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## Cluster observations of EMIC triggered emissions in association with Pc1 waves near Earth's plasmopause

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[1] The Cluster spacecraft were favorably positioned on the nightside near the equatorial plasmopause of Earth at  $L \sim 4.3$  on 30 March 2002 to observe electromagnetic ion cyclotron (EMIC) rising tone emissions in association with Pc1 waves at 1.5 Hz. The EMIC rising tone emissions were found to be left-hand, circularly polarized, dispersive, and propagating away from the equator. Their burstiness and dispersion of  $\sim 30$  s/Hz rising out of the 1.5 Hz Pc1 waves are consistent with their identification as EMIC triggered chorus emissions, the first to be reported through *in situ* observations near the plasmopause. Along with the expected  $H^+$  ring current ions seen at higher energies ( $>300$  eV), lower energy ions (300 eV and less) were observed during the most intense EMIC triggered emission events. Nonlinear wave-particle interactions via cyclotron resonance between the  $\sim 2$ – $10$  keV  $H^+$  ions with temperature anisotropy and the linearly-amplified Pc1 waves are suggested as a possible generation mechanism for the EMIC triggered emissions. **Citation:** Pickett, J. S., et al. (2010), Cluster observations of EMIC triggered emissions in association with Pc1 waves near Earth's plasmopause, *Geophys. Res. Lett.*, 37, L09104, doi:10.1029/2010GL042648.

### 1. Introduction

[2] Electromagnetic Ion Cyclotron (EMIC) waves in the Pc1 frequency range (0.2 to 5 Hz) [Jacobs et al., 1964] were

first observed in 1936 at high latitude ground stations [Harang, 1936; Sucksdorff, 1936]. Based on ground observations, all Pc1 waves are most simply defined by two categories: structured and unstructured [Hayashi et al., 1981; Fraser et al., 1984]. However, all hydromagnetic (HM) emissions (magnetic pulsations which appeared to be related to ion cyclotron waves excited in the magnetosphere) in the frequency range 0.1–2.0 Hz were further classified into eight subtypes based on their spectral structure [Fukunishi et al., 1981]. This classification was modeled after types of spectral structure observed in VLF emissions [Helliwell, 1965] introducing, for example, a distinct subtype called HM chorus. The so-called “pearl pulsations” are a subclass of structured, periodic Pc1 waves which appear as a sequence of discrete wave packets with a repetition period of a few minutes [Troitskaya, 1961]. Since their discovery all types of Pc1 pulsations have been extensively studied through ground observations at high and mid-latitudes [cf. Baransky et al., 1981; Kerttula et al., 2001] and at low latitudes [cf. Bortnik et al., 2008].

[3] Pc1 pulsations observed in space have also been widely reported at various latitudes in the ionosphere and magnetosphere [cf. Perraut, 1982; Iyemori and Hayashi, 1989; Loto'aniu et al., 2005], and with multiple satellites [Engebretson et al., 2008]. However, observations in space of fine-structured Pc1 waves have been primarily limited to pearl pulsations in the form of repetitive bursts [Erlandson et al., 1992; Mursula, 2007]. Mursula et al. [1994] and Mursula [2007] reported the first space-based observations of dispersive Pc1 waves, but did not classify them as HM chorus. To date, there has been no report of space-based observations of EMIC triggered chorus emissions.

[4] The discovery of Electrostatic Solitary Wave (ESW) bursts modulated at 1.5 Hz near the plasmopause for an event on 30 March 2002 was the motivation for the current study (see Pickett et al. [2004] for a discussion of ESWs observed throughout Cluster's orbit). An investigation of the cause of the 1.5 Hz modulation eventually led to the further discovery of Pc1 waves at the modulation frequency of the ESW bursts and triggered emissions of the EMIC type. Our investigation, which is presented below, consists of the analysis of this unique event through the observations of the wave, magnetic field and ion instrumentation on Cluster, some discussion of the observations and theoretical basis for the underlying physics of this event and our conclusions based on the analysis presented. A discussion of the modulation of the ESW bursts at the

