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Key Points:
- Inverse ion cyclotron damping is observed in the northern cusp
- The waves are generated at the ion cyclotron frequencies and therefore effective in ion heating
- The mechanism may cause asymmetries between the Northern and Southern Hemispheres

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Observations of multiharmonic ion cyclotron waves due to inverse ion cyclotron damping in the northern magnetospheric cusp

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Abstract We present a case study of inverse ion cyclotron damping taking place in the northern terrestrial magnetospheric cusp, exciting waves at the ion cyclotron frequency and its harmonics. The ion cyclotron waves are primarily seen as peaks in the magnetic-field spectral densities. The corresponding peaks in the electric-field spectral densities are not as profound, suggesting a background electric field noise or other processes of wave generation causing the electric spectral densities to smoothen out more compared to the magnetic counterpart. The required condition for inverse ion cyclotron damping is a velocity shear in the magnetic field-aligned ion bulk flow, and this condition is often naturally met for magnetosheath influx in the northern magnetospheric cusp, just as in the presented case. We note that some ion cyclotron wave activity is present in a few similar shear events in the southern cusp, which indicates that other mechanisms generating ion cyclotron waves may also be present during such conditions.

1. Introduction

The magnetospheric cusps serve as the most direct coupling between the solar wind and the terrestrial magnetosphere and ionosphere, and consequently, they are the regions where the largest ion outflows as well as the most intense electric and magnetic wave activity are observed. Intense plasma influx in the cusps and the effect of convection and mirroring may naturally give rise to velocity gradients transverse to the magnetic field in the parallel plasma flow, $\mathrm{d}v_{\|}/\mathrm{d}x_{\perp}$ (referred to as parallel velocity shear). Generation of instabilities in magnetized plasmas associated with transverse shear was predicted by *D'Angelo* [1965], and excitation of electrostatic ion cyclotron waves associated with parallel velocity shears has been observed in Q-machine experiments; see, e.g., *Agrimson et al.* [2002].

Specifically, waves may be excited at the ion cyclotron frequency and its harmonics through the process of inverse ion cyclotron damping. The effect of parallel velocity shear can be described by a damping factor [*Ganguli et al.*, 2002]

$$\sigma^2 = 1 - \frac{k_\perp}{k_\|}\left(1 - \frac{n\omega_c}{\omega}\right)\frac{1}{\omega_c}\frac{\mathrm{d}v_\|}{\mathrm{d}x_\perp}, \qquad (1)$$

where $k_{||}$ and $k_\perp$ are the parallel and perpendicular wave numbers, respectively; ω and ω_c are the wave angular frequency and the ion cyclotron frequency, respectively; and n is the harmonic number. The parallel velocity shear, $\mathrm{d}v_\|/\mathrm{d}x_\perp$, refers to the perpendicular direction of the largest gradient. For $\sigma^2 > 0$ the velocity shear contributes to wave damping and for $\sigma^2<0$ to inverse damping, that is to say, growth. The velocity shear modifies the ion cyclotron wave so that the condition for wave growth becomes independent of the harmonic number, and therefore, growing waves can be expected for many harmonics of the ion cyclotron frequency [*Gavrishchaka et al.*, 2000]. The process has been observed in Q-machine experiments for ion flows in the same direction as the magnetic field [*Teodorescu et al.*, 2002; *Koepke et al.*, 2003]. The experiments confirmed no ion cyclotron wave excitation for antiparallel ion flows, independent of the degree of transverse shear.

The auroral regions have been reported to contain ion cyclotron waves, which are correlated to enhanced electron fluxes [see, e.g., *Temerin and Lysak*, 1984; *Chaston et al.*, 2002; *Hamrin et al.*, 2002]. Observation of multiharmonics of the ion cyclotron waves in the auroral region associated with field-aligned currents have also been reported, and inverse ion cyclotron damping has been suggested to be a possible mechanism behind them [*Gavrishchaka et al.*, 2000; *Koepke et al.*, 2003]. Northern cusp observations of enhanced magnetic wave intensity around the ion cyclotron frequency, associated with parallel velocity shear, were studied and reported by *Nykyri et al.* [2004, 2006], and inverse ion cyclotron damping may possibly be the mechanism behind the excitation.

