Cluster Observations of Pc 1-2 Waves and Associated Ion Distributions During the October and November 2003 Magnetic Storms

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Abstract

Unusual wave activity in the Pc 1-2 frequency band (0.1 – 5 Hz) was observed by the Cluster spacecraft in association with the two large geomagnetic storms of late 2003. During the onset of the Hallowe'en storm on October 29, 2003, intense broadband activity between ~0.1 and 0.6 Hz appeared at all 4 spacecraft on both sides of the magnetic equator at perigee (near 1400 UT and 08:45 MLT). Power was especially strong and more structured in frequency in the compressional component: a minimum in wave power was observed at 0.38 Hz, corresponding to the oxygen ion cyclotron frequency. Poynting vector calculations indicated that wave power was primarily directed radially inward rather than along the magnetic field. Narrowband purely compressional waves near 0.15 Hz appeared at higher dayside latitudes in the southern hemisphere. CIS ion spectrometer data during this pass revealed that O^+ was the dominant energetic ion. During the recovery phase of the November storm, on November 22, 2003, predominantly transverse 1.8 Hz waves with peak-to-peak amplitude of 10 nT were observed by all four spacecraft near perigee at L = 4.4. During this more typical Pc 1 event, wave power was directed along **B**, toward the northern ionosphere. An unusually polarized 2.3 Hz emission (with power in the radial and compressional, but not azimuthal directions) was observed at L = 5.4-5.9, 10-15° south of the magnetic equator. We infer that this wave event may have been generated on lower L shells and propagated obliquely to Cluster's location. Consistent with other recent observations, anisotropic plasma sheet / ring current proton distributions appeared to be a necessary condition for occurrence of waves during both passes, but was not always a sufficient condition. The transverse waves of Nov. 22 occurred in regions which also contained greatly increased fluxes of cool ions (E < 1 keV). On both days Cluster observed features not previously reported, and we note that the purely compressional nature of the October 29 events was not anticipated in previous theoretical studies. The fact that these unusually polarized waves occurred in association with very intense geomagnetic storms suggests that they are likely to be extremely rare.

1. Introduction

Most early studies of Pc 1-2 waves (0.1 Hz < f < 5 Hz) were based on data from ground-based magnetic observatories [e.g., Troitskaya, 1961; Tepley, 1961; Tepley and Wentworth, 1962]. Theoretical studies [Jacobs and Watanabe, 1963, Cornwall, 1965; Liemohn, 1967] and satellite observations [e.g., Bossen et al., 1976; and others reviewed by, e.g., Fraser, 1985 and Anderson et al., 1992a,b] soon converged to show that anisotropic populations of energetic protons in the magnetosphere were responsible for many, if not all, of these emissions [Mauk and McPherron, 1980; Anderson et al., 1996a]. Kangas et al. [1998] provide a recent review of the morphology and physics of these waves. Waves in this frequency range have also been observed in the subsolar magnetosheath [Anderson et al., 1994; Denton et al, 1994], and studies by Menk et al. [1992], Dyrud et al. [1997], and Engebretson et al. [2005a] have revealed the unexpected occurrence of Pc 1-2 waves on open field lines poleward of the dayside cusps, but in each of these regions the same physical mechanism is understood to be at work.

An association between geomagnetic storms and Pc 1-2 waves was observed in early work by Wentworth [1964], and considerable effort has been devoted in recent years to testing this association [Erlandson and Ukhorskiy, 2001] and in working out the consequences of these waves for removing both ring current ions and radiation belt electrons [e. g., Kozyra et al., 1997; Jordanova et al., 2001; Summers and Thorne, 2003; Meredith et al., 2003].

This study will focus on wave events and ion characteristics occurring during and after the great geomagnetic storms of October and November 2003, and in particular on unusually polarized Pc 1-2 wave events observed during these intervals at all four spacecraft. The polar orbit of the Cluster spacecraft, with perigee at ~4.4 R_E near the geomagnetic equator, provides spacecraft trajectories approximately along a given field line in the inner magnetosphere. Nearly all of the Pc 1-2 events observed so far during our studies of dayside Cluster perigee pass data during 2003 (~6 months at each of four spacecraft) were transverse waves, consistent with earlier in situ spacecraft observations of wave activity in this frequency range. During these storms, however, we observed two wave events with unusual polarizations and characteristics: a) purely compressional waves below the O^+ gyrofrequency, and b) waves above the local He^+ gyrofrequency that occurred only in the radial and field-aligned components, and thus appear to be propagating oblique to the local magnetic field. Although we believe that both events may be generated by an ion cyclotron instability, to our knowledge neither has before been observed.

Figure 1 shows the D_{st} index for the two large magnetic storms of late 2003 (cf. Baker et al. [2004], and Gopalswamy et al. [2005] and related special sections on the Violent Sun-Earth connection events of October-November 2003 in *Geophysical Research Letters, Vol. 32*, Nos. 3 and 12, 2005, *Journal of Geophysical Research, Vol. 110*, No. 9, 2005, and *Space Weather, Vol. 2*, 2004, and *Vol. 3*, 2005). For each storm interval Figure 1 indicates the time spans covered by three successive passes of the Cluster spacecraft. The upper panel shows the progression of the Hallowe'en storm from October 27 through October 31, and in particular the double minima of this storm, reaching -363 at the beginning of October 30 and -401 near the end of that same day. Cluster passes through perigee occurred from 02 to 08 UT October 27, well before storm onset and during an interval of D_{st} values near -70; from 10 to 16 UT October 29, during the main phase of the first part of this storm, as D_{st} increased from -180 to -98 and then resumed its rapid drop toward its first deep minimum; and from 20 UT October 31 to 01 UT November 1, near the end of a rapid recovery phase as D_{st} increased from -84 to -72.

The lower panel of Figure 1 shows the progression of the November storm from November 19 through November 24, and in particular the minimum D_{st} of -472 nT late on November 20. Cluster passes through perigee occurred from 21 UT November 19 to 02 UT November 20, a few hours before storm onset, when D_{st} was near -15; from 06 to 11 UT November 22, again near the end of a rapid recovery phase, when D_{st} rose from ~ -80 to ~ -60; and from 15 to 20 UT November 24, by which time the D_{st} index had returned to ~ -35 nT.

2. Instrumentation

The four Cluster spacecraft were launched into a polar orbit of 4 x 19.6 Earth radii (R_E) in late summer 2000, and began full operations in February 2001 [Escoubet et al., 2001]. Because the Cluster orbits are fixed with respect to inertial space, they sweep through all local times every year. During October and November 2003 the perigee of the Cluster spacecraft precessed from ~10:30 MLT to ~06:30 MLT. A ~5-6 hour perigee pass (from the southern cusp/auroral zone through the geomagnetic equator and to the northern cusp/auroral zone) occurred every ~56 hours.

The FGM instrument on each Cluster spacecraft consists of redundant triaxial fluxgate magnetic field sensors on one of the two radial booms of the spacecraft [Balogh et al., 2001], and provides 3-axis magnetic field measurements at 22.416 vectors/s in its nominal mode. Data originally provided in GSE coordinates were rotated into local mean-field-aligned coordinates using a 15 minute average for the mean field. In this coordinate system the Z axis is in the direction of the averaged magnetic field (approximately northward). The Y axis is transverse to **B** and to the radius vector from the Earth to the spacecraft, and is directed approximately azimuthally eastward. The X axis completes the right-handed system, and is directed approximately radially outward from Earth. No further frequency filtering was applied to the magnetic field data shown here.

The CIS instrument on the Cluster spacecraft measures the full, three-dimensional ion distribution of the major magnetospheric ions (H^+, He^+, He^{++} and O^+) from thermal energies to about 40 keV/e [Rème et al., 2001]. The experiment consists of two different instruments: a Composition and Distribution Function analyzer (CODIF) that gives the mass per charge composition with medium 22.5° angular resolution, and a Hot Ion Analyzer (HIA) which does not offer mass resolution but has a better angular resolution of 5.6°.

The Cluster Electric Field and Wave instrument (EFW) uses two pairs of spherical probes deployed on 88-m tip to tip wire booms in the spin plane to measure electric fields [Gustafsson et al., 2001]. In its normal operating mode two electric field components in the spin plane are low-pass filtered at 10 Hz and sampled at 25 samples/s. EFW makes a two dimensional measurement of the electric field in the satellite spin plane (which is close to the X-Y GSE plane). To rotate the electric field into a physical coordinate system and to calculate the Poynting flux, it is necessary to make an assumption about the unmeasured (spin-axis) component of the electric field. Usually, the assumption is made that $\mathbf{E}\bullet\mathbf{B}=0$, which is reasonable for the waves of interest for this study, and Ez = -Ex(Bx/Bz)-Ey(By/Bz), where Ez is the unmeasured component and Ex and Ey are the measured components. During intervals when (Bx/Bz) and/or (By/Bz) are too large, usually because Bz is small, this assumption can lead to significant errors. This situation was true for two intervals discussed below, 11/29/2003 near 12:20 UT and 11/22/2003 near 07:45 UT. During these intervals, the rotated electric field and the Poynting flux are calculated assuming that the on-axis component is zero, and, therefore, both values generally represent a lower limit. The electric field data shown herein are filtered over the frequency range of the observed waves, 100 to 400 mHz for 10/29/2003 and 1-3 Hz for 11/22/2003. The Poynting flux calculation uses magnetic field data filtered over the same bands. The data are then rotated into a field-aligned coordinate system based on the smoothed mean magnetic field

3. The October 2003 (Hallowe'en) Storm

As noted in Figure 1, Cluster perigee passes during this storm period occurred roughly 2 days before storm onset, early during the main phase, and approximately 1/2 day after a very rapid recovery of D_{st} from its second main phase value. No Pc 1-2 wave activity was observed during the October 27 pass prior to storm onset, and only very weak transverse activity centered near 0.5 Hz was observed during the October 31/November 1 pass.