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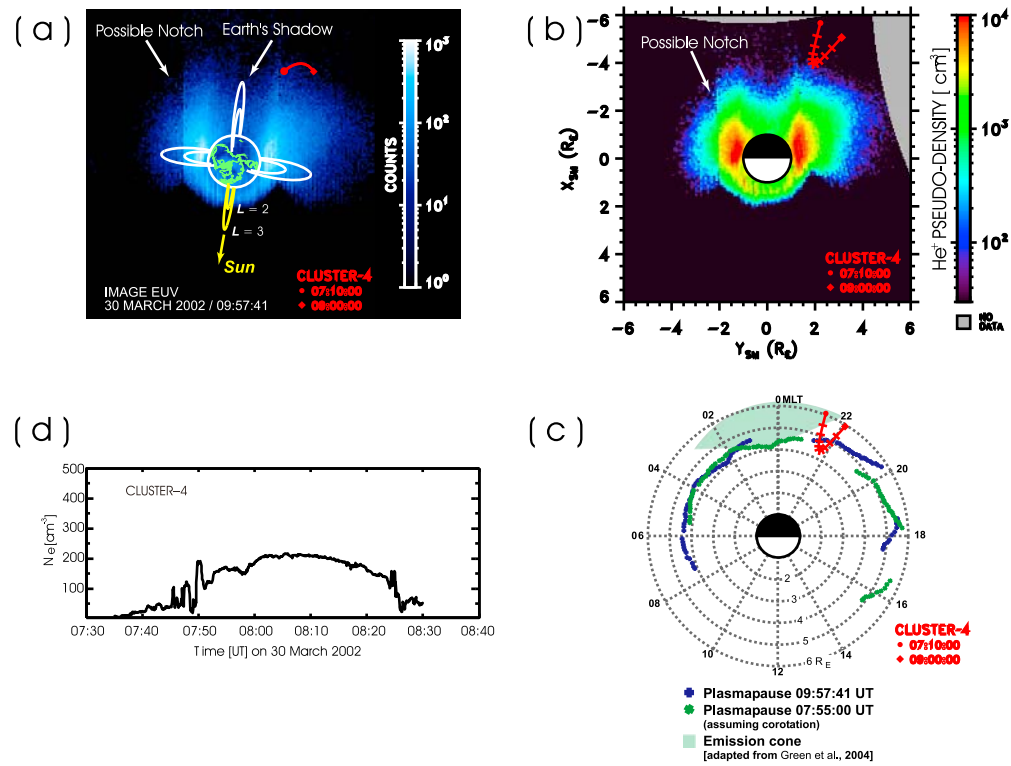
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**Figure 1.** Location of CLUSTER 4 with respect to the plasmapause on 30 March 2002. (a) IMAGE EUV snapshot of the plasmasphere and CLUSTER's location (red line) with respect to it ~ 2 hours earlier assuming corotation. (b) Equatorial map of the  $\text{He}^+$  pseudo-density in a solar magnetic coordinate system. (c) Location of the plasmapause assuming co-rotation (green crosses) at time of Cluster measurements (red line). (d) Electron density measured by CLUSTER 4 two hours before the EUV image.

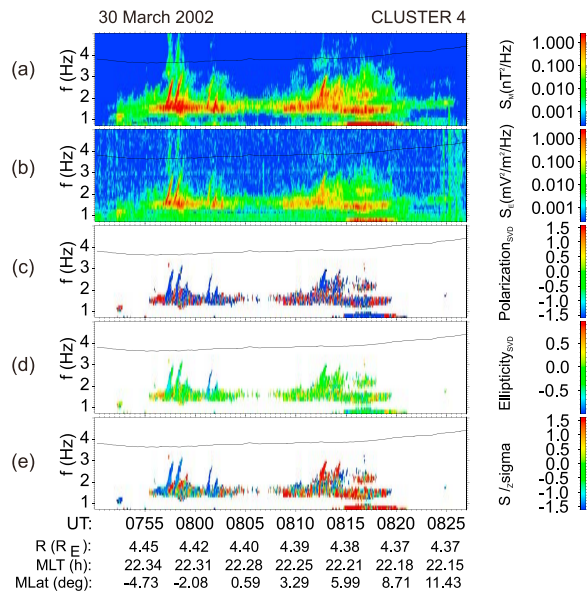
Pc1 frequency, which is also a new result, is left for future work.

