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Ion cyclotron waves in the high altitude cusp: CLUSTER observations at varying spacecraft separations

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[1] We have analysed high-resolution Cluster magnetic field data during three high-altitude cusp crossings in 2001 and 2002. The Cluster separations for these crossings varied between 100 and 600 km and therefore provided an unique opportunity to study wave properties at different length scales. In the cusp Cluster sees frequent intervals of magnetic field fluctuations with clear peaks in power close to the local ion cyclotron frequency, and both left- and right-handed polarisations. At large separations the power seen at different spacecraft can differ by orders of magnitude. For smaller separations, the power seen at the four spacecraft agrees better but still shows some differences. For all separations there was no significant correlation between the signals seen at different spacecraft, indicative of very local structure. The origin of the waves appears to lie in highly filamented sheared plasma flows present in the cusp. *INDEX TERMS:* 2159 Interplanetary Physics: Plasma waves and turbulence; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2772 Magnetospheric Physics: Plasma waves and instabilities; 7859 Space Plasma Physics: Transport processes; 7867 Space Plasma Physics: Wave/particle interactions. **Citation:** Nykyri, K., P. J. Cargill, E. A. Lucek, T. S. Horbury, A. Balogh, B. Lavraud, I. Dandouras, and H. Rème, Ion cyclotron waves in the high altitude cusp: CLUSTER observations at varying spacecraft separations, *Geophys. Res. Lett.*, *30*(24), 2263, doi:10.1029/2003GL018594, 2003.

1. Introduction

[2] The four spacecraft Cluster mission has shed important new light on the physics of the high-altitude magnetospheric cusp [e.g., *Lavraud et al.*, 2002; *Cargill et al.*, 2001] in terms of its overall phenomenology (especially its dependence on sub-solar or lobe reconnection), the motion of the boundaries surrounding it, and smaller-scale plasma processes occurring locally within the cusp itself. In particular, the cusp is the site of copious magnetic and electric field turbulence [e.g., *Rezeau et al.*, 2001] over a wide range of frequencies from below the ion cyclotron frequency (sub-Hz) to the electron plasma frequency (kHz).

[3] Low-frequency turbulence (either MHD or ion cyclotron) has been detected before in the cusp using magnetometer measurements from a single spacecraft [*Scarf et al.*, 1972; *Chen and Fritz*, 1998; *Le et al.*, 2001]. The last of these studies used data from the Polar spacecraft, and showed a wide range of fluctuations with both left- and right-hand polarisations, and a wide range of angles of propagation throughout the parts of the cusp sampled by the apogee of the Polar orbit at 8.9 R_E.

[4] Cluster has the potential to make major discoveries in the field of plasma turbulence, with a range of spacecraft separations between 10^2 and 10^4 km, permitting a study of both the localisation and propagation properties of the turbulence. For spacecraft separations small with respect to the wavelength, one might expect to see good correlations between signals at some of the spacecraft (see *Lucek et al.* [2001] for an analysis of mirror waves in this context). For ion cyclotron waves, one expects the condition $kV_A/\Omega_i \geq 1$ to hold, implying wavelengths shorter than $2\pi V_A/\Omega_i = 2\pi c/\omega_i$. For a proton number density of 10 cm^{-3}, this is of order 500 km or less. Here k, V_A, Ω_i, and c/ω_i denote wavenumber, Alfvén velocity, ion cyclotron (IC) frequency and ion inertial length, respectively.

[5] In this paper we present results from three high-altitude cusp crossings: one with 600 km separations on March 17, 2001 and two with 100 km separations (March 2 and 9, 2002), so that these would appear to be optimal conditions for analysing IC waves therein. We will study wave polarisation, ellipticity and propagation angle with respect to the background magnetic field. Here we will show results of a complete survey (Figure 3) of the wave properties only for the 2nd of March, and show examples of the waves for other crossings. The complete wave analysis for the 17th of March is documented elsewhere (Nykyri et al., submitted to Annales Geophysicae, 2003) and for 9th of March there were only few wave intervals with clear polarisation signature.

2. Data and Cusp Encounters

[6] We use data from two instruments on Cluster. From each spacecraft, we use magnetic field measurements from the Flux Gate Magnetometer (FGM) [*Balogh et al.*, 2001], with a sampling rate of 22 vectors/sec, and ion spectra and moments from the Cluster Ion Spectrometer (CIS) [*Rème et al.*, 2001] from spacecraft 1, 3 and 4.