Figure 2 shows a Fourier spectrogram of 0-1 Hz ULF wave activity from 12:00 to 14:00 UT, near the center of the October 29 Cluster perigee pass on this day, early in the main phase of the 2003 Hallowe'en storm. In both Fourier spectrograms shown in this paper, a 256-point fast Fourier transform (FFT) with a 10% cosine taper window was applied to differenced magnetic field data. Differencing is used to facilitate display of a wide range of spectral power by removing the f^{-2} falloff in spectral power, but without loss of information about the background signal. Takahashi et al. [1990] give a quantitative relationship between spectral power calculated from differenced and undifferenced data.

Intense broadband activity appeared on both sides of the magnetic equator near perigee, from 12:50 to 14:00 UT. Activity in the transverse components (upper panels) was most intense between 0 and ~300 mHz, but high frequency tails (corresponding to broadband, impulsive activity) extended to well over 1 Hz. Power in the compressional component was considerably more intense during this period, but was much more limited in frequency. In particular, Figure 2 shows a deep minimum in compressional power at frequencies corresponding to the local oxygen ion cyclotron frequency (f_O^+), shown as a white trace superposed on the bottom panel of this figure. Note the continuous presence of intense power below this frequency from 13:15 to 13:55 UT, and the less intense power above it. The temporal variation of the power in both frequency ranges was roughly similar during much of this interval. Brief increases in wave intensity correlated with intensifications in the total field (as indicated by increases in f_O^+, for example near 12:26 UT, 12:52 UT, from 13:10 to 13:35 UT, and from 13:45 TO 13:57 UT.

In addition, a more narrowband, purely compressional wave signal appeared between 12:25 and 12:45 with frequency near 150 mHz, well below the local O^+ gyrofrequency, with no trace of compressional power above that frequency, while again transverse power was dominated by irregular, broadband activity (vertical strips). Similar activity was evident at all four spacecraft. Figure 3 shows a ten-minute sample of the waves during this time interval, from 12:30 to12:40 UT. Sinusoidal wave packets with peak-to-peak amplitudes of 3-5 nT were evident in the compressional (Bz) trace near 12:31, 12:33, 12:35, and 12:38-39 UT. The Bx and By traces were dominated by irregular and mostly longer period variations. Although some weak signals in the Pc 2 frequency range can be seen in these components during this interval, there is little evidence of sinusoidal, packet-like oscillations such as those in the compressional component. Poynting vectors, calculated as described above, show that the energy flux associated with these wave packets propagated primarily earthward (in the –X direction), but also with a somewhat smaller eastward (sunward) component. The bottom panel of Figure 3 shows that there was very little net energy flow in this frequency range along **B**.

A similar ten-minute sample of waves from 13:25 to 13:35 UT, during the interval of more intense, broadband wave activity is shown in Figure 4, along with the components of the Poynting vector. The compressional oscillations during this interval were much less often sinusoidal, and had no consistent frequency. For example, the oscillations near 13:28 UT had a higher frequency than those between 13:29 and 13:30 UT, and those between 13:33 and 13:34 UT were less sinusoidal and clearly of even lower frequency. The transverse components (Bx and By) displayed both larger amplitude variations and a much wider scale of frequencies, both lower and higher than those evident in the compressional component. Even with the use of 100-400 mHz bandpass filtering in preparing the Poynting vectors for this interval, the lower panels of Figure 4 contain spikes that reflect large, impulsive variations in the magnetic and electric field (e.g., as shown in Figure 2). Variations in Poynting flux associated with the ~0.1-0.4 Hz compressional wave packets, however, were again essentially absent from the field-aligned Sz component, and were instead mostly directed radially inward (negative in the Sx component).

Figure 5 shows CIS ion energy and pitch angle spectrograms during this same time interval, from 12 to 14 UT October 29, 2003. The energy distributions of protons (panel 1) and oxygen ions (panel 5), indicate significant temporal/spatial variations in energy flux on scales from ~2 min to several tens of minutes throughout this interval. The longer term spatial / temporal dependence of O^+ differed greatly from that of H^+ at the higher energies (above 1 keV): O^+ was the dominant energetic ion near the magnetic equator, with the proton density actually reduced there below its off-equatorial levels. Pitch angle spectrograms of H^+ (panels 2-4) and O^+ (panels 6-8) show that while the more energetic protons were highly anisotropic, the O^+ ions more often exhibited a butterfly distribution (with a reduced flux near 90° pitch angle) or a nearly isotropic distribution. Irregularly spaced, 3-5 min minima in Bx and/or Bz (not shown) corresponded to intensifications in H^+ energy fluxes near 10 keV from 12:23 to 13:00, in an apparently diamagnetic response, but a detailed examination showed that the temporal and often dispersive "pulsing" evident in both ion distributions above ~10 keV after 13:00 was not associated consistently with any temporal features in the magnetic field, and was often not simultaneous in the two species. The only evident correlation between ion fluxes and wave intensity is that as the O^+ flux above ~ 3 keV increased from 12 to 14 UT, the compressional Pc 1-2 waves became more intense and broadband.

4. The November 2003 Storm

As Figure 1 shows, Cluster perigee passes during this storm occurred roughly 1 day before storm onset, 1.5 days after onset, near the end of a very rapid recovery phase, and again 4 days after onset. Pc 1-2 waves were observed only during the November 22, 2003 pass. Figure 6 shows a 0- 5.6 Hz spectrogram of the waves observed by Cluster 4 during this pass (all four spacecraft again observed very similar wave activity). The most intense waves appeared between 08:25 and 08:50 UT near perigee, on L shells ranging from 4.4 to 4.6. With frequency centered near 1.8 Hz, they were predominantly left-hand polarized (as determined using the algorithm of Rankin and Kurtz [1970]). Compared to the local proton gyrofrequency of 5.3 Hz, these waves had a normalized frequency of X = 0.34, well above the He^+ gyrofrequency of 1.32 Hz (X = 0.25). Weaker transverse waves appeared between 08:22 and 08:33 near 2.5 Hz (X = 0.47) and between 08:37 and 08:46 near 3.4 Hz (X = 0.64). In addition, waves with only radial and compressional components appeared between 07:38 and 07:52 UT, with a frequency falling from 2.5 to 2.1 Hz, as the satellite traveled equatorward from L = 6.1 to L = 5.3 in the southern hemisphere.

Figure 7 shows a 1-min sample of these radial/compressional waves, between 07:45 and 07:46 UT. These waves, with ~0.3 nT p-p amplitude, occurred in ~3-second duration wave packets sporadically during this time interval, and showed very little power in the azimuthal (By) component. Three features of these waves are unusual. First, their frequency fell even as L decreased, opposite the commonly observed tendency for ion cyclotron wave frequency to rise as satellites cross L shells to lower values. Second, their frequency is higher than that of the waves that occurred an hour later at lower L, although without knowledge of the equatorial value of **B** on these field lines no reliable estimate of X is possible. Third, although there have been theoretical suggestions that ion cyclotron waves would under certain circumstances veer away from field-aligned propagation [e.g., Rauch and Roux, 1982], we believe this is the first observation of waves with this particular combination of components, which might provide direct evidence for such propagation. If these waves were indeed generated at lower L, possibly nearer the geomagnetic equator, and propagated outward in L after initial generation and propagation along **B**, their observation at larger L values south of the geomagnetic equator follows naturally. The lack of field guiding might be expected to cause the waves to spread out in direction, leading to a rapid falloff in amplitude away from the source region – which might also explain why such waves can only rarely be observed. The combination of a strong source and a reasonably nearby satellite may be needed to make such observations possible. Further comments on this possibility and its consequences will be provided below.

Magnetic field, electric field, and Poynting fluxes are shown for a two-minute interval, from 08:42 to 08:44 UT November 22, 2003, during the strong mostly transverse wave event (Figure 8), with amplitudes up to 10 nT p-p, well beyond typical values. Both the magnetic and the electric field exhibited overlapping packet-like structures, with center separations of ~5 – 20 seconds. The field-aligned Poynting vector component shown in the bottom panel confirms that the wave energy was predominantly field-guided, parallel to **B** (northward). Sz was directed antiparallel to B (southward) during two intervals, near 08:42:08 and 08:42:37, and had equal power northward and southward near 08:42:27, but at all other times shown Sz was northward, and typically with much larger amplitude.

The top panel of the CIS proton spectrogram from Cluster 4 for this day (Figure 9) shows strongly banded proton fluxes with energy peaks near 35 keV, 20 keV, 3.5 keV, and for a shorter time interval, 550 eV. Deep gaps in flux were evident from 07:25 to 09:00 UT between ~5 and 10 keV, and from ~07:45 to 09:00 near 1 keV. Fluxes of protons with energies below 400 eV appeared at the lowest L values. Their energy decreased from 07:45 to ~08:30 and then increased again (as their fluxes intensified) from 08:30 to 09:00. Similar patterns appeared in spectrograms from Cluster-1 and Cluster 3 (although the latter was noisy), but the intense burst of 30 – 300 eV protons near 08:43 UT, toward the end of the interval of 1.8-Hz waves, appeared only at Cluster-4.

Proton densities integrated over the full CIS energy range (not shown) showed broad, gradual increases of roughly 20% (excluding the burst at Cluster 4) at all three spacecraft roughly between 08:30 and 08:50, consistent with the increased fluxes below 1 keV shown in this panel (slight temporal differences in these increases between spacecraft were consistent with their different orbits). Densities were a factor of two lower between 07:40 and 07:50 UT, when the compressional waves were observed. There was a nearly monotonic density increase from ~07:40 to 08:15 at all three spacecraft, with no features to distinguish the interval of observations of radial/compressional waves (from 07:40 to 07:50 UT) from the later interval (07:50 – 08:15 UT) when no waves were observed.

The bottom panel of Figure 9, showing pitch angle distributions of protons with energy > 10 keV, indicates that such protons were anisotropic from ~07:45~09:00 UT, and most strongly so between 08:25 and 08:50, at the time of the 1.8 Hz wave activity. The pitch angle distribution was somewhat less anisotropic from 07:40 to 08:15, a span which includes the time of the 2.1-2.5 Hz oblique waves (07:40-07:50 UT) but also the interval from 07:50 to 08:15 when no waves were observed in any component. Protons in the 1-6 keV and 10-800 eV energy ranges (middle two panels) both exhibited butterfly distributions (with flux minima both perpendicular and parallel/antiparallel to **B**) during much of the perigee pass shown. Fluxes of 1-6 keV ions had similar intensity during much of the interval, while fluxes of 10-800 eV ions increased by over an order of magnitude, peaking at the times the 1.8 Hz waves were observed.