## 2. Observations

[5] On 30 March 2002 during the period 07:55–08:20 UT the four Cluster spacecraft were located near the plasmapause at  $\sim 4.4 R_E$ , 22:15 Magnetic Local Time (MLT), and L-shell  $\sim 4.3$ . All four Cluster spacecraft crossed the magnetic equator at approximately 08:05 UT in the order of C1, C4, C3, C2, traversing from about  $-4.5$  to  $+8.5$  degrees geomagnetic latitude during the analysis interval. The interspacecraft separations at 08:00 UT varied from 85 to 260 km. All of the wave emissions described in this study were observed on all four spacecraft, but we will confine the observational analysis to just one of the spacecraft, in this case C4 since the essential ion observations are available on that spacecraft. Analysis of the cross spacecraft correlations and the information to be obtained from such will be delegated to future work.

[6] Approximately 10 hours before our analysis interval the solar wind pressure more than doubled from about 4 to 9 nPa with a positive Dst of 45 nT at that time. By the time of our observations, the pressure had dropped to about 7 nPa and the Dst to  $-8$ . The Kp index was moderate at 3–4. The IMAGE spacecraft was not ideally positioned to obtain images of the plasmasphere at the exact time of the Cluster measurements. It did, however, get to high enough latitude

in the Northern Hemisphere about 2 hours later at 09:57:41 UT and obtained an Extreme Ultraviolet Imager (EUV) snapshot of the plasmasphere [Sandel et al., 2000]. This image, provided in Figure 1a, along with its projection into the equatorial plane of the solar magnetic coordinate system in Figure 1b as an equatorial map of  $\text{He}^+$  pseudo-density, shows a well formed plasmasphere, displaying a structured plasmaspheric boundary layer that includes a notch [Gallagher et al., 2005] centered at approximately 02:30 MLT. Note that the orbital segment of Cluster-4 from 07:10 (red dot) to 09:00 UT (red square) is projected into the EUV field-of-view. Figure 1b indicates that, if the plasmasphere were not subject to changes in convection, Cluster-4 penetrated the plasmaspheric boundary layer, and we can extract the plasmapause location from Figure 1a and propagate that location to the interval of Cluster's observations, assuming co-rotation, as shown in Figure 1c. From this picture it is clear that Cluster was located close to, but not within, the notch and did indeed penetrate the plasmapause boundary layer. Figure 1d shows the total electron density as determined from Cluster Whisper sounding and EFW spacecraft potential measurements per the method described by Masson et al. [2009] and Moullard et al. [2002], clearly showing densities typical of the plasmasphere and plasmapause boundary layer ( $\sim 50$ – $200 \text{ cm}^{-3}$ ) from  $\sim 07:50$  to 08:26 UT, as well as the small scale density perturbations associated with this boundary layer. Comparable small-scale density perturbations are also seen in the EUV observations presented in Figures 1a and 1b.