[7] The three cusp crossings selected are on the outbound leg of the Cluster orbit in the Northern hemisphere, and are similar in many ways. Their timing and average solar wind properties are summarised in Table 1. The interplanetary magnetic field strengths and directions are averages over the event, and do not reveal interesting details such as brief

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Table 1. Average Solar Wind Properties During Cusp Crossings on 17.3.2001, 2.3 and 9.3 2002

Date	Cusp (UT)	N_{SW} (cm^{-3})	V_{SW} (km/s)	(B_x, B_y, B_z) nT
17.3.01	05:08–06:20	3	290	(3,2,3)
2.3.02	00:03–01:18	5	370	(8,4,2)
9.3.02	02:47–03:35	4	440	(−2,4,4)

Southward IMF turnings that do occur. In all cases cusp entry occured at an altitude of approximately 8 R_E. Cluster then spent 1–2 hours in the cusp, as identified by magnetosheath-like plasma, and exited the cusp into the Sunward magnetosphere, subsequently crossing the magnetopause.

2.1. Cusp Crossing on 17th of March, 2001

[8] The first of these events was associated with persistent lobe reconnection, and Earthward streaming plasma, and has been extensively documented by us and others (*Vontrat-Reberac et al.* [2003] and Nykyri et al., submitted to Annales Geophysicae, 2003). Here we focus on only the key magnetic field measurements.

[9] Magnetic field fluctuations commence on cusp entry, and their level correlates well with intervals of streaming magnetosheath plasma. Figure 1a shows detrended magnetic field data in a 30-s interval during enhanced flows at the cusp entry. (The detrending is accomplished by subtracting a linear fit to the data in the relevant interval.) Spacecraft data throughout this paper are color coded such that black, red, green, and blue correspond to spacecraft 1 (hereafter SC1), SC2, SC3 and SC4, respectively. SC2 and SC3 observe several incoherent wave packets that are not seen at SC1 or SC4. We have calculated the cross-correlation coefficients (cc-coef.) of the magnetic field components for each spacecraft pair and find poor correlations for all lag-times. This indicates that the spatial scales of the waves are much smaller than the relevant spacecraft separation of 600 km.

[10] Figure 2a shows power spectra of the total power in magnetic field fluctuations observed by all 4 spacecraft, and hodograms of the wave magnetic field observed by SC2. Clearly the power seen at the four spacecraft differs by orders of magnitude, with clear peaks near the ion cyclotron frequency (1.5 Hz here) at only SC2 and SC3. SC3 is located in a high density region, and measures field-aligned plasma flow. SC1 and SC4 are located in a region of lower plasma density, and observe smaller field-aligned plasma fluxes when compared to SC3. These waves are strongly transverse (the ratio of the power in the perpendicular to

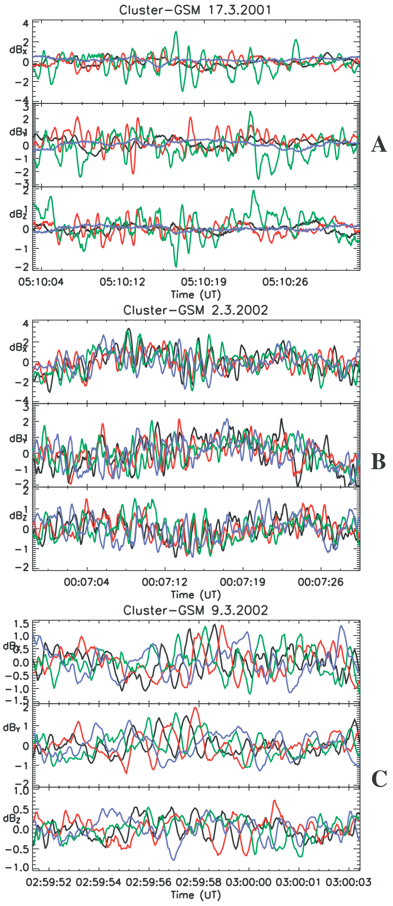

Figure 1. Detrended magnetic field (dB_x, dB_y, dB_z) measurements on 17.3.2001 at 05:10:04–05:10:33 UT (A), 2.3.2002 at 00:06:59–00:07:30 UT (B), and 9.3.2002 at 02:59:52–03:00:03 UT (C) for four Cluster spacecraft (SC1-black, SC2-red, SC3-green, and SC4-blue).

