Cluster observations of energetic ionospheric ion beams in the auroral region: Acceleration and associated energy-dispersed precipitation

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[1] This paper presents a detailed study of the Feb. 14, 2001 Cluster northern auroral pass at mid-altitudes (4–5 R_E), characterized by observations of a series of energy-dispersed ion structures in a region of poleward convection. In contradiction with one current view, that ions populating these energy-dispersed signatures originate sporadically in the magnetotail, Cluster directly observed energetic (0.2–15 keV), field-aligned H^+ ions of ionospheric origin. The ions were ejected at the top of a steady auroral acceleration region near 72.5° ILAT, then bounced on closed field-lines, and were finally dispersed poleward in latitude by the $\mathbf{E} \times \mathbf{B}$ drift effect. Simple but realistic latitudinal drift computations demonstrate that the anticipated location of successive bouncing echoes coincides rather well with the Cluster observations. Best agreement is reached when the particles are further accelerated (presumably nonadiabatically) by 1–2 keV, as they periodically cross the tail neutral sheet. **Citation:** Bosqued, J. M., et al. (2006), Cluster observations of energetic ionospheric ion beams in the auroral region: Acceleration and associated energy-dispersed precipitation, *Geophys. Res. Lett.*, *33*, L12102, doi:10.1029/2006GL025708.

1. Introduction

[2] Since their original detection at geosynchronous orbit by ATS [*Quinn and McIlwain*, 1979] and, later, in the low altitude nightside auroral region by the DE 1-2 spacecraft [*Winningham et al.*, 1984] and Aureol-3 spacecraft [*Bosqued et al.*, 1986a], energy-dispersed ion structures have been considered as basic signatures that remotely provide invaluable information about acceleration and transport processes in the near or distant magnetosphere. More recently, numerous types of dispersed bands were also observed at mid-lower altitudes by Akebono [*Hirahara et al.*, 1996] and Interball [*Sauvaud and Kovrazhkin*, 2004], and at the near-Earth equatorial plane (~10 R_E) by Geotail [*Kazama and Mukai*, 2003, 2005]. Most, if not all, of these events were interpreted in terms of time of flight effects, and assumed the ions originated in the equatorial magnetotail. An ionospheric origin has received considerably less attention. However, *Bosqued et al.* [1986a] interpreted energy-dispersed ion structures as signatures of bouncing ions being ejected from an ionospheric source and subsequently dispersed in space (latitude) by the $\mathbf{E} \times \mathbf{B}$ drift effect (magnetospheric "filter"). This study was the first to establish the correlation between each ion structure and an observed electron inverted-V that was the signature of field-aligned acceleration. At higher altitudes (7400–9600 km), *Hirahara et al.* [1996, 1997] interpreted Akebono observations of overlapped energy-dispersed bands as resulting from strong azimuthal drift effects acting on bouncing ionospheric beams.

[3] This paper presents a unique and exciting example of multiple energy-dispersed structures observed by the CIS instrument on February 14, 2001, when the Cluster spacecraft crossed the nightside auroral oval at an altitude of ~4.5 R_E. This event illustrates how a multiple spacecraft, well-instrumented mission, like Cluster, can help in clarifying the space vs. time ambiguities that continue to hinder the interpretation of such dispersed structures.

[4] This paper includes in Section 2 a brief description of the orbit, instruments, and the convection pattern produced by the SuperDarn radar chain. Section 3 presents a survey of the Cluster multi-instrument data provided by SC1 and SC3. A quantitative model of the expected energy-latitude bouncing echoes is compared to ion observations in Section 4. Finally, Section 5 discusses various aspects of the generation of energy-dispersed structures observed during this event.

2. Cluster Orbit and Instrumentation

[5] The four identical Cluster spacecraft mission move along an elliptical orbit with a perigee of 4 R_E, an apogee of 19.6 R_E, a period of ~58 h, and an inclination of 90°. When the apogee is in the dayside, the Cluster spacecraft successively cross the southern and northern auroral regions at an altitude of R = 4–5 R_E in a specific configuration: the spacecraft are strung out in a line, with SC1 in the lead, followed by SC3 and SC2, and finally by SC4. For the present event the s/c orbits were along the 1.3–1.5H MLT meridian.