**Figure 2.** STAFF-SC and EFW data from CLUSTER 4 showing the Pc1 waves at  $\sim 1.5$  Hz and the EMIC triggered emissions rising from  $\sim 1.5$  Hz to 3 Hz. (a and b) Sum of the power spectral densities of the three measured magnetic field components and two measured electric field components, respectively, according to the color bars at the right, in the frequency range of 0.7 to 5.0 Hz. (c) Sense of polarization using the method of singular value decomposition (SVD) of the magnetic spectral matrix [Santolik *et al.*, 2003], with the color blue indicating left-handed and red right-handed polarization. (d) Ellipticity of the magnetic field of the waves, also using the SVD method, with a value of 0 indicating linear polarization,  $-1$  indicating left-hand circular polarization, and  $+1$  indicating right-hand circular polarization. (e) Component of the Poynting vector parallel to the magnetic field  $\mathbf{B}_0$  normalized by its standard deviation, a negative value indicating opposite to  $\mathbf{B}_0$  and positive value in the same direction as  $\mathbf{B}_0$ . The black line in all panels is the proton cyclotron frequency. At the bottom of the figure is a listing of the spacecraft distance, R (in  $R_E$ ), the magnetic local time, MLT (in hours), and the magnetic latitude, MLat (in degrees).

[7] The primary ULF wave observations associated with this passage of Cluster in and near the plasmopause boundary layer are presented in Figure 2. Here we show the measurements made by the STAFF-SC and EFW instruments onboard Cluster spacecraft 4 (C4) for the period 07:51–08:27 UT. The most notable waves observed in Figure 2 are: 1) A prominent nearly constant frequency wave at  $\sim 1.5$  Hz, and 2) short bursts of waves showing a dispersion of approximately 30 s/Hz (as risers). Both of these are below the proton cyclotron frequency and above the helium cyclotron frequency and are electromagnetic in nature since they have magnetic and electric components as shown in panels a and b. The 1.5 Hz waves are localized close to the equator, and their Poynting flux also seems to predominantly come from the direction of the magnetic equator. In addition they have mixed left- and right-hand polarizations (Panel c). All of these features are consistent

with Pc1 waves which fall in the range of 0.2 to 5 Hz [Jacobs *et al.*, 1964; Erlandson *et al.*, 1992]. On the other hand, the bursty, dispersive rising tone waves, which appear to be triggered out of the Pc1 waves, are characteristics of triggered emissions (similar to the VLF-equivalent classified by Helliwell [1965]). Because they are in the range of ion cyclotron waves and exhibit left-hand polarization, unlike traditionally-reported VLF chorus which is in the electron whistler-mode frequency range and is right-hand polarized, we choose to call these waves EMIC triggered chorus. These emissions are clearly coming from the direction of the magnetic equator as shown in panel e, i.e., blue in the southern hemisphere indicating opposite to the direction of  $\mathbf{B}_0$  and red in the northern hemisphere indicating in the same direction as  $\mathbf{B}_0$ . In addition, panels c and d show that these waves have a dominant left-hand polarization (blue color in panel c). Although not shown their wave normal angles fall in the range of 25 to 70 degrees. Even though we have presented the data from C4 only, both the Pc1 waves and EMIC triggered emissions are observed similarly on all three of the other spacecraft at almost the same time. In addition, their magnetic components are observed equally well with all of the same features by the fluxgate magnetometer, FGM.