5. Comparison of Ion Distributions During the Two Storm Intervals

In contrast to the October 29 pass, no Pc 1-2 waves were evident at any of the four Cluster spacecraft during the October 27, 2003 pass, which occurred roughly two days before storm onset. CIS energy and pitch angle spectrograms (not shown) indicated that energetic protons were highly structured in energy, similar to what was observed during November 22, with a deep minimum near 10 keV, dropping to near 5 keV at higher latitudes (and higher L shells), and with >10 keV protons strongly peaked near 90° pitch angle near the magnetic equator. Very similar energy and pitch angle structure in the energetic proton distributions appeared during the October 31-Nov. 1 cluster pass, which occurred near the end of a very rapid recovery phase. However, proton fluxes down to 2 keV were strongly peaked near 90° pitch angle near perigee, at which time two bursts of weak, purely transverse wave activity centered near 0.5 Hz were observed. The CIS ion data for November 19-20 and November 24 also showed deep flux minima in H^+ near 10 keV at higher latitudes. In contrast to the particle fluxes observed during these passes before and after the storm, during the October 29 pass all energetic ion species showed significant temporal variations but exhibited no similar detailed structuring in energy.

Table 1 shows off-equatorial densities of energetic H^+, He^+, and O^+ ions during the six passes shown in Figure 1, as measured by the CIS CODIF instrument. Note, however, that as panels 1 and 5 of Figure 5 suggest, the upper energy range of increased fluxes of H^+ and O^+ ions may well extend beyond the 40 keV limit of this instrument. Unfortunately, no data at higher energies were available from the RAPID instrument for October 29, and only limited data were available for November 22. As Table 1 shows, O^+ densities were roughly an order of magnitude larger before the October storm than before the November storm, although post-storm levels receded to nearly equal values (as observed during the third pass in each set). During the October 29 pass, O^+ densities equaled or exceeded H^+ densities even far from the equator, and as Figure 5 suggests, O^+ energy fluxes increased and H^+ energy fluxes decreased as Cluster neared the equator. These observations of greatly increased O^+ levels were corroborated by Nosé et al., [2005], who found using Geotail EPIC ion data in the range 9 – 210 keV that the O^+ /H^+ energy density ratio in the plasma sheet during the October storm interval reached the extremely large value of 10-20, a factor of at least 5 larger than the largest value previously recorded for a magnetic storm. Similar but smaller variations were evident in the CIS He^+ ion fluxes: flux levels were higher before the October storm, but receded to similar levels afterward.

6. Discussion

The availability of magnetic and electric field data and multispecies energetic ion data for these Cluster passes allow us to provide a reasonably complete picture of these wave events, although the lack of full energy coverage of the energetic ions prevents a full modeling effort. In this section we will first review prior observations and selected theoretical studies, and will then compare them to the Cluster data.

6.1 Wave Modes in a Multi-ion plasma

In a cold plasma, there are two propagating modes at frequencies near and below the ion gyrofrequencies. The observations presented in this study have non-negligible amounts of oxygen, helium, and hydrogen present. For frequencies less than the heaviest ion cyclotron frequency, the two branches are the compressional magnetosonic wave and the shear Alfven wave. The shear Alfven-ion cyclotron branch propagates along **B** while the magnetosonic branch tends to be unguided. A magnetosonic wave will tend to propagate in the direction of its wave vector, which will bend away from regions of increasing magnetic field strength and into regions of increased density. It is for this reason that magnetosonic waves tend to refract and propagate outward in L unless there is some density gradient (e.g., the plasmapause) to guide them down the field, as is commonly seen in ray-tracing studies [Rauch and Roux, 1982]. Near the heavy ion cyclotron frequency, the wave modes become circularly polarized with the shear branch connecting to the left-hand circularly polarized (LHCP) ion cyclotron branch while the compressional wave becomes right-hand circularly polarized (RHCP) and does not interact as efficiently with the heavy ions.

Between the ion cyclotron frequencies, the modes are more complicated. For parallel propagation, the waves are decoupled and the magnetosonic branch is not affected by the ion resonances while the LHCP wave propagates in bands between the various cyclotron frequencies. For oblique propagation the wave modes couple near the cross-over frequency and there can be a change in polarization along the same dispersion surface between RHCP and LHCP. Where the wave is LHCP, it is guided along the magnetic field, but where it becomes RHCP it tends to radiate across the field. For large perpendicular wavevector, there is only one propagating mode, which is primarily linearly polarized and propagates between the cyclotron frequencies and the ion-ion hybrid (or Buchsbaum) frequencies. Because LHCP waves commonly refract as they propagate along magnetic field lines into regions of stronger magnetic field, they commonly reflect near this frequency and cannot propagate through an evanescent stop band. Gradients in the magnetic field strength allow for coupling between the propagating and evanescent modes which allows wave energy to pass through the stop bands so that in spite of the fact that ray tracing studies indicate that waves cannot reach the ground (e.g. Rauch and Roux [1982]; Horne and Thorne [1993]) significant wave power can reach the ground due to mode conversion and/or tunneling [Johnson et al., 1989; Johnson et al., 1995; Johnson and Cheng, 1999], as observed by, for example, Perraut et al. [1984], Anderson et al. [1996b], Engebretson et al. [2002], and Arnoldy et al. [2005].

Locally, the wave modes are unstable due to a number of free energy sources including ion anisotropy, loss cones, ring-beam distributions, and/or energetic electron and ion beams. The transverse branch which is mostly LHCP exhibits significant instability due to wave particle cyclotron resonance with ions. Oscarsson and Andre [1986] and Ludlow [1989] presented linear growth rate calculations for ion cyclotron waves in a multicomponent plasma, the former including H^+ and He^+, and the latter including O^+ as well. These studies found that although growth rates peaked when the wave vector k was directed along **B** ($\theta = 0°$), they did not depend strongly on θ for $\theta < 30°$. Further, for particular loss-cone ion distributions, Oscarsson and

Andre [1986] found that growth occurred only at wave normal angles greater than 45°. Ludlow [1989] did, however, find that significant Landau damping occurred for larger θ, again consistent with the rarity of observations of obliquely propagating Pc 1-2 waves.

The primarily RHCP compressional/magnetosonic wave branch is not subject to bulk cyclotron instabilities, although it may be unstable to velocity space driven instabilities such as in the foreshock or strong cyclotron damping due to Doppler shifted wave-particle interactions near the ion-ion hybrid resonance. Perraut [1982] found that magnetosonic waves can be destabilized by energetic protons ($E \sim 15$ keV) with an anisotropic, ring-like distribution function at frequencies above the hydrogen cyclotron frequency. Perraut [1982] cited two modeling efforts which showed that the free energy source which feeds the magnetosonic waves is a $\partial f / \partial v_\perp > 0$ kind of source (ring-like or loss cone) rather than one based on temperature anisotropy ($T_\perp > T_\|$).

Ray tracing provides information about how much waves grow as they propagate and where the energy eventually goes. Rauch and Roux [1982] used ray tracing studies to examine the propagation paths for LHCP waves in a multi-ion plasma and found that (a) waves below the heaviest cyclotron frequency are guided along the field, (b) waves just below the proton gyrofreuqency are trapped between the equator and the ion-ion hybrid resonance, and (c) left-handed waves in the equatorial region with frequency between the cutoff frequency and the crossover frequency in an H^+ - He^+ plasma (denoted Class II), were unguided. When launched at the equator at various angles (including along **B**) the ray path quickly deviated outward, toward regions where the gyrofrequency was lower and the wave polarization reverses. They concluded that such waves would not experience a large gain, and thus would seldom be observed by spacecraft such as GEOS. Kozyra et al. [1984] and Horne and Thorne [1993] performed similar ray tracing studies, and came to similar conclusions.

Although the earlier ray tracing efforts found refraction of waves off-equator, the observations reported here have noted purely compressional waves over the entire magnetic latitude range from -35° to +20° MLAT. This suggests either that wave growth occurs predominantly at angles near 90° from **B**, or, if wave growth occurs over a range of angles, that there was an extremely strong tendency for wave vectors to align with the gradient of the magnetic field, which in the equatorial region at least is perpendicular to the field direction. Our observation of Poynting flux directed radially during the event reported here, near the equator, is consistent with this picture.

6.2 Waves in the "oxygen band"

In the October 29, 2003 event, the most prominent wave observations were compressional waves near the oxygen cyclotron frequency. The effects of heavy ions on the growth and propagation of Pc 1-2 waves were first reported by Young et al. [1981] and Roux et al. [1982], who observed minima in wave power near the He^+ gyrofrequency ($f_{He}{}^+$) in data from GEOS 1 and 2, and by Mauk et al. [1981] and Fraser [1982], who observed similar effects in data from ATS-6. Anderson et al. [1992a,b] found a similar occurrence minimum in data from AMPTE/CCE.

Waves occurring below $f_O{}^+$ were reported somewhat less frequently. Inhester et al. [1984] found large-amplitude waves with frequency below $f_O{}^+$ in GEOS 2 data during an interval of several successive substorms. Fraser et al. [1992] reported observations of left-handed, transverse 0.1 Hz Pc 2 waves near the O^+ gyrofrequency in the near-equatorial outer dusk plasmapause region, again after an interval of strong substorm activity. Their observations showed a minimum in wave power between $f_O{}^+$ and f_{XO}, the O^+ crossover frequency. Bräysy et al. [1998] reported a sequence of Pc 1-2 waves observed during the April 1993 magnetic storm by the F1 double-probe electric field instrument on the Freja satellite. A number of oxygen band waves were observed, but were limited to a 7-hour interval during the main phase of the storm, and below 60° invariant latitude ($L = 4$). Wave orientation was not available, but the authors concluded that the observations were consistent with mainly transverse polarization. All of the oxygen band waves were found in the evening-midnight sector, and none in the prenoon sector. They attributed this local time pattern to the presence of a spatially limited (partial) ring current dominated by O^+, and suggested that ion cyclotron waves might be the dominant factor in the loss of oxygen ions, and hence be responsible for the rapid initial recovery of great storms. Bräysy et al. [1998] concluded that only during strong magnetosphere perturbations, from substorm and/or storm activity, are a sufficient number of O^+ ions extracted from the ionosphere (and possibly, based on the data presented here, also energized) in order for the O^+ wave band to be generated. Similarly, Bräysy and Mursula [2001] found four O^+ band waves between 08:00 and 19:00 MLT in a study of 31 Pc 1-2 events observed by the electric field instrument on the

Polar satellite and simultaneously on the ground at the Sodankylä observatory, each with frequency near 0.15 Hz, in the invariant latitude range from 57 to 63°, but no polarization information was given.