[6] This paper uses particle data provided by the Cluster Ion Spectrometers, CIS, fully described by *Rème et al.*

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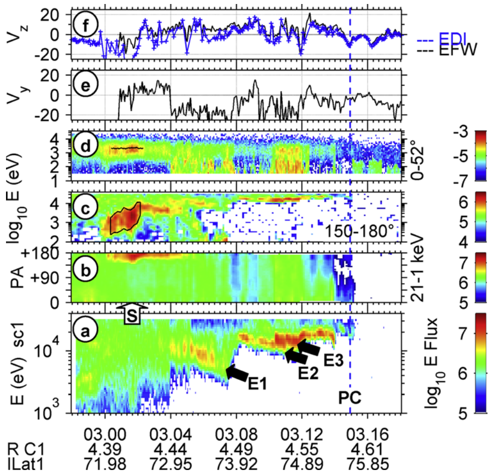

Figure 1. Cluster/SC1 data. From bottom to top: (a) CIS-2 high-resolution 1D energy-time spectrogram (integrated over 4π sr.); (b) CIS-2 pitch angle distribution for ions from 1 to 21 keV; (c) CIS-2 energy-time spectrogram for upflowing ions (pitch angle range: 150–180°); (d) PEACE/HEEA energy-time spectrogram for downward moving electrons (pitch angle range: 0–52°); (e) EFW-V_y *gse* component of the local E × B drift (km/s); (f) EFW-V_z *gse* component; the V_z component measured by the EDI instrument is also plotted. Flux units are: ergs/cm^2.s.sr.eV for electrons, keV/cm^2.s.keV (Figure 1a), and keV/cm^2.sr.s.keV (Figures 1b and 1c), for ions. Spacecraft altitude R (R_E) and invariant latitude (ILAT) are given at the bottom.

[2001], and the Plasma Electron and Current Experiment, PEACE, by *Johnstone et al.* [1997]. Magnetic field data come from the Flux Gate Magnetometer, FGM [*Balogh et al.*, 2001], the electric field data from the Electric Field and Wave (EFW) instrument [*Gustafsson et al.*, 2001], and the drift velocity from the Electron Drift (EDI) Instrument [*Paschmann et al.*, 2001]. This study examines data from spacecraft SC1 and SC3.

[7] This event occurred during a quiet period (AE ∼250 nT) and, at the foot of the Cluster field lines (south-west Greenland), the ionospheric convection pattern measured by the Stokkseyri and Goose Bay SuperDARN coherent HF radars (not shown) was characterized by the formation of a localized vortex, with a poleward/eastward convection of the order of 0.5 km/s at high latitude.

3. Experimental Data

[8] Figure 1 shows the SC1 data obtained on Feb 14, 2001, between 0258 UT and 0318 UT; the spacecraft is moving poleward from the Central Plasma Sheet (CPS) and crosses the polar cap boundary at ∼0315:17 UT (∼75.68° ILAT, labeled PC). The first basic observation is presented in Figure 1a: a series of energy-decreasing ramps is evident in this high resolution spectrogram from 0304 UT (∼73° ILAT) up to 0314 UT (∼75.3° ILAT), with variable energy-time (or latitude) slopes. Three successive signatures can be easily identified (labeled E1 to E3) covering a variable energy range, ∼15–4 keV for E1, ∼20–10 keV for E2. Even one or two additional dispersed features could be added between 0312 and 0314 UT, but VDIS structures typical of the PSBL [*Bosqued et al.*, 1993] are not identified.

[9] The second basic result is revealed by the 3D ion spectrogram of upflowing, field-aligned ions (UFIs), for the pitch angle range 150–180° (Figure 1c) and the pitch angle distribution (Figure 1b). Between ∼0300 UT and ∼0304 UT, SC1/CIS-2 detected the presence of an intense, highly collimated, upward flowing ion flux, with wide peak energy, ranging from ≤1 to ∼10 keV, or even higher in the center (∼0302 UT, ∼72.4° ILAT, labeled S) of the ion inverted-V structure. SC1 was crossing the top of the auroral acceleration region and ionospheric ions were mostly accelerated by a parallel electric field distributed below the spacecraft. Although the CIS-1 instruments were set off on SC1 and SC3, the CIS1 data for SC4 (not shown) indicated that H^+ was dominant, both for the UFI event ($n(O^+)/n(H^+) \leq 0.2$) and the dispersed structures ($n(O^+) \ll n(H^+)$).