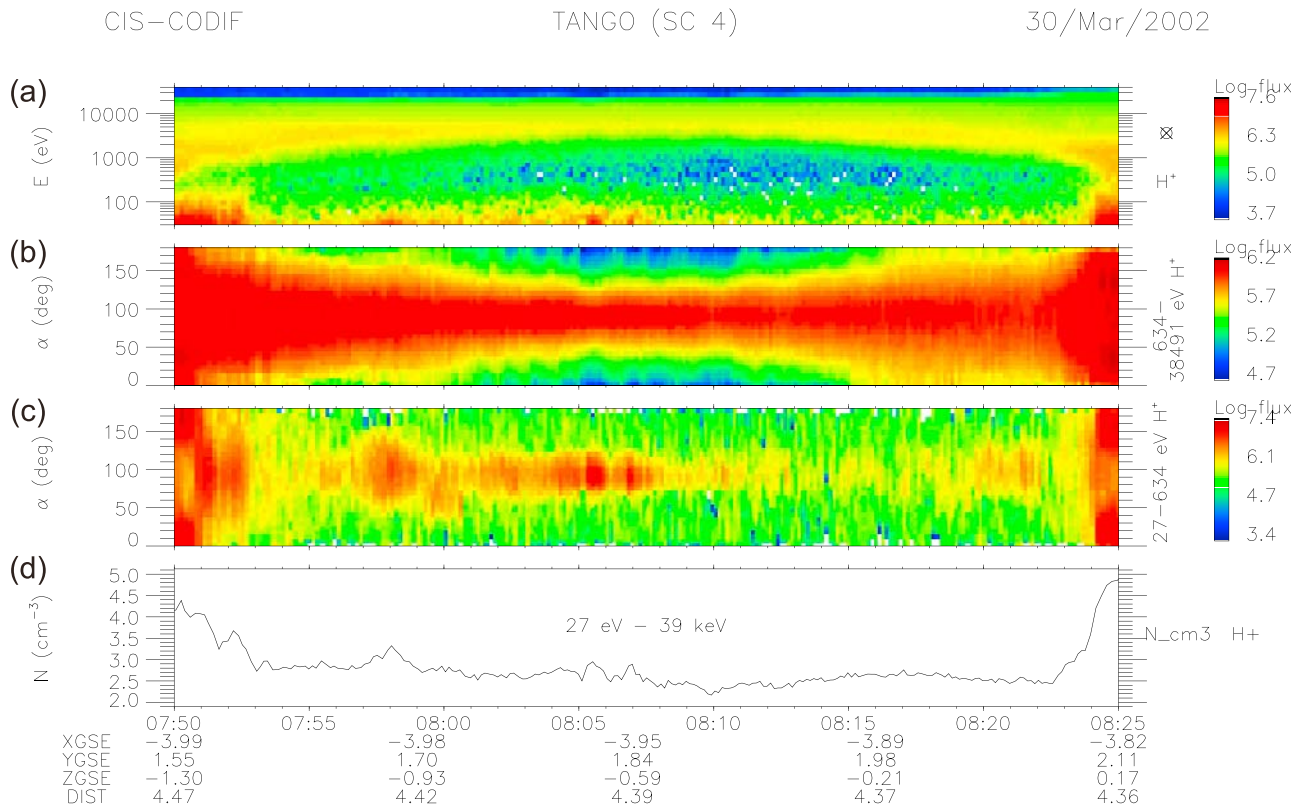
[8] To round out the pertinent observations for this event, we provide the CIS-CODIF ion data in Figure 3. The lower energy  $H^+$  ions ( $< 300$  eV) that are observed in Figure 3a are probably of ionospheric or plasmaspheric origin. The ions observed at energies  $> 300$  eV up to  $\sim 28$  keV are characteristic of the ring current and are clearly observed on this date. Of special interest to our study is the density of  $H^+$  (Figure 3d), which peaks in the time interval 07:57–08:00 UT and appears to be associated with the two triggered emissions observed in the same interval. Using the total density of  $\sim 178 \text{ cm}^{-3}$  obtained just prior to the heating event at 07:57 UT (see Figure 1d) as a normalization factor and making some assumptions about the unmeasured cold population, the densities for each of  $H^+$ ,  $He^+$  and  $O^+$  are determined to be  $\sim 144$ , 17, and 17  $\text{cm}^{-3}$ , respectively, based on dispersion analysis using the frequency cut-off of the Pc1 wave. Figure 3b shows that a clear  $H^+$  temperature anisotropy exists throughout much of the full time interval shown in Figure 2.