The cusps are reported to contain plasma waves at all altitudes over a wide range of frequencies [see, e.g., *D'Angelo*, 1977; *Gurnett and Frank*, 1978; *Pottelette et al.*, 1990; *Waara et al.*, 2011]. Ions of ionospheric origin reaching the high altitudes of the cusp and plasma mantle have high perpendicular temperatures and parallel bulk velocities [*Nilsson et al.*, 2006], suggesting transverse ion heating due to wave-particle interaction as a feasible and significant process. Often associated with ion outflow are broadband waves, and *Chang et al.* [1986] introduced a model where the electric power spectral density of left-hand polarized waves at the ion cyclotron frequency is sufficient to describe the energy transfer between the waves and the ions. Indeed, several studies reproduce the observed temperatures and velocities of ion outflow in the cusp at different altitudes using this model and the observed power spectral densities [*Norqvist et al.*, 1996; *Bouhram et al.*, 2003; *Waara et al.*, 2011; *Slapak et al.*, 2011].

The cusps — in addition to the auroral regions — are regions where inverse ion cyclotron damping naturally may occur, due to the continuous and intense magnetosheath plasma influx. However, given the topology of the terrestrial magnetosphere we would expect inverse ion cyclotron damping to take place only in the northern cusp, where the condition of parallel flow is fulfilled for downflowing plasma, as oppose to the southern cusp, where the downflow is antiparallel.

2. Observations

We have studied northern cusp passages analyzing data from instruments on board the Cluster 4 satellite [*Escoubet et al.*, 2001]. The ion data are provided by the composition distribution function (CODIF) instrument [*Rème et al.*, 2001], using a time-of-flight technique, which resolves the major ion species. To study waves at the ion cyclotron frequency and its harmonics, we use data from the Electric Field and Wave experiment (EFW) [*Gustafsson et al.*, 2001] and the Spatio Temporal Analysis of Field Fluctuations (STAFF) [*Cornilleau-Wehrlin et al.*, 2003] instruments when these are operated in burst mode at a sampling frequency of 450 Hz.

The event we studied is presented in Figure 1, where ion and wave data obtained by Cluster 4 covering UT 13:42 to 14:12, 21 September 2003, are shown. The date corresponds to a period when the Cluster satellites had an orbit with the perigee located on the dayside, and in this particular case they cross the northern magnetospheric cusp at an altitude of 4.5 R_E. Figure 1a shows the energy spectrogram for downflowing H^+, implying that the observed abrupt velocity gradient at UT 13:50, seen in Figure 1d, is associated with a boundary in the magnetosphere. This boundary is the equatorward side of the cusp, separating closed magnetic field lines from the most recently opened field lines [see, e.g., *Krauklis et al.*, 2001; *Bogdanova et al.*, 2007]. Before entering the cusp the spacecraft measures high-energy protons (Figure 1a), typical for the populations on closed field lines. In the cusp a typical energy dispersion of the H^+ downflux is seen as a characteristic ion-energy decrease, due to a velocity filter effect [*Shelley et al.*, 1976; *Reiff et al.*, 1977], as the spacecraft moves to higher latitudes and into the polar cap region. The background magnetic field in the cusp is 540 nT, corresponding to a H^+ cyclotron frequency of 8.2 Hz. Approximately between UT 13:50 and 13:52 the H^+ parallel bulk velocity changes from +150 km/s (downflow) to −75 km/s (outflow), as can be seen in Figure 1d. At the same time the perpendicular bulk velocity is low and typically 20 km/s.

Figures 1b and 1c show the total electric and magnetic field spectral densities, respectively, up to 225 Hz. Greatly enhanced magnetic field spectral densities in the whole frequency range are observed coincidentally with the strong velocity shear of downward flow. As the parallel velocity changes sign the wave intensity quickly diminishes, consistent with the concept of inverse ion cyclotron damping. We note, however, that enhancements remain for the very lowest frequencies. Also the electric wave intensity is enhanced in the downflow shear region. However, it remains enhanced for a longer time and decreases gradually with the decreasing H^+ flux intensity.