Although the absence of morning sector waves below f_{O}^{+} in the Bräysy et al. [1998] study may indeed be due to the localization of intense O^{+} fluxes to the afternoon sector during the storm they observed, during the October 29, 2003 Cluster pass O^{+} was the dominant ion on the dawn side. Thus although the physical mechanism they invoked might be valid, it cannot be applied to all magnetic storms. Consistent with this conclusion, we note that in contrast to the above local time pattern, Erlandson and Anderson [1996], using electric and magnetic field data from the low-altitude polar-orbiting Dynamics Explorer-2 satellite, found numerous O^{+} band events in the *L* range from ~2 to 4 at local times before 08:00, as well as He^{+} band events at *L* values from ~2.5 to 5, but very few such events at later local times. A gap in wave occurrence corresponding to f_{O}^{+} was clearly evident in their data set.

Rauch and Roux [1982] showed theoretically that the presence of cold, heavy ions would introduce the observed gaps in transversely polarized wave power near f_{He}^{+} and f_{O}^{+}. Kozyra et al. [1984], who included in their wave growth model multiple ion species in the energetic anisotropic components of the magnetospheric plasma, as well as in the cold component, found that enhanced peaks in the growth rate appeared just below the O^{+} and He^{+} gyrofrequencies, and also that heavy ions could suppress the wave growth, either partially or totally, at higher frequencies. Consistent with this result, there is no evidence that waves much above f_{He}^{+} were excited during the October 29, 2003 wave event.

Both Kozyra et al. [1984] and Horne and Thorne [1993] found that, for model runs in which the number densities of energetic H^{+} and O^{+} were set to equal values of 5 cm^{-3} and 2 cm^{-3}, respectively, the spatial growth rate of the O^{+} branch waves maximized at $f = 0.45\ f_{O}^{+}$, which matches well with the ~0.15 Hz frequency of compressional waves observed on October 29 between 12:15 and 12:45 UT. Their models also showed that spatial growth rates above f_{He}^{+} peaked in the unguided mode, and also noted that the wave normal angle increased very quickly along the ray path, with waves rapidly moving to larger L as they moved away from their origin at the equator.

Kozyra et al. [1984] also showed that the existence of oxygen ions enhances wave growth below the O^{+} gyrofrequency relative to the two higher wave bands. It would be expected that these oxygen band waves could easily propagate to the ground because of the absence of stop bands at lower frequencies [e.g., Thorne and Horne, 1997]. Notably, however, Bräysy et al. [1998] reported no evidence of such waves at near-conjugate ground stations. Ground data was instead dominated by Pi C and Pi B type activity. Similar broadband activity only (not shown) was observed by us at an array of search coil magnetometers in Antarctica during the main phase of the October 29, 2003 storm, but because the lowest latitude station in this set was at 66.5° geomagnetic latitude ($L = 6.3$), we cannot be confident that none of the wave power observed at Cluster reached the ground.

Thorne and Horne [1997] investigated the effects to be expected when the densities of ring current O^+ ions neared or exceeded the densities of ring current protons. For modest storms, with the O^+ fraction less than 30%, they predicted strong wave growth above f_O^+ due to cyclotron resonance with anisotropic ring current H^+ ions, and increased anisotropy of energetic resonant O^+ ions. For the most intense storms, with ring current O^+ fractions above 60%, they predicted that cyclotron absorption by resonant O^+ would be sufficient to totally suppress wave excitation above f_O^+. We note that although the CIS observations of energetic O^+ do not show any significant anisotropy, contrary to the above prediction, the generation of waves above f_O^+ was clearly suppressed at all latitudes, and no such waves were evident more than 15° MLAT away from the equator.

Despite the several areas of agreement with our observations, however, it must be noted that while Kozyra et al. [1984] and Horne and Thorne [1993] found enhanced growth rates below the oxygen cyclotron frequency, the modes they studied were transverse, not compressional. The growth of such waves would not explain the unique polarization of the observations reported here unless mode coupling occurred from this wave branch to the other branch. In addition, the above theories do not give a good match to the observations of waves just above f_O^+.

This focus on transverse wave modes reflects the preponderance of transverse, field-guided waves found in satellite-based observational studies, and it is of course not possible to determine the polarization of Pc 1-2 waves in space from ground observations. As noted above Perraut [1982] observed compressional waves at frequencies above the proton gyrofrequency, and Anderson et al. [1992] noted the occasional observation of compressional waves in data from the AMPTE CCE satellite near the magnetic equator. Further, no compressional waves have evidently been reported at middle or high magnetospheric latitudes (e.g., the Erlandson et al. [1990] study using Viking data). Anderson et al. [1992b] did suggest oblique propagation as a possible explanation for the linear and/or right-hand polarization they observed frequently in the dawn sector.

The theoretical challenge is exacerbated in that all of the crossover, cutoff, and ion-hybrid frequencies are well above the oxygen cyclotron frequency (and essentially off the spectrograms). The means that the ion whistler branch is evanescent and also that waves on the compressional branch are, according to current theory, probably not very oblique (otherwise they also would be cut off). One possibility is that the waves are generated on the shear-cyclotron branch (growth is fastest at parallel propagation) and then as they propagate earthward they become more oblique and couple with the compressional branch (as the wave propagation becomes more oblique, the magnetosonic cutoff moves up through the oxygen cyclotron frequency). Efforts to confirm this possibility using a nonlocal simulation code will be presented in a future study.

Finally, we note that one consequence of a large O^+ density might be to increase the quality of a near-equatorial wave cavity (waves do not reach the ionosphere), and hence contribute to the large wave amplitudes observed, and hence possibly have a greater parasitic effect on radiation belt electrons.

6.3 Oblique waves

The waves near 7:45 UT on November 22, which apparently were propagating obliquely, had a frequency of 2.3 Hz, which is well above the crossover frequency calculated using the observed H^+, He^+, and O^+ energetic ion densities for this interval. Consequently, when they were observed at Cluster's location these waves were likely to be on the magnetosonic-whistler branch above the crossover frequency. The whistler branch itself is probably not unstable above the crossover frequency, so it seems unlikely that the waves were excited locally. This conclusion is supported by data from CIS showing little or no difference between the proton distributions observed during the interval of wave activity and those afterward. As noted earlier, however, such waves may originate from a proton cyclotron instability on a flux tube at lower L that mode converts to the magnetosonic branch and becomes unguided. For such mode conversion to be effective, the waves need to be generated nearly field aligned. They would reflect at some latitude off the equator, couple to the magnetosonic branch as they propagate back equatorward, and then become unguided and veer radially outward. Unfortunately, the amplitude of these waves was too small to allow a reliable determination of the Poynting vector.

6.4. Direction of propagation of transversely polarized wave power

Many early ground-based studies of Pc 1-2 waves noted their highly structured appearance in Fourier spectrograms, and attributed the observed temporal repetition to the existence of bouncing wave packets that, although generated near the magnetic equator and guided along the magnetic field, would reflect from the ionosphere and return equatorward to be re-amplified [e.g., as summarized by Kangas et al., 1998]. However, several satellite studies have called that picture into question [e.g., Mursula et al., 1997, 2001]. Loto'aniu et al. [2005], who provide the most comprehensive recent study and review of this issue, used both magnetic and electric field data from the CRRES satellite in the *L* range from 3.5 to 8.0 to determine Poynting vector directions for all Pc 1-2 wave events observed during that spacecraft's ~15-month lifetime. They found unidirectional energy propagation away from the equator for all events located above 11° |MLAT|, but bidirectional propagation, both away and toward the equator, for events observed below 11° |MLAT|. Observations of propagation by Erlandson et al. [1990; 1996] using Viking satellite data at ~3R_E altitude far from the magnetic equator showed purely downward propagation (toward the ionosphere), as did those by Arnoldy et al. [2005], using Polar satellite data near -22° MLAT. Most recently, Engebretson et al. [2005b] found a similar propagation dependence, with mixed direction within approximately ±20° MLAT, and consistently toward the ionosphere for higher latitudes, during three roughly field-aligned passes of the Polar satellite in the outer magnetosphere, near $L = 9$. The predominantly northward propagation observed for the transverse wave event from 08:25 to 08:50 UT on November 22, 2003 is certainly consistent with these earlier observations.

We suggest that the mixed directions observed in the above studies near the equator is evidence of wave reflection at the off-equatorial magnetic latitude corresponding to the ion-ion hybrid frequency. Waves that reflect would then set up a standing (bi-directional) pattern in the equatorial magnetosphere. Waves that tunnel through would tend to be absorbed in the ionosphere and not be able to return to equatorial latitudes.

6.5 Effects of cool plasma

The observations on November 22, 2003 highlight the importance of cool plasma, in addition to the more energetic ring current and/or plasma sheet ions, in governing the instability of magnetospheric plasmas to ion cyclotron waves. A ~20% increase in proton density below ~ 1 keV corresponded to the time of Pc 1 wave observations at all four Cluster spacecraft. (Curiously, the transient sharp increase of 30-300 eV protons observed by Cluster-4 near 08:43 UT appeared to have no distinguishing effect on the waves observed by that spacecraft.) Engebretson et al. [2002] similarly found, using data from the Polar satellite at ~ 45° MLAT, that although distributions of protons that were highly structured in energy and highly anisotropic at ring current energies were often observed over large ranges of L in the outer magnetosphere, they were in many cases associated with transverse Pc 1-2 waves only when large fluxes of cool ions were also present. This "spatial" category of events presented by Engebretson et al. [2002] matches well to the predominantly transverse wave event observed by all four Cluster spacecraft on November 22, 2003 as well as to other Pc 1-2 events we have observed in the Cluster perigee data set. Similarly, Arnoldy et al. [2005] also found that greatly increased fluxes of lower energy protons (100s of eV to a few keV), predominantly aligned along **B**, were important in determining whether the population was unstable at a given time.

