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VLF chorus emissions observed by POLAR during the January 10, 1997, magnetic cloud

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Abstract. VLF chorus emissions occur near the dawn meridian in fast response (<60 s) to magnetospheric perturbations caused by sudden fluctuations in solar wind dynamic pressure and southward turnings of the interplanetary magnetic field (IMF) at the arrival of the Jan. 10, 1997 magnetic cloud. Raytracing analysis indicates the likely chorus source region to be near the magnetic equator with rays launched at oblique wave normal angles, for which likely resonant electron energies are in the range $E\sim$14-30 keV, consistent with observed particle data.

Introduction

VLF Chorus – named for its characteristic sequence of repeating, usually rising and often overlapping coherent tones – ranks as the most intense of all naturally-generated VLF plasma wave emissions observed in the Earth's magnetosphere, occurring regularly in association with disturbed magnetospheric conditions and seen frequently in conjunction with microburst electron precipitation and other auroral activity [*Inan et al.*, 1992, and references therein].

Chorus emissions are thought to involve a 1st-order gyroresonant pitch-angle instability during times of enhanced transverse anisotropy in the energetic (10-100 keV) electron distribution within spatial regions having minimal inhomogeneity in the static $\mathbf{B}_o$ field [*Burton*, 1976; *Isenberg et al.*, 1982; *Sazhin and Hayakawa*, 1992, and references therein]. In addition, field-aligned focusing of wave ray paths (i.e. by ducts or special features of the refractive index surface) may play an important role [*Burtis and Helliwell*, 1976].

A class termed *equatorial chorus* (having source region near the magnetic equator) is commonly observed throughout the post-midnight to post-noon sector just outside the plasmapause and has been shown to be related to strong southward turnings of the interplanetary magnetic field (IMF) [*Tsurutani and Smith*, 1977], to storm sudden commencements (SC) and impulses (SI), and to magnetospheric compressions in general [*Gail and Inan*, 1990].

Shock compressions of the magnetosphere and sudden turnings of the IMF are common effects of the impact of magnetic clouds created by solar coronal mass ejection (CME) events [*Farrugia et al.*, 1997]. In this paper, we discuss the relationship between the Jan. 10, 1997 magnetic cloud and the occurrence of VLF chorus.

Observations

The Plasma Wave Instrument (PWI) sensors include one spin-axis aligned (14 m) and two orthogonal spinning (100 m, 130 m) electric dipoles, and three orthogonal magnetic search-coils (70 μV/nT-Hz sensitivity) aboard the POLAR satellite (~18 hr, ~2×9 R_e, ~90° inclination, North pole apogee orbit, 6 s cartwheel spin). PWI electronics include a Swept Frequency Receiver (SFR) providing continuous single-component E, B data (26 Hz - 810 MHz, <1 min resolution), and a High-Frequency Waveform Receiver (HFWR) providing coincidently-sampled 6-component E, B wave field snapshots (0-26 kHz, ~1/2 s duration, 9.2 s intervals) [*Gurnett et al.*, 1995].

Interplanetary and magnetospheric conditions are assessed with solar wind data from the WIND three-dimensional plasma instrument (3DP) [*Lin et al.*, 1995] and magnetic field data from the WIND magnetic field (MFI) [*Lepping et al.*, 1995] and Geotail magnetic field (MGF) instruments [*Kokubun*, 1994].

Fig. 1a shows the locations of these satellites in the ecliptic plane for the ~1 hr event following the arrival of the magnetic cloud near ~0500 UT on Jan. 10, 1997. WIND was ~90 R_e sunward (inset), Geotail was ~9 R_e also sunward near local noon, and POLAR was near the dawn meridian, north of the magnetic equator and moving southward (Fig. 1b), ideally situated to observe dawn chorus. Also shown are two magnetopause profiles (either side of Geotail), one for strong compression (solid), the other for relaxed conditions (dashed) after the empirical model of *Shue et al.* [1997] for relevant data observed by WIND during this event.

Fig. 2a shows POLAR/PWI/SFR plasma wave data for the 48 hr period 0600 UT, Jan. 9 to 0600 UT, Jan. 11, 1997 (bracketing the magnetic cloud arrival) with solar wind pressure ρV^2 and magnetic field data from WIND and Geotail and provisional ring-current *Dst* plotted above. The data have been coaligned after adjusting for magnetic cloud travel time to infer prevailing conditions during PWI observations.

Chorus onset, indicated by event line A, occurs coincident with the strong sustained southward IMF turning ($B_z < -10$ nT, WIND/MFI) at the front edge of the magnetic cloud while the solar wind pressure is strong (~5 nPA, WIND/3DP). The dashed lines $f_{heq}/2$ in the SFR spectrogram track the electron half-gyrofrequency at the magnetic equator for the field line passing through the satellite, identifying these emissions as *lower* band chorus [*Burtis and Helliwell*, 1976].

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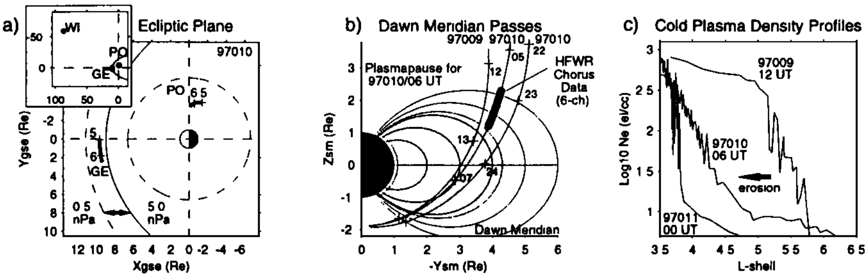

Figure 1. a) WIND (WI), Geotail (GE) and POLAR (PO) locations, b) three successive POLAR dawn meridian passes, c) cold plasma density scaled from POLAR/SFR f_{uhr} data.