Spectral densities as functions of frequency are plotted in Figure 2 for the electric (upper panel) and the magnetic spectral density (top), for UT 13:50 to 13:51, corresponding to the cusp downflow. We note that there are two distinct solar wind injections (of 150 km/s and 50 km/s, respectively) associated with the cusp downflow. However, the parallel velocity shears and the power spectral densities of the two injections are very similar,

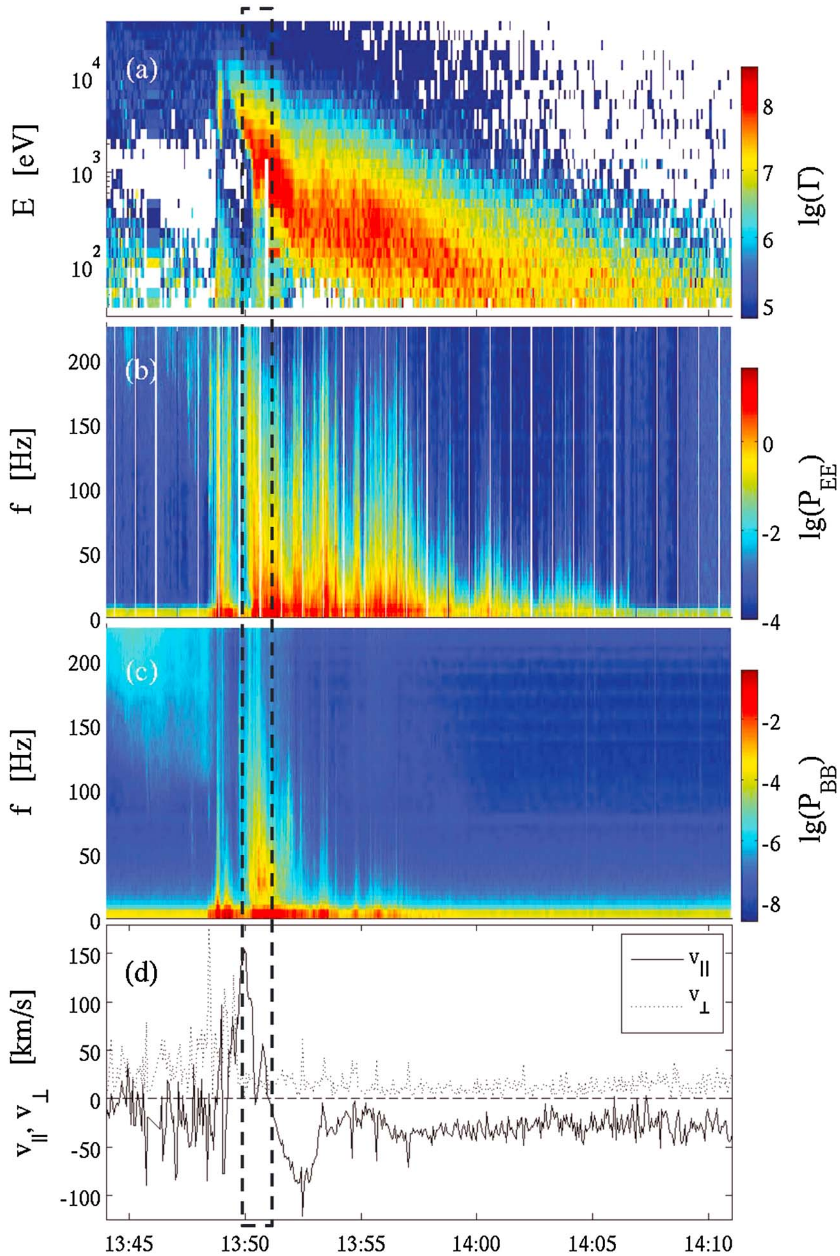

Figure 1. The data in the panels above are obtained by instruments on board Cluster 4 and cover the time interval UT 13:42 to 14:12, 21 September 2003. (a) The downflowing H^+ energy spectrogram, where the color bar defines the downward parallel flux ($cm^{-2}s^{-1}$). (b and c) The electric ($(mV/m)^2/Hz$) and magnetic field spectral densities ($(nT)^2/Hz$) up to 225 Hz, with the spectral densities defined by the corresponding color scales on the right. (d) The parallel (solid line) and perpendicular (dotted line) H^+ bulk velocities. The dashed box marks the region of strong shear and simultaneous H^+ downflow, ranging between UT 13:50 and 13:51. The left side of the dashed box corresponds to the equatorward cusp boundary.

