 R_E$). Therefore, we need to calculate the propagation time t_P for the solar wind to reach the magnetosphere and then to communicate in the ionosphere. Since ACE is located at a close separation distance $d_{\perp} \sim 20 R_E$ to L1, using the X distance method is more convenient. We use the same technique as in the work of Ridley et al. (1998). The maximum error associated with the X distance method is about $0.25 (\text{min}/R_E) \times d_{\perp}$ (Collier et al., 1998), which is equal to 5 min for our case studies. Cluster satellites are travelling in the Northern Hemisphere close to noon at invariant latitudes ranging from 72° up to

85° and at radial distances from 4.5 up to $6.5 R_E$, with a configuration according to the drawing in Fig. 1.

During this event, Cluster/CODIF detected strong O⁺ fluxes during a period of southward IMF and several solar wind pressure pulses (from 3 up to 12 nPa), mainly related to the solar wind density. For each Cluster satellite crossing, two distinct regions associated with different types of O⁺ distributions can be distinguished. Figures 3a and b show O⁺ velocity distributions measured by C4 inside these two regions. First, Cluster crosses a transverse heating region, limited by vertical lines in Fig. 2, as evidenced by a sudden increase in ion mean energies. Inside this region, the observation of an elevated conic (Fig. 3a) with a peak flux broadly extended in pitch angle and a significant upgoing bulk velocity indicates that transverse heating occurs over a broad altitude range as long as ions convect poleward through the region. Here, the characteristic energies and elevation angle of the conic depend on the strength of the heating averaged over the time of flight (typically a few minutes) of ions between the topside ionosphere and the satellite location. Poleward of the heating region, cold beam-like distributions at lower energies are observed along the satellite track (Fig. 3b). This picture can be explained by transverse heating in a region of finite latitudinal extent, followed by adiabatic convective flow to the satellite orbit (Horwitz, 1986; Dubouloz et al., 1998; Bouhram et al., 2003a,b). The latter stage also contributes to a velocity filter effect, as evidenced by the observation of latitude-energy dispersion in ion energy spectra.

Because O⁺ outflow is a permanent phenomenon over the dayside polar region, and in order to suppress satellite time lag effects, it is more convenient to compare satellite data in a spatial coordinate system. Because Cluster satellites have a

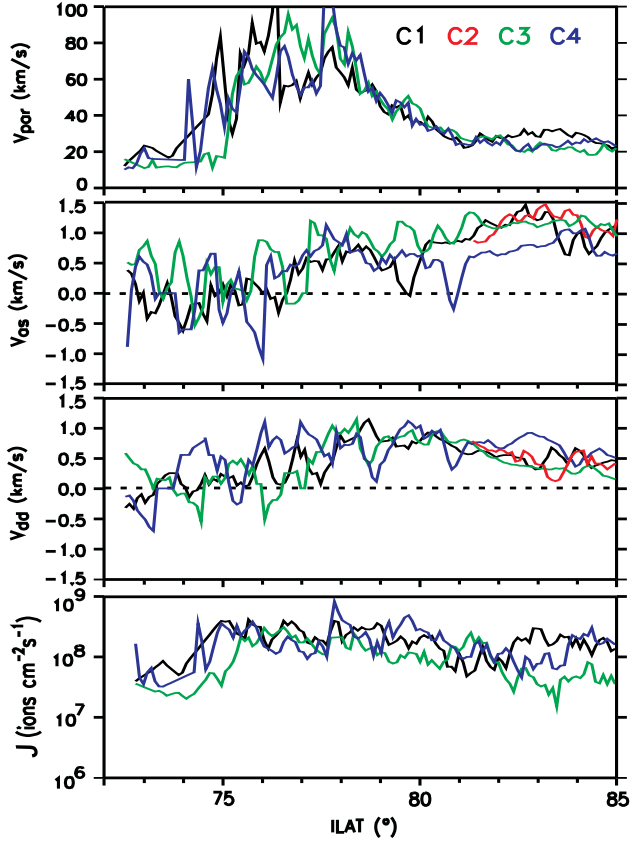


Fig. 4. From top to bottom, plots of the upward mean velocity, the antisunward and the dawn-dusk components of the ionospheric convection drift, and the integral upward flux as a function of invariant latitude on 23 September 2001. All quantities are averaged in latitudinal bins of 0.1° . The colours refer to C1 (black), C2 (red), C3 (green) and C4 (blue).