7. Summary

This study has documented unusual Pc 1-2 wave activity and associated energetic ion characteristics observed by the Cluster spacecraft on two perigee passes during the extreme geomagnetic storms of late October and November, 2003.

1. Two aspects of the waves observed on October 29, 2003 provide interesting puzzles in light of theoretical predictions for storm-time conditions during which the ring current is dominated by O^+. First, although narrowband waves with frequency near 1/2 f_{O^+} and the absence of significant (or any) waves above f_{O^+} have been predicted for the transverse mode, there has evidently been no prediction that under such conditions the waves should be purely compressional, both at the equator and for a considerable latitudinal extent (-35° to +20° MLAT). Moreover, there is further no evident theoretical prediction for the occurrence of wave power that essentially spans the entire O^+ frequency band, whatever its polarization. Second, prior ray tracing studies suggest that the Poynting vector associated with compressional waves on the magnetosonic branch should refract and propagate outward, but we have instead observed

radially inward direction of the Poynting vector associated with the compressional waves observed near the equator. This observation is, we believe, the first determination of such propagation in Earth's magnetosphere, although as noted above such radially inward alignment, in the direction of a plasmapause density gradient, has been predicted on the basis of linear theory.

2. The most intense wave event observed by Cluster on November 22, 2003, from 08:25 to 08:50 UT, fits reasonably well within our current and evolving understanding of ion cyclotron wave growth. Waves were primarily transverse, propagated away from the equator, and were predominantly left handed. However, consistent with other recent studies using Polar magnetic field and ion data [Engebretson et al., 2002; Arnoldy et al., 2005], we note that although the anisotropy of the ring current was high during the entire November 22 perigee pass, waves were observed only in association with intensifications of ion fluxes below 1 keV.

3. The waves observed from 07:38 to 07:52 UT November 22, 2003 appear to be the first instances reported of Pc 1 waves below f_{H^+} directed oblique to **B**. Because of this oblique, unguided propagation, Cluster most likely did not pass through the flux tube on which these waves were generated. Although it is consistent with existing theory that the waves were generated at lower *L* and veered outward toward regions of weaker field, the absence of in situ data at these lower *L* values severely limits our knowledge of the plasma conditions under which they were generated.

We anticipate further studies of such waves as they appear in subsequent Cluster passes, and we hope the presentation here will stimulate extensions of the current theory of these waves to the extreme conditions that have now been shown to occur during such large magnetic storms.

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Table 1. CIS ion densities (#/cc) for three passes each during the time of the October and November 2003 magnetic storms. Data shown were obtained one hour before and after perigee in order to avoid contamination from radiation belt particles.

	October Storm				November Storm		
	Oct. 27	04:00 UT	06:00 UT		Nov. 19-20	22:50 UT	00:50 UT
H^+		1	1	H^+		0.8	0.5
He^+		0.08	0.08	He^+		0.03	0.05
O^+		0.5	0.5	O^+		0.04	0.05
	Oct. 29	12:30 UT	14:30 UT		Nov. 22	07:40 UT	09:40 UT
H^+		2	2	H^+		1	1
He^+		0.2	0.15	He^+		0.04	0.03
O^+		2	2.5	O^+		0.2	0.1
	Oct. 31-Nov. 1	22:10	0:10		Nov. 24	16:45 UT	18:45 UT
H^+		0.9	1	H^+		1	1
He^+		0.09	0.11	He^+		0.08	0.08
O^+		0.4	0.5	O^+		0.3	0.2

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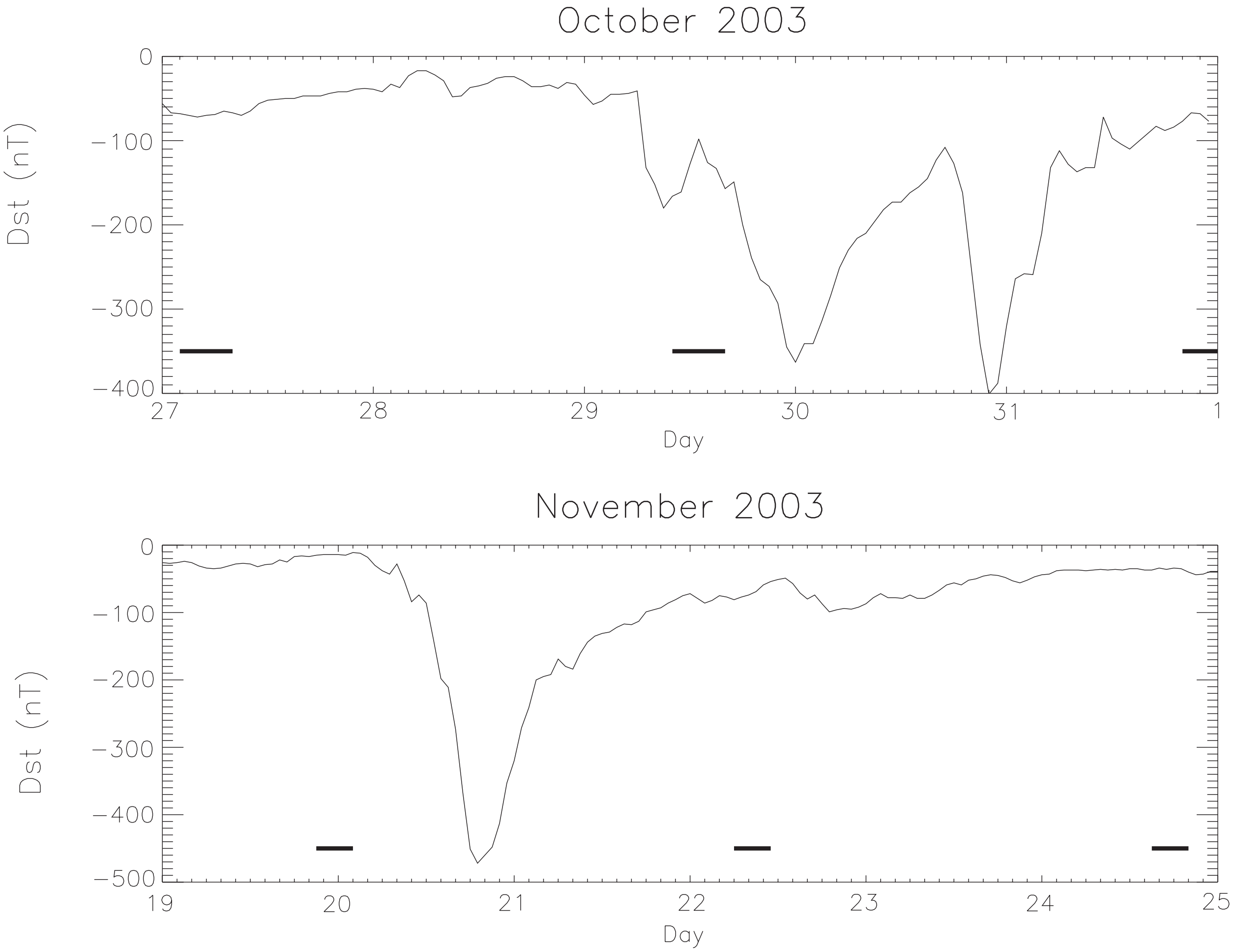

Figure 1. D_{st} index for the October and November 2003 magnetic storms. Upper panel: October 27-31, 2003. Lower panel: Nov. 19-24, 2003. The thick line segments near the bottom indicate the times of dawn sector perigee passes of the Cluster spacecraft during these intervals.