and we do not need to treat them separately. The first thick dashed vertical line in Figure 2 is centered at the largest peak in the magnetic field spectrum, and the distances between the consecutive lines are set to equal the ion cyclotron frequency. The magnetic spectral density shows multiple peaks. These peaks are separated by the local ion cyclotron frequency, consistent with the separation between the peaks in the electric spectral density seen in experiments [*Teodorescu et al.*, 2002; *Koepke et al.*, 2003]. For frequencies smaller than the frequency of the first spectral density peak, there is a distinct dip in the power; up to 2 orders of magnitude lower than what we would expect based on the shape of the spectrogram. Moreover, there are no indications of spectral density peaks at the expected first-order harmonics in the corresponding frequency range.

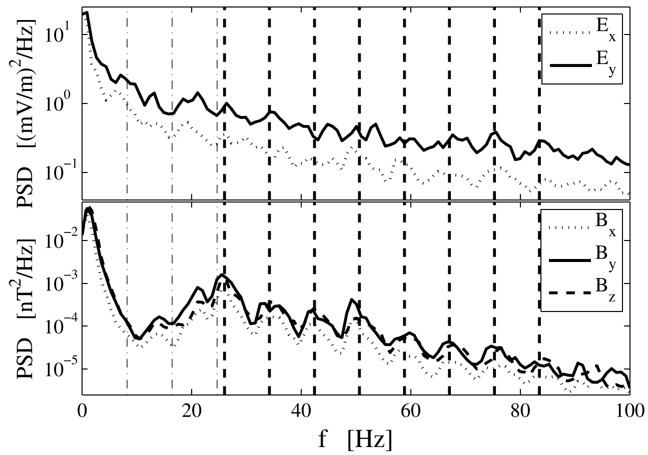

Figure 2. The (top) electric and (bottom) magnetic field spectral densities as functions of frequency for the time interval UT 13:50 to 13:51, 21 September 2003, corresponding to downward flowing solar-wind plasma with high parallel velocity shear in the northern midlatitude cusp. The spectral densities are calculated for each field component, respectively, and the thick dashed lines are separated by the local H^+ cyclotron frequency, with the first line marking the first peak. The thin dash-dotted lines mark the local H^+ cyclotron frequency and the first two multiples.

The position of the largest peak is affected by a Doppler shift as a result of the spacecraft and the plasma being in relative motion, as can be seen by comparing the frequency of the largest peak to the local H^+ cyclotron frequency and its multiples, marked by thin dash-dotted vertical lines in the same figure. The Doppler shift is constant over the period for which the spectra in Figure 2 are calculated. We have verified a constant Doppler shift for UT 13:50 to 13:51 by calculating the magnetic spectral density for smaller time intervals, confirming the first peak to be positioned approximately at the same frequency for all cases, and that the frequency differences between the first peaks of the different time intervals are considerably smaller than the frequency widths of the first peaks. As from UT 13:55, where shear is no longer observed but H^+ fluxes are still relatively intense, the calculated magnetic spectral densities are several orders of magnitude lower than in the downflow shear region, consistent with the fast decline of magnetic wave activity outside the shear region of ion downflow.

3. Discussion

From Figure 1 it seems that the enhancement of magnetic wave activity is better correlated with the strong parallel velocity shear than what the enhancement of electric wave activity is. Also, as can be seen in Figure 2 the electric spectral density does not show as clear peaks at the multiharmonic cyclotron frequencies, but they are distinguishable for some of the higher-order harmonics. From UT 13:55, when the magnetic wave activity more or less has ceased, the electric wave intensity has decreased about 1 order of magnitude for frequencies corresponding to the higher-order harmonics. The electric and magnetic wave components are generally related to each other and *Scarf et al.* [1972] present and discuss such observations in the cusp. The electric wave activity is lower but still significant and enhanced, which indicates that there are one or several other mechanisms associated with strong H^+ flows (and independent of shear) that generate electrostatic waves. The absence of clear peaks at the ion cyclotron harmonics for the electric spectral density can be explained by considering that "noise" from electrostatic waves associated with other wave generation processes smoothen out the multiharmonic peak shape. We noted before that the magnetic spectral density, plotted in Figure 2b, shows a clear dip in the frequency range containing the first-order H^+ harmonics. *Kintner* [1980] presented an equivalent behavior for a type of electrostatic wave and referred to it as the ion cyclotron harmonic mode. The dip is, however, not seen in the corresponding electrical component, supporting that additional electrostatic wave modes are present.