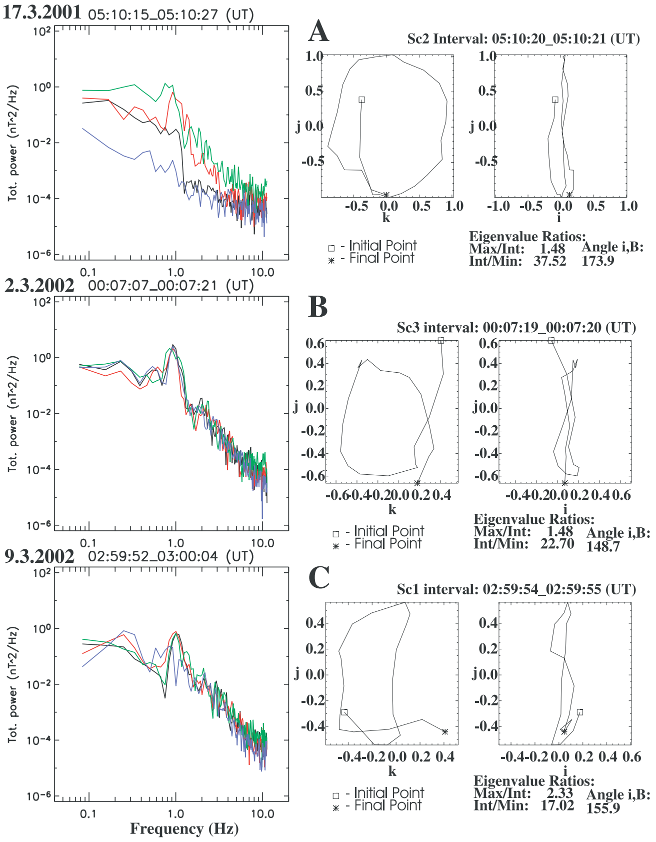

Figure 2. Total power of the magnetic field fluctuations for four Cluster spacecraft (left) on 13.7.2001 at 05:10:15–05:10:27 UT (A), on 2.3.2002 at 00:07:08–00:07:21 UT (B) and on 9.3.2002 at 02:59:52–03:00:04 UT (C). Hodograms of the wave magnetic field (right) for SC2 at 05:10:20–05:10:21 UT (A), for SC3 at 00:07:19–00:07:20 UT (B), and for SC1 at 02:59:54–02:59:55 (UT) (C).

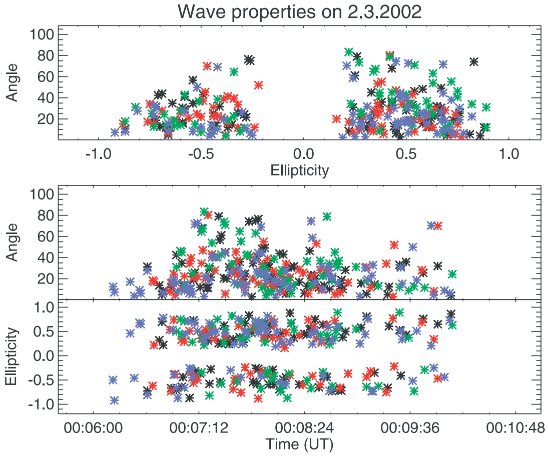

Figure 3. Wave properties observed by 4 Cluster spacecraft on 2.3.2002: θ_{kB} as a function of ellipticity (top), θ_{kB} (middle) and ellipticity (bottom) as a function of time.

compressional fluctuations (C) is >160 for SC2 and SC3), and the frequency of the peak power is 0.65 and 0.56 times the local Ω_i for SC2 and SC3, respectively.

[11] Minimum variance analysis [*Sonnerup and Scheible*, 1998] is used to present the wave magnetic field in directions of maximum (j), intermediate (k) and minimum (i) variance. The eigenvalue ratios and angle between the minimum variance direction and the background magnetic field are shown below each hodogram in order to define wave ellipticity and polarisation. In the j, k-plots the magnetic field comes out of j, k-plane. The hodograms indicate that SC2 observes a right-hand polarised wave propagating at angle $\theta_{kB} = 6°$ with respect to the background magnetic field and with an ellipticity of 0.8. The ellipticity (e) is defined as a square root of the intermediate and maximum eigenvalue ratio. We expect the Alfvén/ion cyclotron mode to be left-handed, so this wave must belong to the right-handed magnetosonic mode.