quasi-polar orbit and their separation in magnetic local time (MLT) is not significant (~ 0.02 h), we analyzed the data as a function of invariant latitude (ILAT). Figure 4 shows the evolution of different O⁺ moments and components of the ionospheric convection drift as a function of ILAT. In this kind of representation, identical structures observed by two satellites can be interpreted as stationary on time scales of the order of the satellite time lag. If these structures are different, it suggests that clear temporal changes occur on such time scales. For example, a slight change in the location or the intensity of the upward velocity peak may indicate a motion of the heating region or a change in its strength, respectively. Similarly, a change in the upward velocity dispersion may be interpreted by temporal changes in the global convection field. In the analysis, the Cluster orbit and convection velocities are projected in the topside ionosphere at 1000 km altitude using the Tsyganenko 96 magnetic field model (Tsyganenko, 1995), which depends on the B_y and B_z components of the IMF, the solar wind pressure and the disturbance storm-time (DST) index. This technique uses the relation $V_D = (E \times B) / B^2$ between the drift velocity V_D and the electric field E , and assumes that the magnetic field lines are

Table 1. List of rank correlation coefficients of invariant latitude series of upward velocity, convection drift and upward integral flux between C1 and C4, and between C1 and C3, on 23 September 2001. The last row indicates the corresponding flux variability.

Parameter	C1/C4	C1/C3
Upward mean velocity	0.85	0.74
Convection drift	0.36	0.67
Upward integral flux	0.47	0.37
Flux variability	2.8	6.0

equipotentials when mapping the electric field in the topside ionosphere. Then, the ionospheric convection drift has been decomposed into two components: an antisunward component, V_{as} (i.e. in the $X_{SM}-Z_{SM}$ plane) and a dawn-dusk component, V_{dd} (i.e. in the $Y_{SM}-Z_{SM}$ plane). We defined the integral upward flux by $J = n \times u_{\parallel} \times A$, where n and u_{\parallel} are the ion density and upward mean velocity, and $A \approx [B_i / B(r)]^{1/2}$ is the ratio of the cross-section areas of the magnetic flux tube between the topside ionosphere (i) and the point of observation r . The quantity J may be used as a proxy to investigate temporal changes associated with the ionospheric source of the outflow.

We remind the reader that the time lag τ_{14} between C1 and C4 is about 4 min, while the time lag τ_{13} between C1 and C3 is longer, about 35 min. Because the autocorrelation function of parameters associated with the outflow presumably falls down with increasing lag, we would expect a larger correlation between C1 and C4 than between C1 and C3. On the other hand, the time needed for each satellite to travel across the latitudinal range of interest is relatively long (about 90 min). Figure 4 shows that a similar behavior is observed for all quantities. However, because of systematic small differences, we see the direct evidence that the steady-state picture used to describe dayside ion outflows does not ideally exist. In particular, we can see that upward integral fluxes may differ locally by up to 1 order of magnitude. Table 1 shows the results of rank cross correlations of the spatially binned data from C4 and C3 with data from C1. As expected, cross correlation coefficients of data between C1 and C4 are higher than those of data between C1 and C3. We also defined an average local variability in ion fluxes between two Cluster satellites C_m and C_n by $\sigma[\text{Log}(J_{mn})] = \langle |\text{Log}(J_m / J_n)| \rangle$, where J_m and J_n are the integral upward flux profiles as a function of invariant latitude. Hence, we can see that fluxes differ on average by about a factor of 3 between C1 and C4, and 6 between C1 and C3.