Inverse ion cyclotron damping requires a parallel velocity shear, and it is important to verify that the velocity gradient between UT 13:50 and 13:51 (Figure 1d) is a spatial and not a temporal effect. Unfortunately, the separation distances between the spacecraft are larger than the scale of the event, so it is not possible to use multispacecraft analysis to distinguish spatial from temporal variations. However, from Figure 1a we concluded that the satellite travels from a closed field line region, across the equatorward cusp boundary, transversing the cusp and further into the polar cap region of open field lines. Just at the cusp boundary the flows are strongly downward and consistent with solar wind input into the dayside cusp [*Shelley et al.*, 1976; *Reiff et al.*, 1977]. The velocity decrease and the flow direction change further away from the equatorward cusp boundary are due to the effect of mirrored plasma at lower altitudes in combination with poleward convection [*Rosenbauer et al.*, 1975]. This interpretation of the satellite trajectory and associated energy spectrogram observations supports that we indeed observe a velocity shear. Also, as noted above, the Doppler shift remains constant during the observation of the enhanced ion cyclotron harmonics, supporting the interpretation of the velocity change as a spatial gradient rather than a temporal change, which would have resulted in a changing Doppler shift.

The condition for inverse ion cyclotron damping is that the damping factor σ^2, as defined in equation (1), is negative. Calculating σ^2 from observations requires good estimates of $k_\parallel/k_\perp$. However, using the method of *Means* [1972] gives $k_\parallel/k_\perp$ values typically between 0.1 and 10, and they show no correlation to the frequency. The parallel velocity shear term in equation (1) is easier to calculate, and considering the spacecraft perpendicular velocity $u_\perp$, we can rewrite the shear expression as

$$\frac{1}{\omega_c}\frac{\mathrm{d}v_\parallel}{\mathrm{d}x_\perp} \approx \frac{1}{\omega_c u_\perp}\frac{\mathrm{d}v_\parallel}{\mathrm{d}t}. \qquad (2)$$

$x_\perp$ corresponds to the perpendicular direction of strongest shear, and therefore, our estimate becomes a lower limit of the strongest shear. In our case the largest lower limit of the shear is 0.03, between UT 13:50:00 and 13:50:25. This is comparable to the shears (∼0.05), possibly associated with inverse ion cyclotron damping, observed in the auroral region by *Koepke et al.* [2003].

Due to the magnetic topology of the terrestrial magnetosphere we expect inverse ion cyclotron damping to take place only in the northern cusp for downflowing solar wind plasma. In this study we will not attempt to make a rigorous statistical study. However, we have gone through STAFF data for cusp crossings during 2001–2004. We focused on August, September, and October, corresponding to Cluster orbit perigee in the magnetospheric dayside, in search for clear parallel velocity shears lasting for about 30 s (at least) and where the perpendicular velocity is relatively stable. We picked the crossing associated with the most clear shears, listed in Table 1, and investigated the power spectral densities. For the northern and southern cusp (labeled N and S) we considered 11 and 13 events, respectively. In the northern cusp six of the events show strong enhancement in the magnetic activity at the H^+ cyclotron frequency and its multiharmonics, similar to the event presented in this study. In four events some moderate enhancement is observed, still clearly seen at the ion cyclotron harmonics, and for one event no enhanced activity is seen at all. For the southern cusp the corresponding numbers are 1, 3, and 9. That is, it is more likely to observe enhanced wave activity at the H^+ cyclotron frequency and its multiharmonics in the northern cusp than in the southern cusp, for conditions associated with shocked solar wind influx and parallel velocity shears. This is not a proof but a strong indication that inverse ion cyclotron damping regularly takes place in the northern cusp.