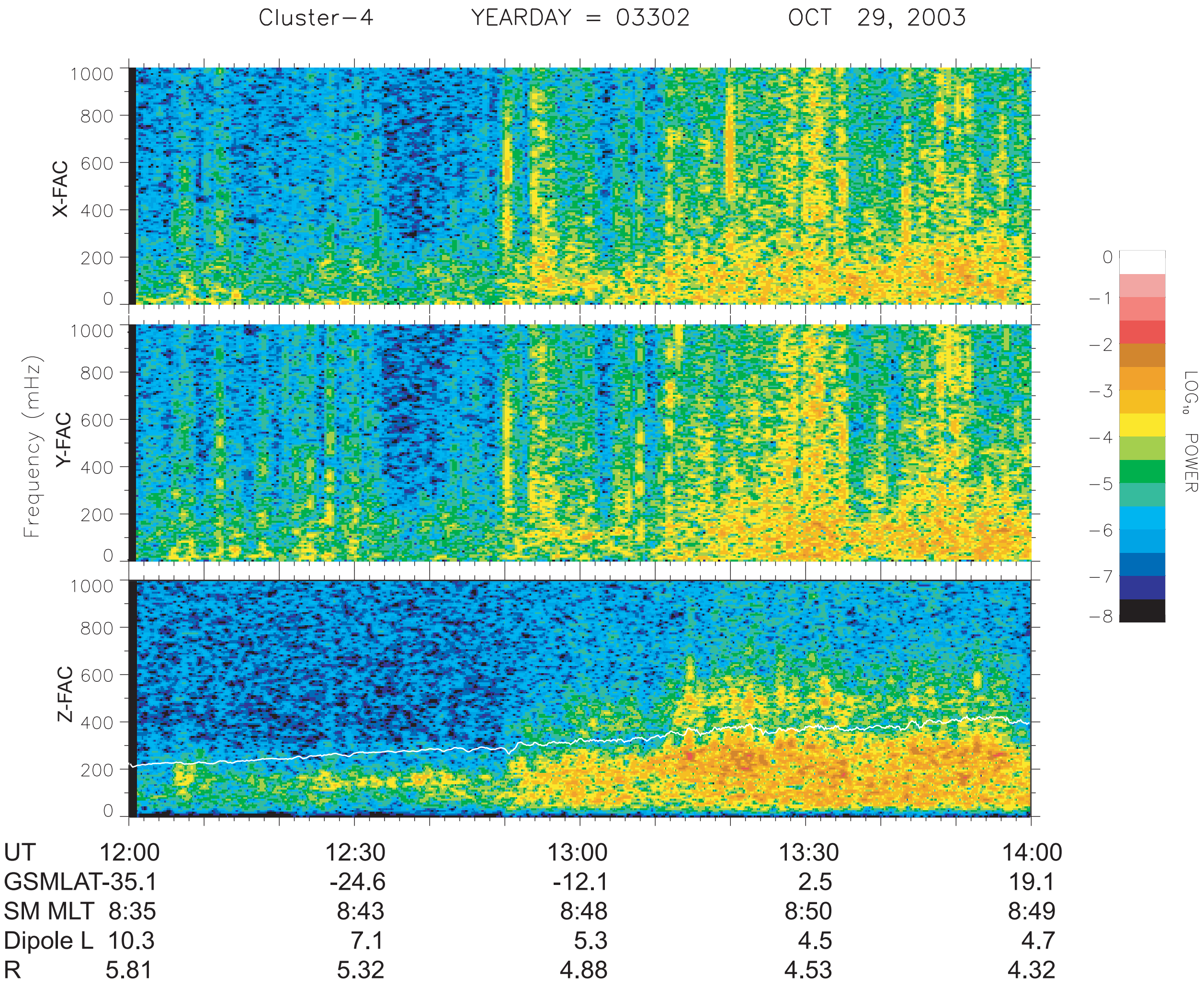

Figure 2. Fourier spectrogram of differenced magnetic field data from Cluster-4 from 12:00 to 14:00 UT October 29, 2003 in 15-minute averaged mean field-aligned coordinates. Wave power is color-coded according the color bar at the right as a function of UT (horizontal scale) and frequency (vertical scale). From top to bottom the panels show the radial (Bx), azimuthal (By), and field-aligned (Bz) components. The white trace in the lower panel is the local O^+ gyrofrequency.

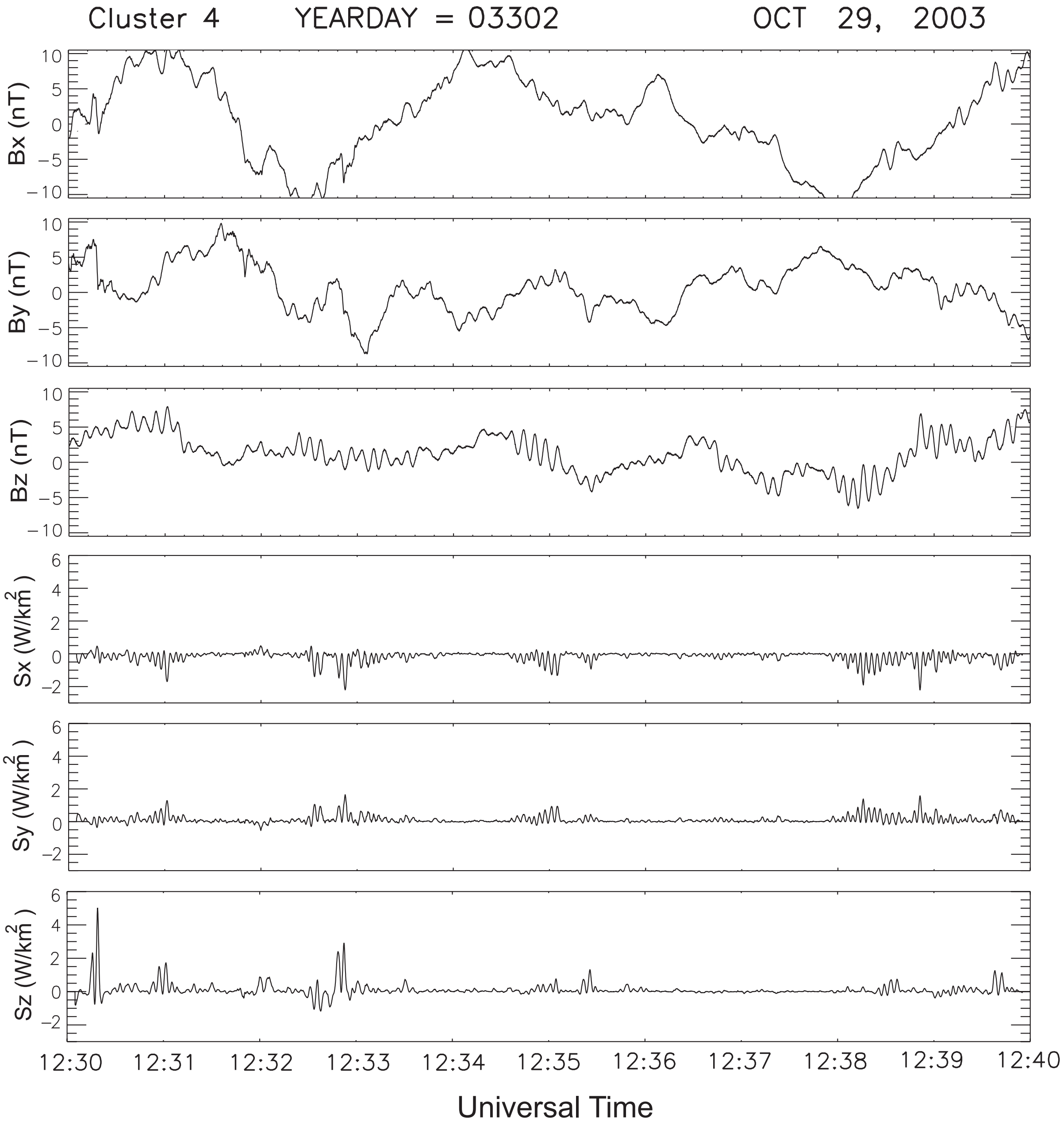

Figure 3. Plots of the vector magnetic field in mean field-aligned coordinates measured by the Cluster-4 spacecraft, and of the Poynting vector, calculated as described in the text using measured electric and magnetic field data, from 12:30 to 12:40 UT. All components for each vector are plotted using the same vertical scale.

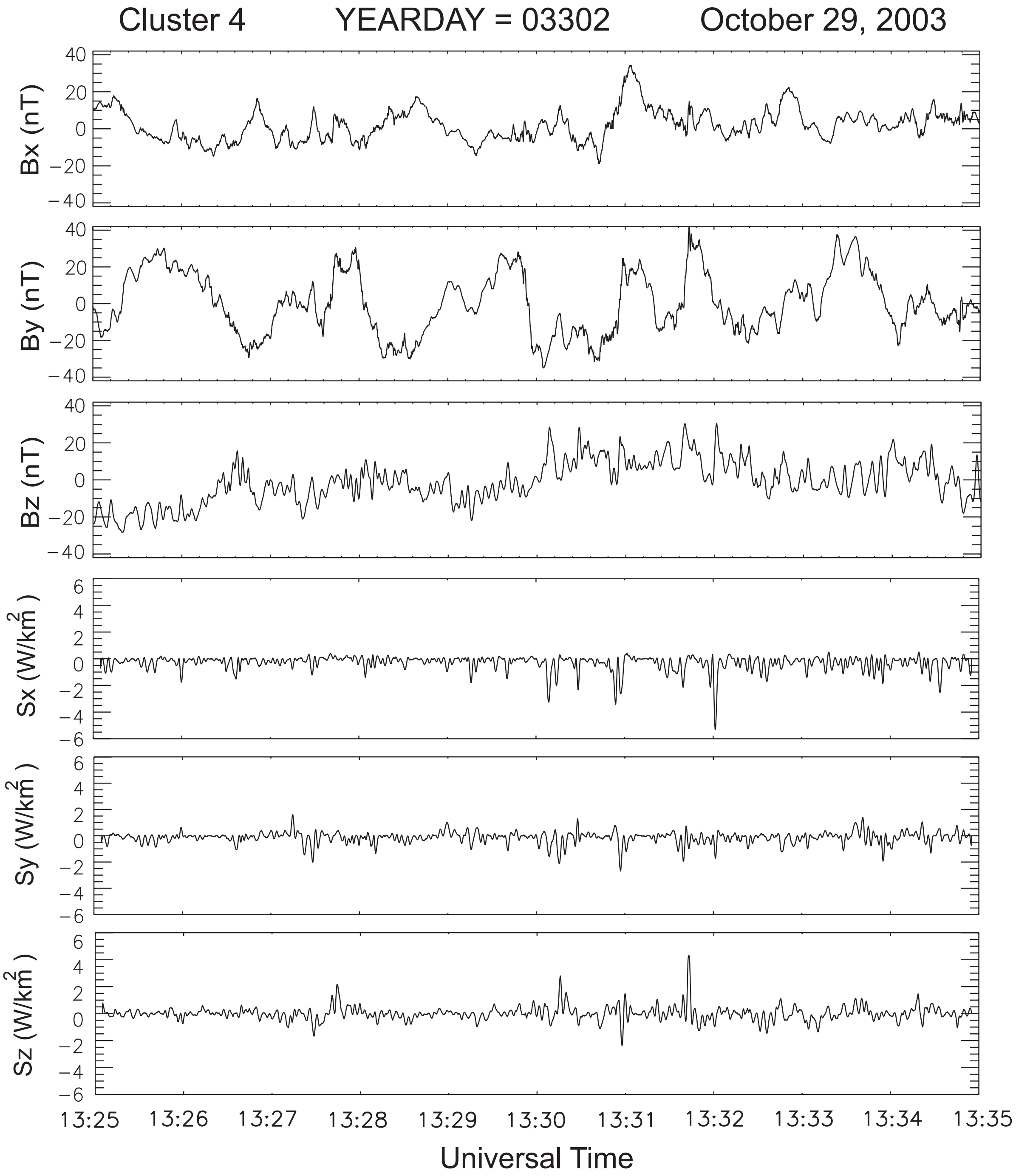

Figure 4. Plots of the vector magnetic field in mean field-aligned coordinates measured by the Cluster-4 spacecraft, and of the Poynting vector, from 13:25 to 13:35 UT October 29, 2003. All components for each vector are plotted using the same vertical scale.