### 3. Discussion

[9] The observation of Pc1 waves at 1.5 Hz by the Cluster satellites on 30 March 2002 at  $L \sim 4.3$  in the equatorial region near the plasmopause is not unexpected based on numerous ground and satellite observations since the discovery of Pc1 waves in 1936. Our purpose here is not to explain how these Pc1 waves observed by Cluster were created, or whether they were created *in situ* or propagated to Cluster's location. Our primary purpose is to show that these Cluster observations of Pc1 waves provided an unprecedented opportunity to explore in detail the interaction of those waves with energetic protons in connection with the first reported observations of well-defined EMIC triggered chorus emissions growing out of that interaction.

[10] Similar to a nonlinear mechanism proposed by Omura *et al.* [2008, 2009] for VLF chorus generation, it is possible for the EMIC triggered emissions to be generated through a nonlinear absolute instability for L-mode EMIC





**Figure 3.** CIS-CODIF  $H^+$  ion data from CLUSTER 4 for the period 07:50 to 08:25 UT. (a) Log of the particle flux (according to the color bar on the right) of  $H^+$  in the energy range of 30 eV to 39 keV (vertical axis). (b and c) Log of the flux (color bar) of  $H^+$  as a function of the pitch angle (ion group velocity with respect to the local magnetic field (vertical axis)) in two energy ranges, 634 eV to 38.5 keV and 27 to 634 eV, respectively, (d)  $H^+$  density, in  $\text{cm}^{-3}$ , as measured by CIS-CODIF in the energy range 27 eV to 39 keV. The X,Y,Z components of the GSE location of the spacecraft are listed at the bottom of the figure.

waves which involves the interaction of the Pc1 waves with energetic protons [Omura *et al.*, 2010]. Nonlinear wave growth, which leads to the rising frequency triggered emissions, is initiated through the formation of an electromagnetic proton hole in velocity phase space in the presence of a coherent wave with the amplitude greater than a threshold. The frequency of the coherent wave increases so that the proton hole gives rise to the maximum resonant current anti-parallel to the wave electric field, resulting in the strong nonlinear wave growth. This mechanism, which is driven by the frequency variation, is very different from that of the linear growth rate that takes place at a constant frequency. The inputs for this model were taken from the Cluster observations presented here and the model results are presented elsewhere [Omura *et al.*, 2010]. The average dispersion,  $\sim 30$  s/Hz, associated with the EMIC triggered emissions observed by Cluster as well as the wave growth, 0.2 to 2.5 nT in 10 seconds [Omura *et al.*, 2010], are well produced by this model. The dispersion of the EMIC triggered emissions presented here is similar to that found by Mursula *et al.* [1994] of 50–100 s/Hz from the Freja observations for Pc1 pearl pulsations. Further, we suspect that the dispersive waves shown by Mursula [2007, Figure 8] are probably EMIC triggered emissions, similar to those reported here, although they concluded only that these emis-

sions were not directly related to Pc1 pearls. The reported space-based dispersions are also consistent with typical ground observations of such dispersion [Gendrin *et al.*, 1971], which usually have a positive dispersion slope.

#### 4. Conclusions

[11] We have presented data from a singular, thus far unique, event encountered by the Cluster spacecraft on 30 March 2002 in which Pc1 waves and EMIC triggered chorus emissions were observed on all four Cluster spacecraft by the Cluster wave instruments on the nightside near the equatorial plasmopause at  $L \sim 4.3$ . This is the first report of EMIC triggered emissions from space-based observations. The Pc1 waves, at a frequency of approximately 1.5 Hz, are one of the crucial ingredients for kicking off the processes which lead to the generation of the EMIC triggered emissions, the other being the  $H^+$  ions that are observed in the energy range  $\sim 2$ –10 keV. The Pc1 waves interact with these  $H^+$  ions through a process involving cyclotron resonance. This interaction, after evolution to the nonlinear stage, could produce the fine structure, rising tone EMIC triggered emissions which appear to rise out of the Pc1 waves with a dispersion of  $\sim 30$  s/Hz. Future work on the event presented here will include an expanded analysis of

the EMIC triggered chorus emissions to more fully expose their characteristics.

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