3.2 14 August 2001 case

Figure 5 shows an overview of solar wind parameters and O⁺ data on 14 August 2001. Cluster travels close to noon with the same orbit as for the first event during a period following

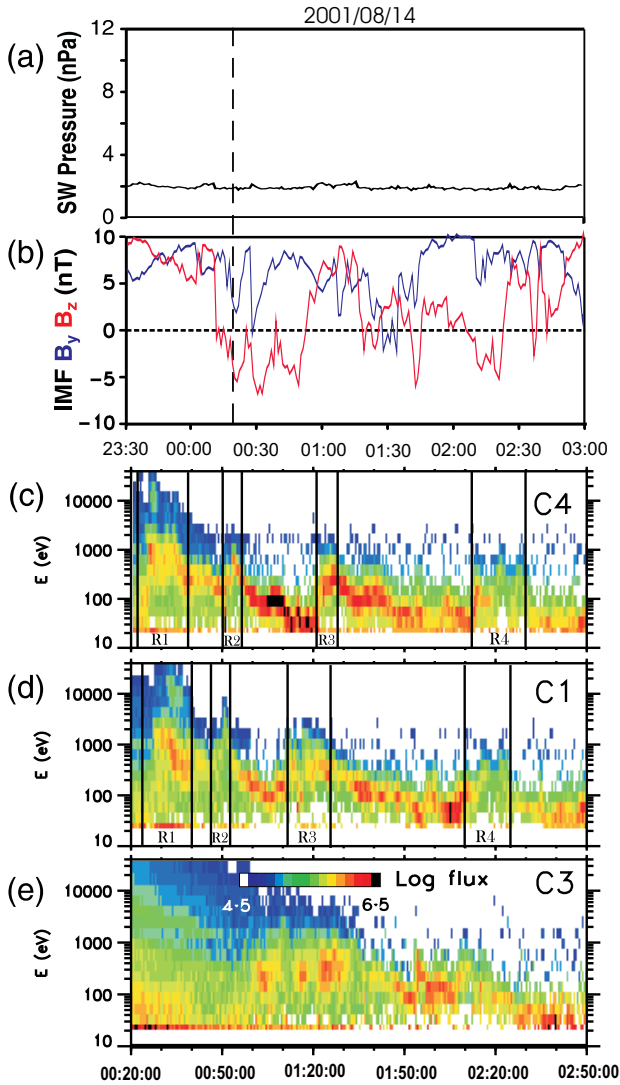


Fig. 5. Overview of an upflowing ion event on 14 August 2001. The format is the same as that in Fig. 2.

several turnings of the IMF B_z component, and steady solar wind bulk parameters (pressure ~ 2 nPa). In contrast to the previous event, one counterintuitive feature on the three energy spectra is the observation of multiple sudden increases in the mean energy, each of them followed by latitude-energy dispersions. Plots in the velocity phase space of both O⁺ and H⁺ distributions indicate that these structures are associated with multiple transverse ion energization regions and are also accompanied by protons injections from the magnetosheath (not shown). In a rough visual comparison, we can identify four such regions on C1 and C4, labeled R1 through R4 and limited by vertical lines in Fig. 5. Note that later, on C3, only two structures are observed, a first one between 1:00 and 1:30 UT and another one between 2:00 and 2:20 UT.

To investigate the consistency of the features observed by the three spacecraft for this event, we have plotted in Fig. 6 different ion moments as a function of ILAT in the same format as in Fig. 4. We also indicated with color bars the lo-