[12] In contrast to SC2, SC3 observes a left-hand wave between 5:10:22–5:10:24 UT (not shown here) with $\theta_{kB} = 36°$. The difference in polarisation is unlikely to be reconciled by Doppler effects since the plasma velocity is much smaller than the phase velocity of either wave. Consider the angular frequency of the wave in spacecraft frame (index sc)

$$\omega_{sc} = \omega_{plasma}\left(1 + \frac{v_{plasma}}{v_{ph}}\cos(\theta_{kv})\right) \qquad (1)$$

where v_{plasma} and v_{ph} are the plasma velocity and phase velocity of the wave which propagates at an angle θ_{kv} with respect to the flowing plasma. Taking $v_{ph} = v_{\text{Alfvén}} = 700$ km/s, $v_{plasma} = 200$ km/s and $\theta_{kv} = 0°$, the Doppler shifted wave frequency in plasma frame would be ~0.8 times the observed frequency in spacecraft frame. However, the v_{ph} for the ion cyclotron/Alfvén modes depends on the angle θ_{kB} ($v_{ph} = v_{\text{Alfvén}} \cos(\theta_{kB})$), so that for very obliquely propagating waves, the Doppler effect might become important in regions of strong plasma flow. Doppler effects on wave polarisation merits further investigation and we will return to this in our future work.

[13] In addition to these shear flow generated waves, we also found waves above the local Ω_i at the boundary of stagnant plasma between 05:25–05:29 UT and between 05:45–05:49 UT. These waves were more coherent than during the shear flow cusp interval and had lower amplitudes of ~0.5 nT. During these intervals the first and sometimes the second harmonic of the fundamental frequency were also observed (Nykyri et al., submitted to Annales Geophysicae, 2003).

2.2. Cusp Crossing on 2nd of March, 2002

[14] Consider now the crossing of March 2, 2002 when the spacecraft separation was of order 100 km. In this case there is an interval of IC waves between 00:07:00 and 00:09:30 starting at the time of entry into the cusp from the magnetosphere.

[15] Panels B of Figures 1 and 2 show the detrended data and power spectra in a sub-interval. The spectra now show an enhanced level of turbulence at all the spacecraft below the Ω_i, with a peak at ~0.7 times the Ω_i. The waves are again highly transverse (C > 10 for all spacecraft). Given the small separation between the spacecraft (70–140 km), this is consistent with them flying through an relatively homogeneous region of turbulence.

[16] An inspection by eye of the detrended data suggests that waves at the different spacecraft move into and out of correlation with each other. However a formal cross-correlation analysis again shows no significant correlation (cc-coef. <0.7 for all spacecraft pairs), indicating that the individual wave packets are localised on scales of <100 km. It should be noted that an examination of the spacecraft configuration with respect to the magnetic field indicates that none of the spacecraft are located along the same magnetic field line, so it is likely that we are seeing wave packets which are propagating along different field lines. We can say nothing however about the correlation length along field lines, which may be much longer.

[17] Figure 2b also shows a hodogram of the wave magnetic field observed by SC3 between 00:07:19–00:07:20 UT. This is a left-handed wave propagating with $\theta_{kB} = 31°$ and $e = 0.82$.

[18] Figure 3 summarises the wave properties observed by all four spacecraft between 00:06:00 and 00:10:00 UT. The search for the wave intervals is automated so that a 1-s window slides over the data set with a 10% overlap, and all the wave intervals with intermediate/minimum -eigenvalue ratios greater than 10 are selected. From these, the intervals that have a clear polarisation signature are further selected manually. The upper panel shows the wave ellipticity (e) as a function of θ_{kB}. The negative (positive) ellipticities correspond to left-handed (right-handed) waves. We can see that Cluster observes both left- and right-handed waves, with a wide range of ellipticities and propagation angles. There is no identifiable correlation between e and θ_{kB}. The lower panels show the θ_{kB} and e as a function of time. There are no clear regions of single polarisation, but all spacecraft observe both left- and right-handed waves with polarisation changing from one wave cycle to another.