A case of strong velocity shear in the Southern Hemisphere cusp ($f_c = 3.5$ Hz) is presented in Figure 3. Figure 3 (top) shows the parallel and perpendicular bulk velocities during UT 08:57–09:57, 14 August 2003, and intense cusp downflow (defined as positive) is seen between UT 09:00:30 and 09:02:30, as the parallel component ranges between ∼200 km/s and 0 km/s, with highest shear values of 0.07 and 0.08 between UT 09:00:25–09:01:00 and UT 09:01:15–09:01:30, respectively. Between UT 09:02:10 and 09:02:35 a high velocity shear of 0.05 is present. Figure 3 (bottom) shows the magnetic spectral densities during the shears (solid line) and for a neighboring region (UT 09:03–09:06) of no downflow and no shear (dashed line). There are no indications of enhanced wave activity during the parallel velocity shear, compared to its surroundings.

The waves excited in the cusp in association with strong velocity shear are seen in the magnetic field and so were the ion cyclotron waves associated with parallel velocity shear in the northern cusp investigated by *Nykyri et al.* [2006], who studied the magnetic field components in detail. This is in contrast to the theoretical concept of inverse ion cyclotron damping [*Ganguli et al.*, 2002] and to the lab experiments that demonstrated the mechanism [*Teodorescu et al.*, 2002; *Koepke et al.*, 2003], which were of electrostatic nature. However, in an electrostatic system there will be magnetic fluctuations associated with the induced currents. For example, *Huba* [1981] used electrostatic theory to describe plasma instabilities with variable magnetic field components. However, in another experiment, performed by *Tejero et al.* [2011], the conditions allowed for a higher thermal over magnetic pressure ratio β, thus allowing the plasma to affect the magnetic field to a

Table 1. Events of Parallel Velocity Shears Associated With Cusp Passages[a]

Date	Time (UT)	Cusp	f_c (Hz)	$\frac{1}{\omega_c}\frac{dv_{\parallel}}{dx_{\perp}}$	Enhancement
17/3/2001	05:16	N	1.4	0.12	Yes
17/10/2001	06:58	N	6.3	0.01	Weak
13/8/2002	01:06	N	7.6	0.04	Yes
20/8/2002	04:19	N	7.7	0.06	Yes
10/9/2002	14:09	N	8.9	0.01	Weak
11/10/2002	12:40	N	9.1	0.01	Yes
12/9/2003	02:22	N	8.2	0.04	No
21/9/2003	13:51	N	8.2	0.03	Yes
7/8/2004	02:07	N	5.9	0.02	Weak
23/9/2004	15:14	N	8.3	0.02	Yes
3/10/2004	04:07	N	6.9	0.03	Weak
3/8/2002	09:09	S	5.3	0.01	Yes
5/9/2002	16:20	S	3.7	0.04	No
	16:22	S	3.8	0.05	No
15/9/2002	05:27	S	5.9	0.03	Weak
27/9/2002	03:00	S	5.9	0.02	No
	03:02	S	5.9	0.02	No
13/10/2002	18:08	S	3.6	0.06	No
7/8/2003	06:02	S	4.1	0.02	No
14/8/2003	09:01	S	3.5	0.08	No
21/8/2003	12:01	S	2.8	0.08	No
2/9/2003	09:22	S	2.8	0.09	Weak
	09:40	S	3.0	0.02	Weak
4/9/2003	18:01	S	2.1	0.12	No

[a]The second column gives the approximate time of the event followed by a cusp identification; southern (S) or northern (N). The local ion cyclotron frequencies f_c are specified, as well as the dimensionless parallel velocity shear numbers (fifth column). Last column notes if significant enhancement of magnetic wave activity—at the H^+ cyclotron frequency and its multi harmonics—is related to the events by addressing Yes or No (or Weak if some tendencies of increased wave activity is seen). Dates are formatted as day/month/year.

larger extent, and they showed that enhanced magnetic signatures around the ion cyclotron frequency were generated under strong velocity shear conditions. They showed that both electrostatic and electromagnetic waves were generated in the shear region. The minimum β for observable magnetic field fluctuations in the lab experiment was $\sim 10^{-6}$, which is much lower than observed in the cusp for the event presented in our study, where $\beta \sim 10^{-2}$. They also noted that the electromagnetic waves propagated out of the source region, whereas the electrostatic waves did not. The observed waves presented in our study are localized in the source region where the parallel velocity shear is large but not outside of this region, hence suggesting electrostatic waves according to the lab experiment. However, electromagnetic waves in the cusp can also be efficiently damped outside the source region [*Nykyri et al.*, 2006], suggesting that we probably observe both electrostatic and electromagnetic waves within the source region, still in line with the observations of *Tejero et al.* [2011].