[10] The electron spectrogram (Figure 1d) shows an intense precipitation signature centered at 0302 UT (Figure 1d), characterized by a peak in the downward directed electron energy flux around 1–3 keV. A parallel potential drop was also present above the spacecraft's altitude, so that the already-accelerated ionospheric H^+ ions observed by SC1 probably left the ionosphere after an additional acceleration of 1–3 kV. The acceleration region was relatively narrow in latitude, ∼0.5–1° ILAT, that is, similar to inverted-V structures observed at low altitudes [*Bosqued et al.*, 1986b].

[11] Figure 1f gives the V_z component of the convection, deduced from the electric field measured by EFW, together with the direct measurement provided by EDI. The most noticeable point is that the convection was predominantly poleward (and dawnward, see Figure 1e) during the observation of energy-dispersed structures, $\langle V_z \rangle \sim 4–5$ km/s, and $\langle V_y \rangle \sim -10$ km/s, in agreement with SuperDARN detection of a localized vortex with high-latitude convection part directed poleward/dawnward as well.

[12] Using the same format, Figure 2 shows the SC3 data. It is important to note that SC3 and SC1 are separated by ∼90–100 s (or ∼0.4° ILAT). Although all the detailed patterns encountered by SC1 and SC3 nearly look identical, all SC3 observations are shifted in time. This shift appears to be less than 90 s, ∼20–40 s, but is nevertheless significant. Figures 1b and 2b indicate that the UFIs were observed by SC1 between 0300:00 and 0304:40 UT, and later by SC3, between

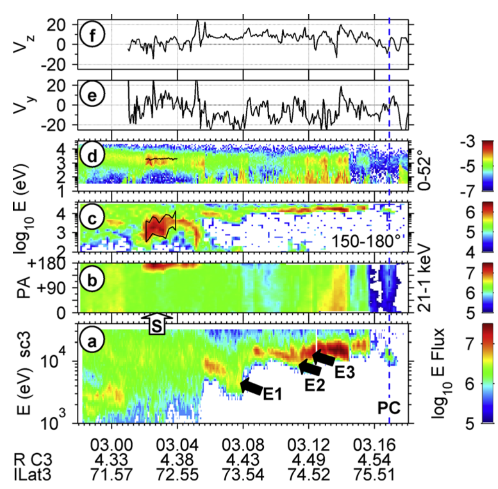

Figure 2. Same as Figure 1 but for Cluster/SC3 data.

0301:50 and 0305:20 UT. This shift indicates that the UFIs were continuously observed at about the same latitude range. Note additional observations by SC2 of the intense electron inverted-V at ~0306:20 UT (~72.6°), and by SC4 of the UFIs at 0304–0307 UT (~71.8–72.6° ILAT).

[13] To summarize, Cluster data demonstrate the existence of a local potential source of energetic H^+ UFIs, first observed by SC1 at ~0300 UT, and was still seen by SC4 at 0307 UT. Moreover, a time delay between the SC1 and SC3 observations have decisive implications as far as the dispersing mechanism is concerned.

4. Modeling of Successive Bouncing Echoes

[14] In this part, we quantitatively investigate the hypothesis that the upflowing ionospheric H^+ ions observed to be continuously ejected from a well-localized region (~72–72.8° ILAT) were the source of the multiple energy-dispersed structures observed (poleward) by Cluster. Very intense fluxes of energetic 1–15 keV H^+ ions are injected on closed field lines and start their bounce motion and their **E** × **B** drift motion. Part of the ions will mirror in the conjugate hemisphere to return back to the northern hemisphere, in a new energy-dependent position. As the **E** × **B** convection is directed poleward/eastward (or tailward/dawnward in the equatorial plane), the successive echoes are expected to be located poleward and eastward of the original source. When crossed at a given MLT by a poleward moving spacecraft, these latitude–longitude energy–dependent regions (echoes) will appear as multiple latitude–energy dispersed signatures.