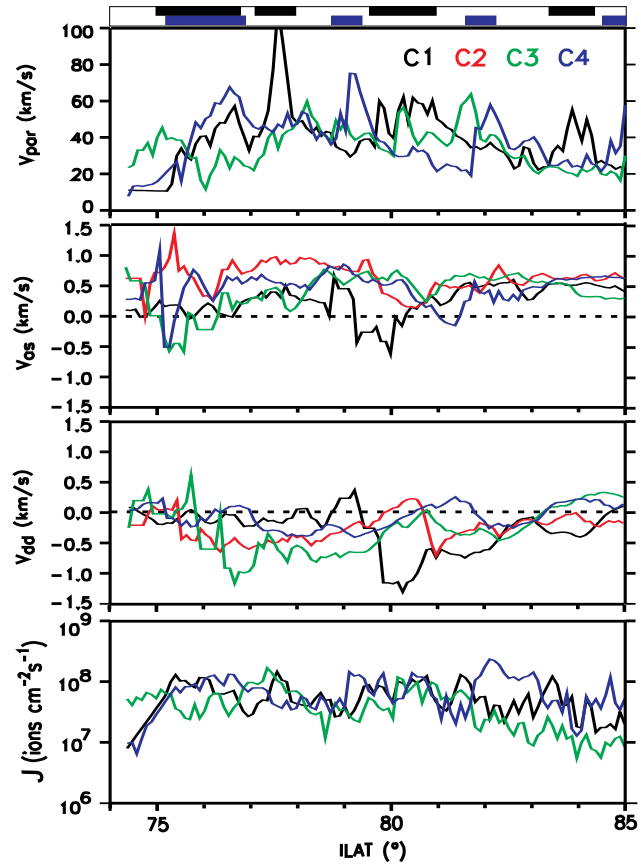


Fig. 6. Plots of particle moments as a function of invariant latitude on 14 August 2001. The format is the same as that in Fig. 4.

Table 2. List of rank correlation coefficients of invariant latitude series of upward velocity, convection drift and upward integral flux between C1 and C4, and between C1 and C3, on 14 August 2001. The last row indicates the corresponding flux variability.

Parameter	C1/C4	C1/C3
Upward mean velocity	0.29	0.26
Convection drift	-0.18	-0.10
Upward integral flux	0.24	0.31
Flux variability	3.4	4.4

cation in ILAT of the multiple acceleration regions observed on C1 and C4. While C1 and C4 detected the heating region R1 at approximately the same location with similar upward velocities and fluxes, the next three other structures are observed at very different locations by both satellites. This result, along with the presence of substantial differences in the upward velocities, make it difficult to definitely state whether structures R2 through R4 observed by C1 are moving, with temporal variations in ion heating, and are observed

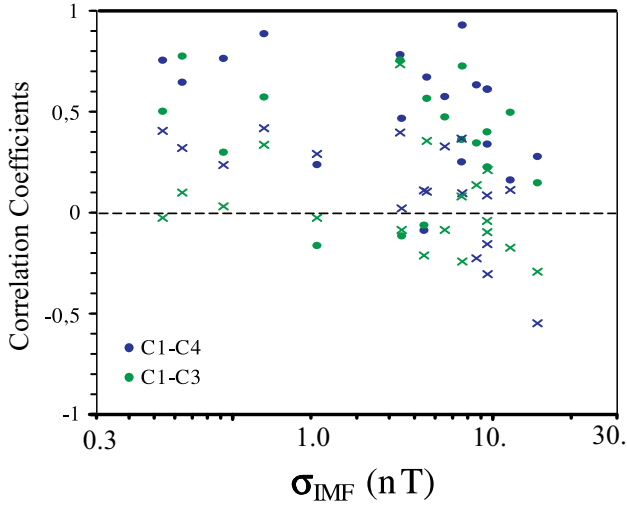


Fig. 7. Comparison between the C1-C4 (blue) and C1-C3 (green) cross correlation coefficients of the upward mean velocity (filled circles) and the ionospheric convection drift (crosses) as a function of the IMF variability in nT.

at different locations by C4, or all of these structures correspond to sporadic (of short duration), small-scale energization regions. This would require the use of additional instruments, which is beyond the scope of the paper. On the other hand, we may note from large differences between C1 and C3 that the structures of O⁺ energization and outflow are highly variable on a time scale of 35 minutes. Note that for this event, the variability in ion fluxes is also higher than for the first event. Table 2 shows the corresponding cross correlation coefficients computed over the full ILAT range in the same format as those in Table 1. Hence, we can see that cross correlations are very poor, in particular between C1 and C4 (e.g. for short time lags).