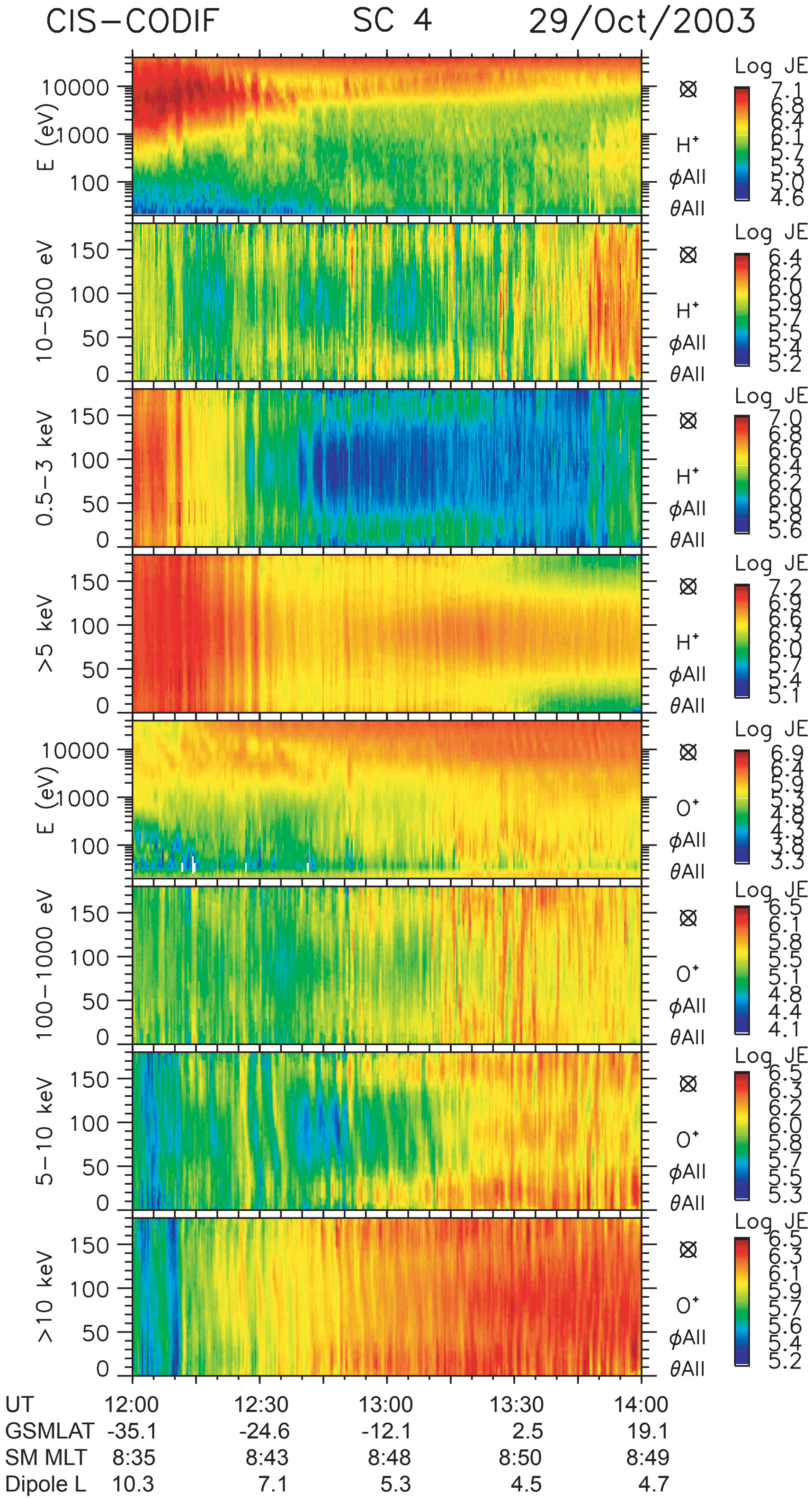

Figure 5. Energy and pitch angle spectrograms of protons and O ions observed by the Cluster-4 CIS instrument from 12 to 14 UT October 29, 2003. Panels 1 and 5 show H^+ and O^+ energy flux as a function of energy (vertical scale) and time (horizontal scale) according to the logarithmic color bars at right. The remaining panels show H^+ and O^+ energy fluxes as a function of pitch angle (0° to 180°) for three energy ranges, each according to its own color bar.

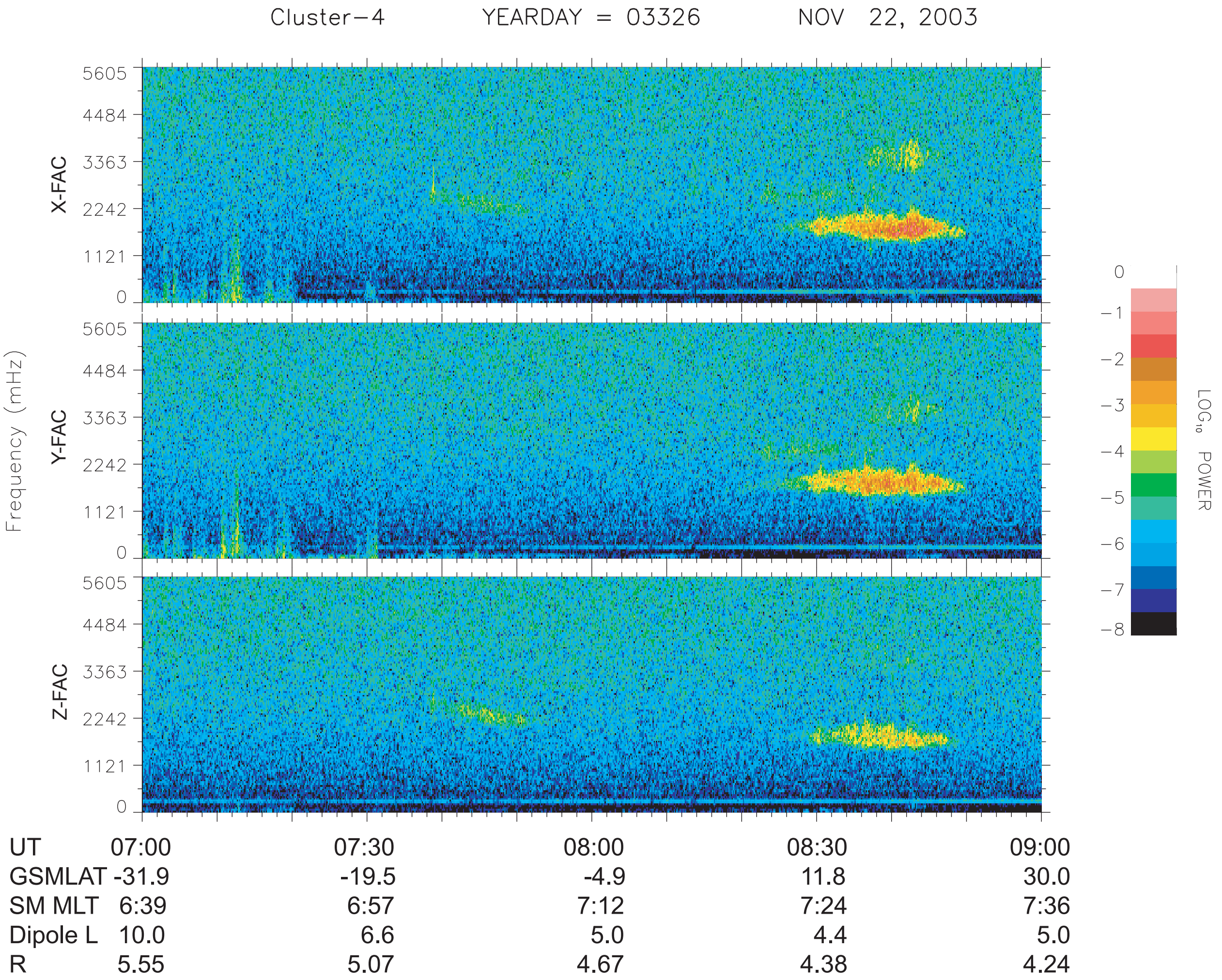

Figure 6: Fourier spectrograms of differenced magnetic field data from Cluster-4 from 07:00 to 09:00 UT November 22, 2003 in 15-minute averaged mean field-aligned coordinates, as in Figure 2.