[15] This hypothesis can be checked by using a very simple model. The latitudinal drift $\Lambda_n(V_n) - \Lambda_0$ after n full bounces will depend on: (*i*) the poleward convection component $v_p(n)$ at ionospheric altitude, averaged over the duration of the bounce n, (*ii*) of the basic field-line half-length l, assuming north-south symmetry, (*iii*) the increment dl of this length during each half-bounce, and (*iv*) a velocity increase ΔV_n at each neutral sheet crossing. Here we do not attempt to reach a precise evaluation of this gain in energy (velocity), which presumably results from nonadiabatic acceleration. For ions that are ejected from the ionosphere at latitude Λ_o and velocity V_o, for three consecutive bounces we will respectively assume that $V_1 = V_o + 2\Delta V_1$, $V_2 = V_1 + 2\Delta V_2$, and $V_3 = V_2 + 2\Delta V_3$, with $\Delta V_1, \Delta V_2, \Delta V_3 \ll V_o$. The relation of $\Lambda_n(V_n) - \Lambda_0$ and the ion velocity V_n, as measured at the echo n, is given by:

$$\Lambda_n(V_n) - \Lambda_0 \propto \sum_n \frac{4.v_p(n).l}{V_n} \left\{ \left[1 + \left(2n - \frac{3}{2}\right).\frac{dl}{l}\right] + \left[1 + \left(2n - \frac{7}{4}\right).\frac{dl}{l}\right] \frac{\Delta V_n}{V_n} \right\} \quad (1)$$

[16] In the simplest case, when $dl = 0$, with $\Delta V_1 = \Delta V_2 = \Delta V_3 = 0$ and $v_p(1) = v_p(2) = v_p(3) = v_p$, the dispersion in latitude, $\Lambda_n(V_o) - \Lambda_o \propto (nv_pl)/V_o$, is directly proportional to $1/V_o$ and depends on the product $v_p.l$. Correcting terms related to the length increment, dl, will change the bouncing times by small factors. For $dl/l \sim 1.4/22 \sim 0.06$, the correction is of the order of 1.03, 1.15, and 1.28, respectively for the three bounces. Even if not negligible, particularly for higher (>2) bounces, that is, ~1 min in time (or ~0.4° in latitude), here we examine only the simplest case $dl = 0$.

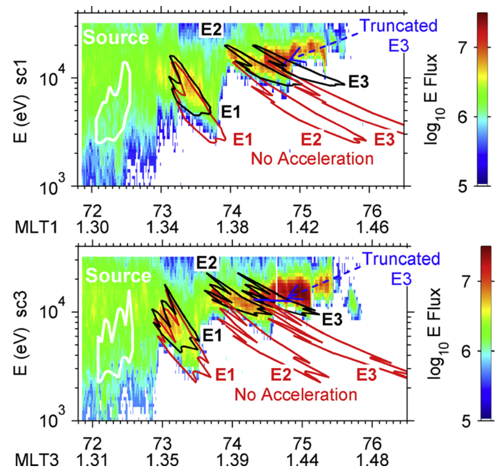

Figure 3. Computed energy-latitude contours superimposed on the 1D ion spectrogram: (top) SC1 and (bottom) SC3. The white contour is the ionospheric source after 1–3 keV additional acceleration above and close to Cluster, the red and black contours are its drifted echoes E1, E2, E3, calculated respectively without and with neutral sheet acceleration jumps.

[17] To determine where the ionospheric upflowing ions will precipitate after 1, 2, or 3 bounces, we use the full, not oversimplified, expression giving $\Lambda_n(V_p)$, and taking into account the s/c altitude (~4.5 R_E); results are displayed in Figure 3, now in an energy-latitude format. For SC1 and SC3 the "source" is defined in two steps: (a) a given energy flux contour is defined in the spectrogram of upflowing ions (Figures 1c and 2c); (b) it is assumed that the ions will gain additional energy through the part of the potential drop present above the s/c. The peak energy of the electron precipitation (1–3 keV) gives a correct estimate of acceleration (defined by black line in Figures 1d and 2d). The resulting energy- shifted ion contour is used as the initial ion source at ~4.5 R_E altitude (Figure 3, top: SC1, bottom: SC3). The source position was chosen similar for the two spacecraft (72.06–72.59° ILAT), and the ions are assumed traveling on closed field lines of constant length, evaluated to be l = 26 R_E from the T-01 model [*Tsyganenko*, 2002]. Three averaged values of the measured poleward convection, corresponding to each of three bounces, were introduced and mapped to the ionosphere: $v_p(1) = 0.45$, $v_p(2) = 0.50$, $v_p(3) = 0.27$ km/s for SC1, and $v_p(1) = 0.36$, $v_p(2) = 0.40$, $v_p(3) = 0.32$ km/s for SC3. For each bounce n the "free" parameter used to adjust the best agreement between the computed contour and the data is the discrete velocity step ΔV_n, presumably located in the neutral sheet. For bounces 1, 2, 3, the "best" energy steps are 1, 2, 0 keV for SC1, and 1, 2.5, 0 keV for SC3.