4 Statistical analysis

The purpose of this section is to quantify the coherence in outflowing ion features. An analysis similar to the previous two examples was done selecting 18 polar cap events (i.e. 54 satellite passes) in the Northern Hemisphere between 10:00 and 14:00 MLT.

Figure 7 shows the results of cross correlations of data from C4 and C3 with data from C1, as a function of the IMF variability σ_{IMF} . Here, let us note that for 70% of events associated with highly variable (mainly B_z) IMF conditions, multiple energization regions similar to those of the 14 August 2001 event were observed. In contrast, other cases, including the 23 September 2001 event, associated with relatively stable IMF conditions, exhibited the classical signature of a single energization region followed by a regular latitude-energy dispersion. Such results are at least consistent with the fact that the IMF B_z component controls the location and latitudinal motion of the cusp (see, for example, Yeoman et

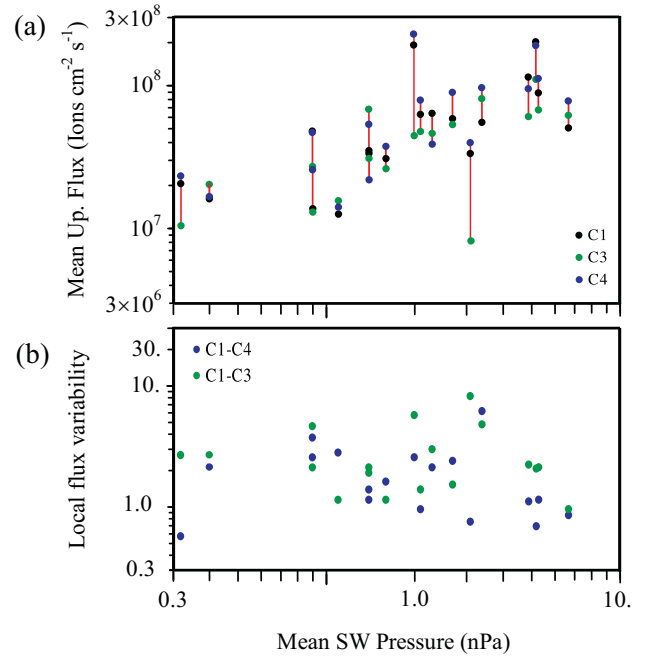


Fig. 8. Scatterplots of (a) the average integral upward fluxes measured on C1 (black), C3 (green) and C4 (blue), and (b) local flux variability between C1 and C4 (blue rounds), and between C1 and C3 (green rounds), as a function of the mean solar wind pressure.

al., 2001). Because the C1/C4 time lag $\tau_{14}=4$ min is significantly lower than typical times of flight of ions and the C1/C3 time lag $\tau_{13}=35$ min, the correlation in the upward velocity is on average better between C1 and C4 than between C1 and C3. This is not the case for the convection drift, where correlation coefficients are comparable in both cases and often close to zero, which indicates that observations are likely uncorrelated. This implies that the correlation time length of the convection field is possibly lower than the minimum satellite time lag τ_{14} , and therefore smaller than the mean time of flight of ions. However, this is not surprising since it is known that dayside convection patterns respond rapidly to changes in the IMF (Ridley et al., 1998; Khan and Cowley, 1999), particularly on time scales comparable to τ_{14} . In short, it is found that the correlation between satellites, is on average higher for the upward velocity than for the convection drift. Note also in Fig. 7 that correlation coefficients of the upward velocity ILAT series follow the same behavior versus σ_{IMF} as those for the convection drift ILAT series. Poleward of the heating region, the latitude-velocity dispersion usually observed is related to time of flight effects: for each ionospheric flux tube, the corresponding latitudinal motion depends on the convection drift averaged over its time history. Therefore, the correlation in the convection drift is partly reflected in the correlation in the upward velocity.