A result of significant inverse ion cyclotron damping in the northern cusp may be that the Northern Hemisphere is associated with more intense wave activity and more effective ion energization as compared to the Southern Hemisphere. Hence, in order to investigate the significance of inverse ion cyclotron damping a statistical study of the wave and ion characteristics are required. However, such a study would involve different issues that need to be considered. For example, no southern cusp crossings of clear parallel velocity shear during burst mode are observed, leading to no possibility of a direct comparison with the event presented in this paper. A statistical study will therefore to a high degree be limited to higher altitudes, where the ion

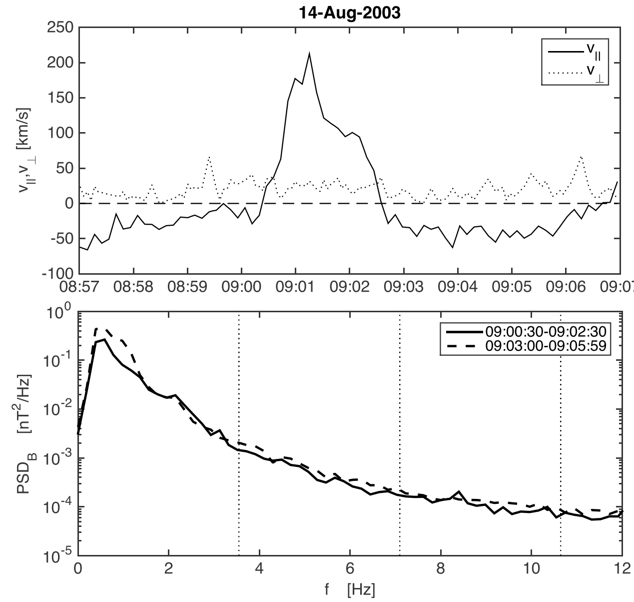

Figure 3. The data in the panels are obtained by instruments on board Cluster 4 and cover the time interval UT 08:58 to 09:07, 14 August 2003. (top) The parallel (solid line) and perpendicular (dotted line) H^+ bulk velocities. Positive parallel velocities correspond to downflow. (bottom) The total magnetic field spectral densities as function of frequency for the time interval UT 09:03 to 09:06 (dashed line) and for UT 09:00:30 to 09:02:30, corresponding to the high parallel velocity shear. The dotted line marks the local H^+ cyclotron frequency.

cyclotron frequencies and first multiharmonics are covered by the normal modes of EFW and STAFF. Also, to quantify the velocity shear by multispacecraft measurements, the separation between the satellites needs to be smaller than typical gradient length scales. Unfortunately, estimates made from single spacecraft measurements suffer from the difficulty in determining the angle between the spacecraft velocity and the direction of maximum parallel velocity shear. In addition, it is important to note that since inverse ion cyclotron damping cannot be responsible for the waves generated at the ion cyclotron frequency observed in a few cases in the Southern Hemisphere (Table 1), there must exist other mechanisms that may generate ion cyclotron waves under similar conditions, and this must be taken into account and discussed in a future statistical study. We also note that due to the satellite orbit there is an asymmetry in altitudes (or local ion cyclotron frequency) between the southern and northern cusps for the reported events (Table 1), a possible bias that also needs consideration in a more complete statistical study.

In summary, we have observed inverse ion cyclotron damping in Earth's northern cusp, a mechanism in which ion cyclotron waves and their harmonics are excited. In a region with parallel velocity shear waves with multiply peaked spectra were observed as predicted by theory and laboratory experiments. If significant, this mechanism should have important implications on ion heating and subsequent acceleration, causing asymmetries between the northern and southern magnetospheric hemispheres in terms of ion characteristics as a result.

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