2.3. Cusp Crossing on 9th of March, 2002

[19] The final cusp encounter was on March 9, 2002. Here the IC waves were present only for short period

between 02:59:45 and 03:00:15. Figure 1c shows the detrended magnetic field observations between 02:59:45 and 03:00:07 UT for all four spacecraft. Like the 2 March 2002 interval, the fields at each spacecraft seem to move into and out of correlation with each other. The spacecraft separations vary between 70–140 km, but again, none of the spacecraft are located exactly along the same magnetic field line. The correlation coefficients are small for this 22 second interval, but one can see clearly a narrow region between 02:59:54 and −03:00:00, where especially data from SC1 and SC2 correlate better (cc-coef. ∼0.8), with data from SC2 lagging behind that from SC1 about 0.4 seconds. However, we cannot unambiguously determine whether this 0.4 second lag-time is between the same wave cycle at the two spacecraft, or just waves with similar properties. Examination of the Cluster constellation indicates that from all the spacecraft, pair SC1 and SC2 are most aligned along the same magnetic field direction with their cross-field distance comparable to ion gyroradius.

[20] Figure 2c shows the total power in magnetic field fluctuations between 02:59:45 and 03:00:07 UT. SC4 now has a lower level of power than the others, indicative in this case of the waves originating on sub-100 km scales. The observed frequencies are now smaller than before (approximately 0.4 times the local Ω_i), but the waves are still strongly transverse (C ranging from 9 to 29).

[21] The right-hand side of the Figure 2c shows an example of a hodogram of the wave magnetic field between 02:59:54 and 02:59:55 UT observed by SC1. The wave is right-handed polarised with e = 0.66 and $\theta_{kB} = 24°$. Between 02:59:59–03:00:00 UT SC2 observes a left-handed wave (not shown here) with e = 0.66 and $\theta_{kB} = 20°$.

3. Discussion and Conclusions

[22] In this study we have presented Cluster high resolution magnetic field measurements of the waves close to local Ω_i during three encounters with the high-altitude cusp for different spacecraft separations. For 600 km separation, it was shown that the wave power seen by different spacecraft can differ by orders of magnitude. For 100 km separation, the wave power was similar at the four spacecraft during 2nd of March 2002, but on 9th of March 2002 one of the spacecraft observed a lower wave power which may be indicative of wave generation on scales <100 km. The only significant cross-correlation coefficients between the fields arose in instances when two spacecraft were located approximately along the same magnetic field line with small cross-field separation.

[23] The wave properties were also highly variable: both left-and right-handed waves were observed above and below the local Ω_i, and there were no correlations between observed ellipticities and θ_{kB}. There were no clear regions with just left- or right-handed waves, but the wave polarisations changed from one wave cycle to another.

[24] Ion plasma data indicates that the waves occur in regions of strong field-aligned plasma velocity and shear. Indeed there are instances in these encounters of the velocity changing from 100 km/s to stagnant on the scale of the spacecraft separation. There is an extensive literature concerning the generation of IC waves due to instabilities in plasma flows, especially for ionospheric parameters [e.g., *Kindel and Kennel*, 1971; *Peñano and Ganguli*, 2002]. For field-aligned flow such as we detect, only electrostatic calculations have been carried out, but they suggest that waves can be excited at many harmonics of the Ω_i [*Gavrishchaka et al.*, 2000; *Ganguli et al.*, 2002]. If these results carry over to the electromagnetic regime, as for IC waves due to shears in the transverse flow [*Peñano and Ganguli*, 2002], and for cusp parameters, then this may be a promising way to account for our observations. We will return to this topic in the future.

[25] These results are indicative of the highly filamentary nature of magnetic field turbulence in the cusp. The differing power levels and polarisations at the closely separated spacecraft indicate that the origin of the turbulence is fragmented at scales of under 100 km at this height in the cusp. If one accepts that the origin of the waves is due to small-scale instabilities in the plasma streaming downward along the magnetic field, then each local bundle of magnetic flux will see wave growth driven by the local plasma properties, with the dominant wave mode determined by the local distribution function. The peaks in power around Ω_i are strongly suggestive of a resonant processes between protons and the wave, and indeed the presence of the first harmonic in some cases is also suggestive in this regard. Future studies will address this issue through an examination of the distribution function.

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