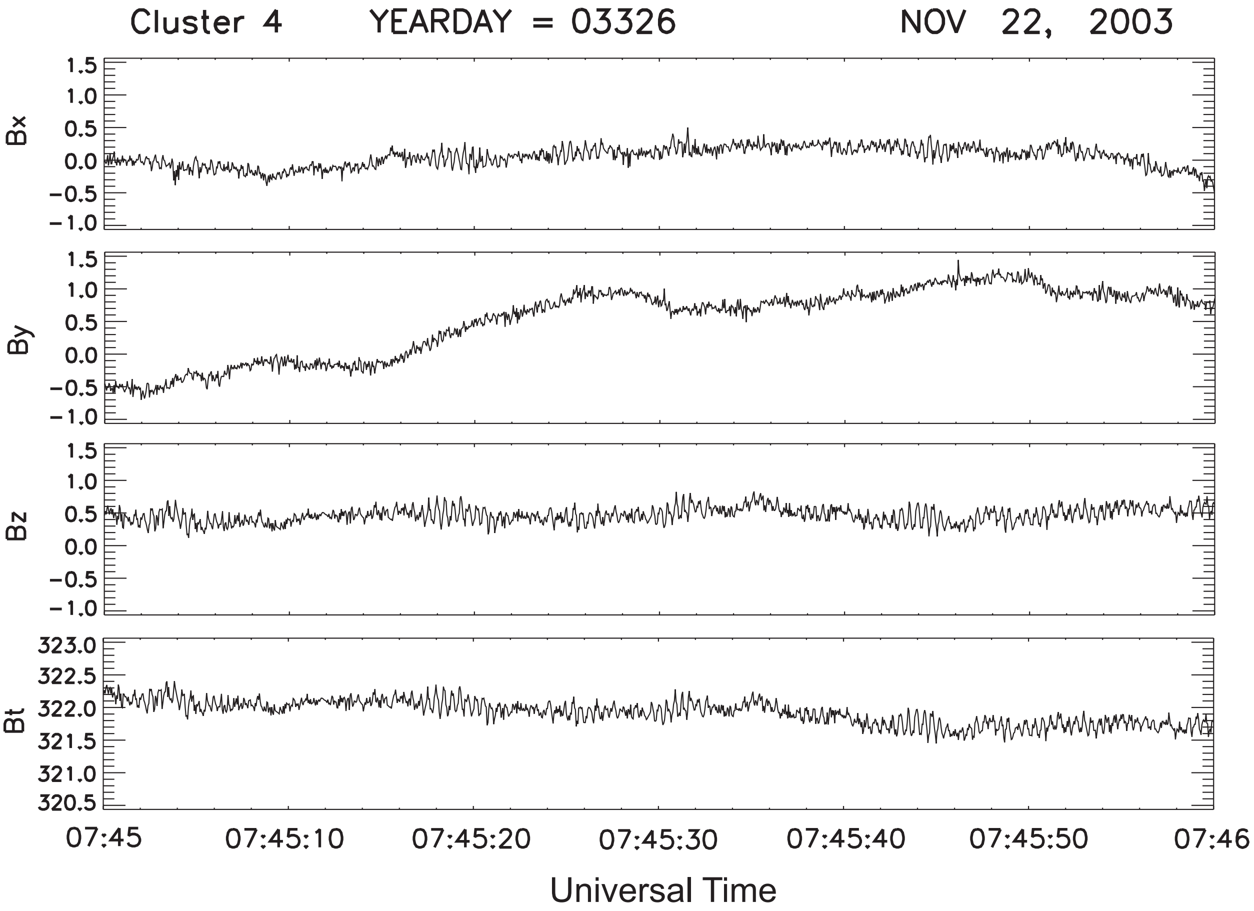

Figure 7. Plot of the vector magnetic field in mean field-aligned coordinates measured by the Cluster-4 spacecraft, from 07:45 to 07:46 UT November 22, 2003.

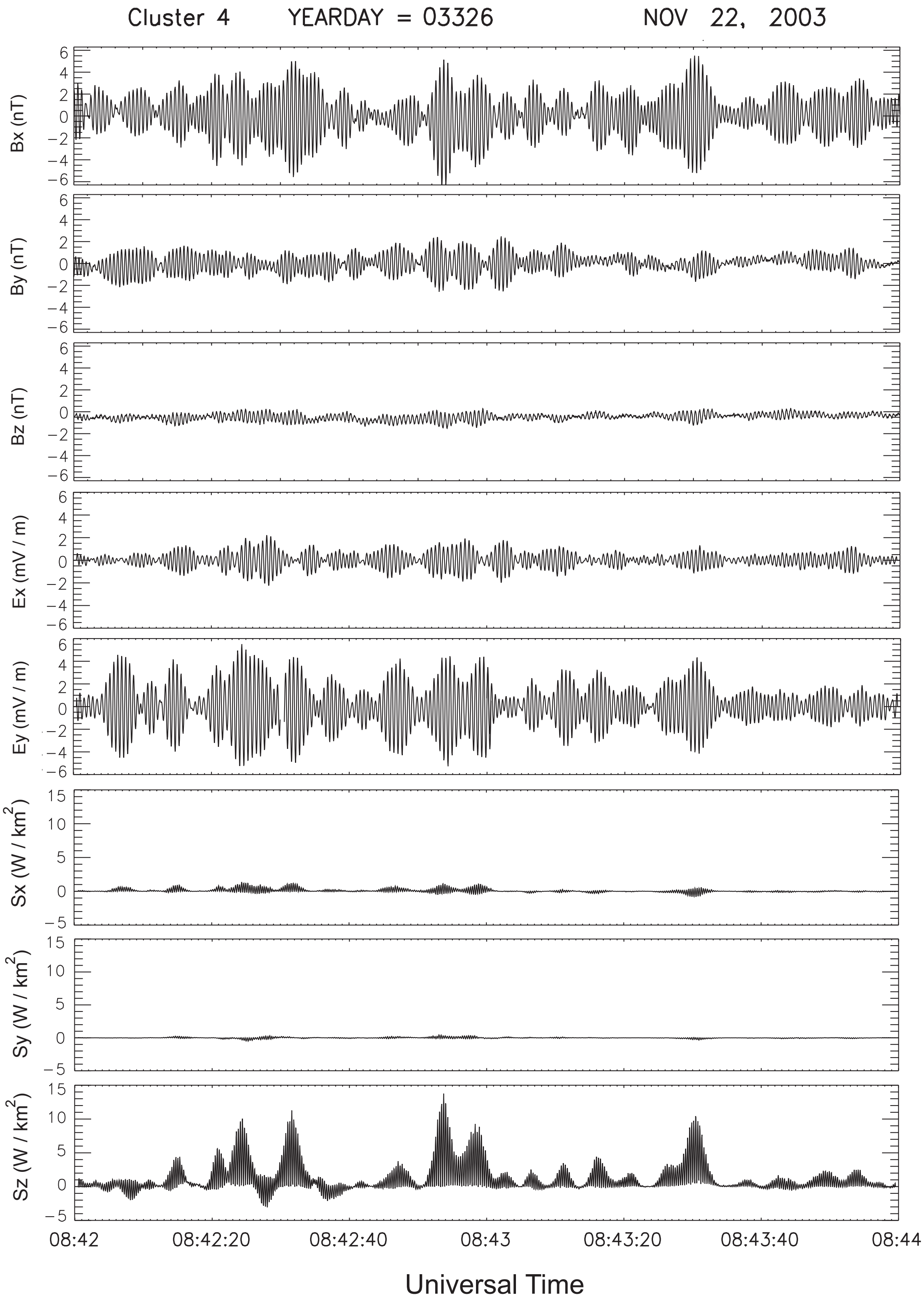

Figure 8. Plots of the vector magnetic field, electric field (transverse components), and Poynting vectors in mean field-aligned coordinates measured by the Cluster-4 spacecraft, from 08:42 to 08:44 UT November 22, 2003. All components for each vector are plotted using the same vertical scale.

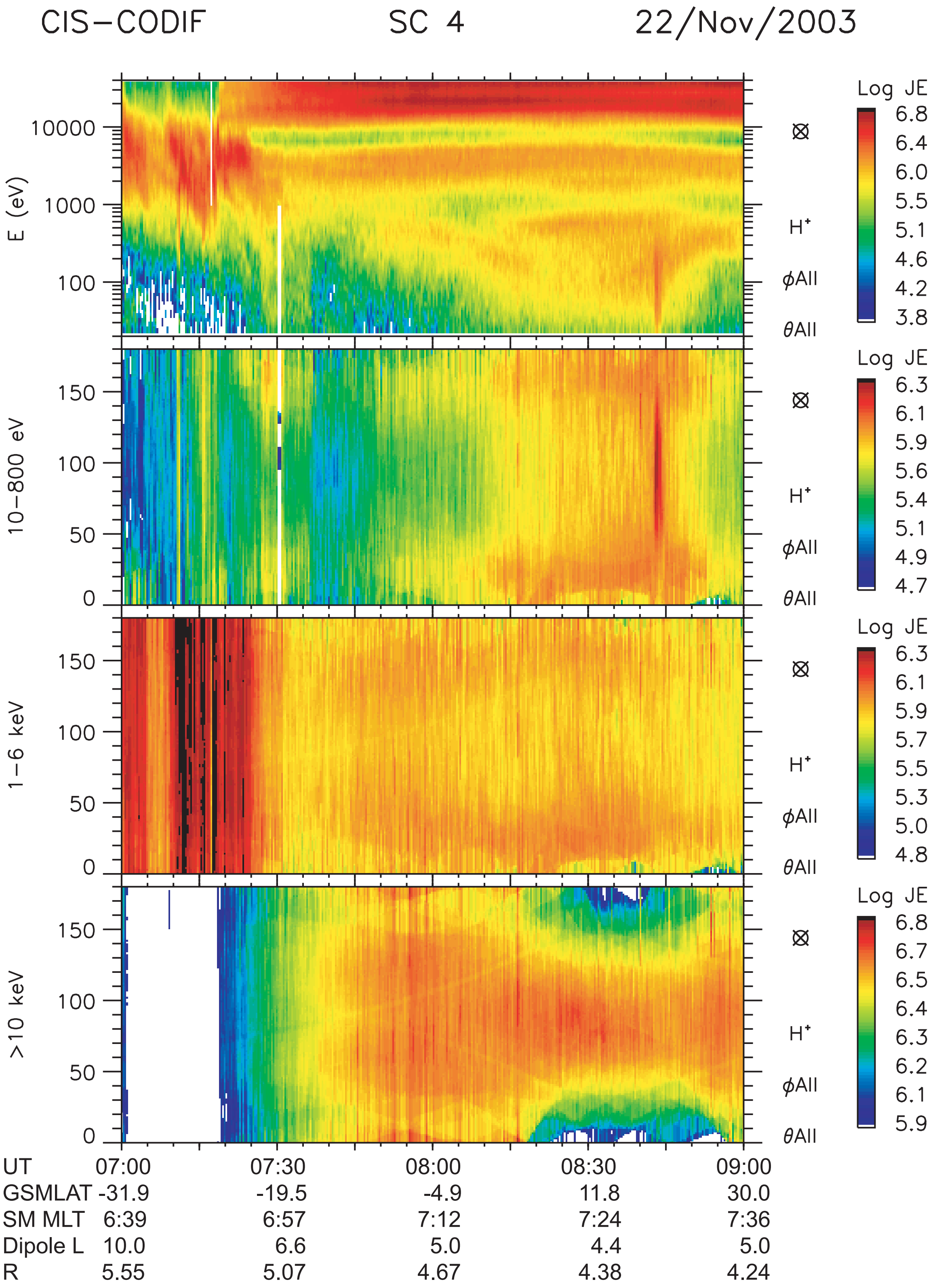

Figure 9. Energy and pitch angle spectrograms of Cluster-4 CIS data from 07:00 to 09:00 UT November 22, 2003.

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