[18] Figure 3 shows the adiabatic $\Delta V_1 = \Delta V_2 = \Delta V_3 = 0$ contours (in red) and the final E1, E2, E3 contours (in black). The comparison with the observed structures gives the clearest possible validation of the hypothesis behind this simple model: the first two echoes (E1, E2) are remarkably well reproduced when 1–2 keV acceleration was added each time the ion crossed the neutral sheet. For the second echo (E2), the additional acceleration drastically reduced the latitudinal dispersion. Interpretation of the E3 echo is more complicated; while the observed energy-dispersed feature is

concentrated around 74.5–74.8° for SC1, the computed E3 extends up to 75.6° ILAT. Here the non-negligible azimuthal drifts must be considered if the source has a finite MLT extent. For $V_y \sim -8$ km/s at Cluster, if the westward extent is limited to 1.2H MLT, only the high-energy part of the E3 contour (truncated at the blue line) can be detected, in better agreement with the data.

5. Discussion and Summary

[19] This unique event presented a number of interesting features that can be summarized as follows:

[20] (a) on the same pass, three Cluster spacecraft unambiguously identified, first a very intense and well-localized ionospheric source of highly-collimated upgoing H^+ ions, active for at least 4–5 minutes, and then a series of energy-dispersed H^+ ion bands;

[21] (b) the **E** × **B** drift measured both by Cluster and SuperDARN was unexpectedly poleward, corresponding to a part of a local vortex.

[22] A simple analysis shows that the poleward-moving spacecraft detected up to three echoes, corresponding to three full bounces, implying rather steady conditions in the magnetotail. Thus the relation between an observed ionospheric ion source and the related multiple energy-latitude dispersed signatures is directly and quantitatively validated, through a rather specific poleward **E** × **B** velocity filtering. Similar observations by two Cluster spacecraft at the same latitude, but not at the same time, lends credit to a spatial interpretation of this event, rather than validating the impulsive model suggested by *Keiling et al.* [2004].

[23] The angle-integrated (nearly isotropic) E1 flux detected by SC1 is $\sim 7 \times 10^6$ keV/cm^2.s.keV at 0305:41 UT (E ~ 9 keV, Figure 1c). It is crucial to check whether the collimated source can supply such an ion flux: at 0301:38 UT, the collimated source flux (at E ~ 2.5 keV) peaks at $\sim 2 \times 10^6$ keV/cm^2.s.keV. The initially supplied energy flux translates to $\sim 10^7$ keV/cm^2.s.keV if the source ions are accelerated from 2.5 keV to the 9 keV observed for E1. This crude evaluation shows that the ionospheric source is sufficient to supply the echo fluxes, even if losses along the bouncing orbits are taken into account. Here it must be stressed that ions detected in the echoes probably do not originate neither at the exact place cut by the s/c, nor at the exact time when the s/c crosses the source.

[24] Data indicates the source is active for many minutes, but time and space variations in the source must be highly probable. On the other hand, energy changes in the source must be insufficient to account for the energy jumps between successive echoes. The best agreement between observed and computed echoes is reached when further periodic acceleration is applied when the ions cross the neutral sheet. When drifting poleward, ions bounce on more stretched field lines, just inward of the closed/open field-line boundary. Numerous papers, including the most recent simulated event [*Ashour-Abdalla et al.*, 2005], have shown that significant acceleration occurs in that stretched region where the κ parameter is $1 < \kappa < 2$. Finally, it must be noted that if ions undergo some nonadiabatic acceleration in the neutral sheet, part of them should mirror there and, in a partial bounce, return back to the northern hemisphere as additional sub-echoes. More refined numerical simulations promise to give greater insight into the exact nonadiabatic motion.

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