Figure 8 shows results of the integral upward flux, averaged in ILAT on C1, C3 and C4, and the average local upward flux variability, as defined in Sect. 3. The results

are plotted as a function of the mean solar wind pressure $\langle P_{SW} \rangle$. Note here that the solar wind pressure is relatively steady for 70% of the cases, which are associated with a low mean pressure (<3 nPa). According to recent statistical results (Cully et al., 2003), outflow intensities globally increase versus $\langle P_{SW} \rangle$. In Fig. 8a, fluxes differ globally by about a factor of 2 and 5, when comparing C1 and C4 data, and C1 and C3 data, respectively. In Fig. 8b, fluxes differ locally on average by about a factor of 5 and 10, when comparing C1 and C4 data, and C1 and C3 data, respectively. Comparison between the local and global variability in ion fluxes suggests that small-scale processes are responsible for a non-negligible variability in O⁺ measurements, at least for time scales smaller or of the order of 30 min. Surprisingly, the local variability in ion fluxes does not depend on $\langle P_{SW} \rangle$, or on the strength of the outflow. This result is at least compatible with previous reports based on multiple satellite passes and showing that the outflow response is prompt, and strong fluxes are continuously observed on high spatial and temporal scales under strong solar wind pressure pulses (Moore et al., 1999; Strangeway et al., 2000).

5 Summary and conclusions

Combining the observations of several Cluster satellites enabled us to assess the spatial and temporal coherence of ion outflow of ionospheric origin from the dayside cusp/cleft. Although non-thermal O⁺ ions are well known to be a permanent feature in the dayside cusp/cleft and polar cap, our multi-point observations show the first direct evidence of non-stationary processes in their transport. In particular, the main findings may be summarized as follows:

(1) O⁺ ion outflows are surprisingly temporally variable. Comparison of O⁺ moments at a given location indicates that ion fluxes may vary significantly on a time scale of a few minutes.

(2) Convection electric fields vary on a time scale that is much faster than the time of flight of ions to reach Cluster perigee altitudes in the dayside polar cap (3.5 to 6.5 R_E). However, upflowing velocities of ions are better correlated between satellites as they depend on the convection field averaged over their time of flight.

(3) Although there is a large variability in local fluxes, no dependence on the total strength is found. Indeed, the global outflow rate is much more stable and depends mainly on the dynamic solar wind pressure, which is in agreement with recent studies (Cully et al., 2003).

(4) This leads to the point that steady-state conditions are never achieved for processes responsible of dayside ion outflow on a time scale of about 30 min.

As already mentioned in Sect. 1, there are several processes which act in the history of the observed flux tubes. Such processes include motion of the ionospheric source region, spatio-temporal variations in the extraction processes in the ionosphere or in the transverse energization in the cusp/cleft, and changes in the convection patterns. Note that

the lack of coherence in this later process may affect not only the horizontal transport, but possibly the ion dynamics along the field lines by means of parallel energization via centrifugal acceleration. Unfortunately, due to the long time of flight of ions to reach Cluster from the ionosphere, a higher number of multipoint measurements or alternatively, an extension of the study in two dimensions (ILAT-MLT), along with ion transport modeling studies, would be needed in order to deconvolve the contribution of all the underlying processes to the variability observed by Cluster/CODIF.

The lack of good coherence in fluxes on time scales of a few minutes and small spatial scales may be critical in terms of mass transport modeling through the magnetospheric system. Indeed, variations in the mass density have the largest geophysical consequences in regions where the magnetic field is relatively weak, e.g. in the plasma sheet and magnetotail region where the magnetic and kinetic pressure are of the same order of magnitude. Hence, the next step would be to understand and quantify the impact of the mass flux variability on the magnetosphere dynamics.

Acknowledgements. We are grateful to the technical and scientific personnel at MPE, Garching; CESR, Toulouse, UNH, Durham; IFSI, Frascati; IRF, Kiruna; MPA, Lindau; UCB, Berkeley; and UW, Seattle; who made the development of the CIS instrument possible. The work at MPE in Garching is supported by DLR (Deutsches Zentrum für Luft und Raumfahrt) under contract 50 OC 0102. We thank the ACE SWEPAM and ACE MAG instrument teams, and the ACE Science Center for providing the ACE data.

Topical Editor T. Pulkkinen thanks C. Cully for his help in evaluating this paper.

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