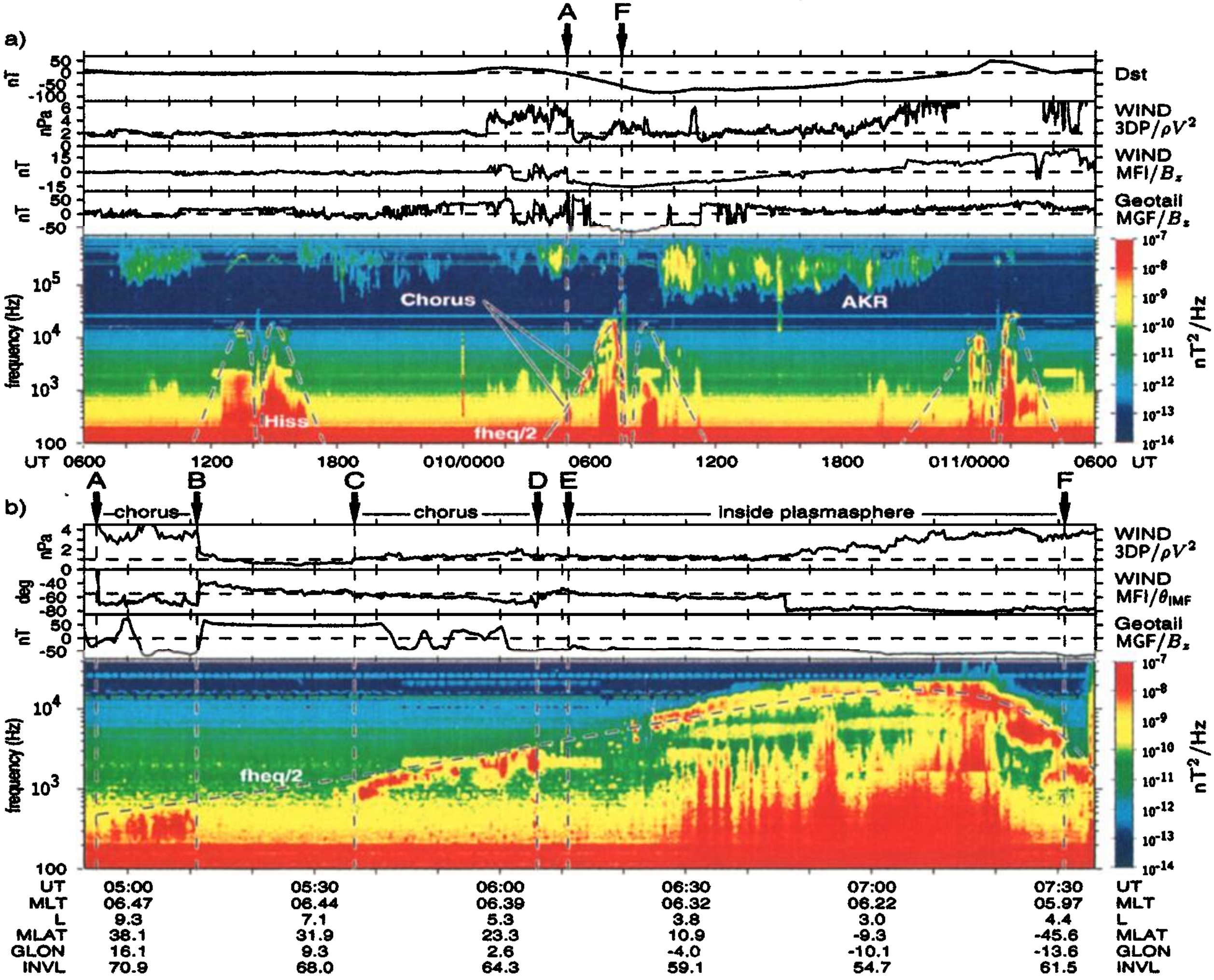

Figure 2. a) 48-hour, and b) 4-hour PWI/SFR spectrograms with correlated *Dst*, solar wind dynamic pressure and IMF (from WIND and Geotail). Chorus begins at event time A (same in both figures).

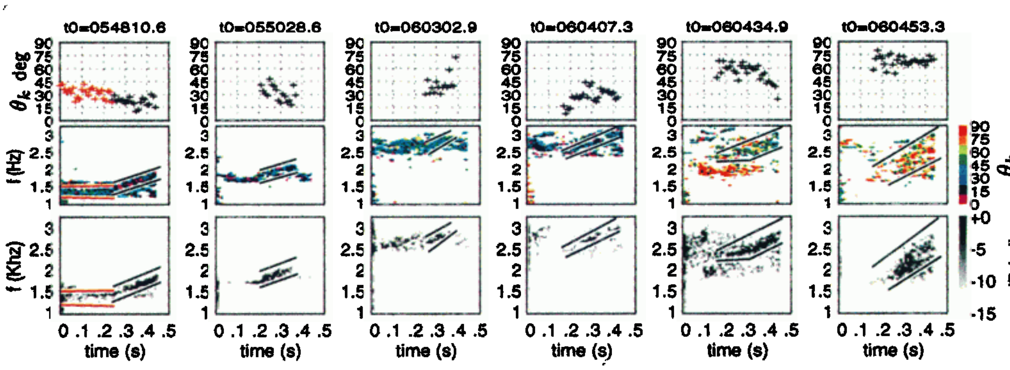

Figure 3. Individual chorus elements from PWI/HFWR data. Lower row: Power spectral density, Middle row: Wave normal angle θ_k (wrt. $\mathbf{B}_o$) in color *f*-*t* format, Upper row: θ_k vs. *t* for the indicated *f*-*t* traces.

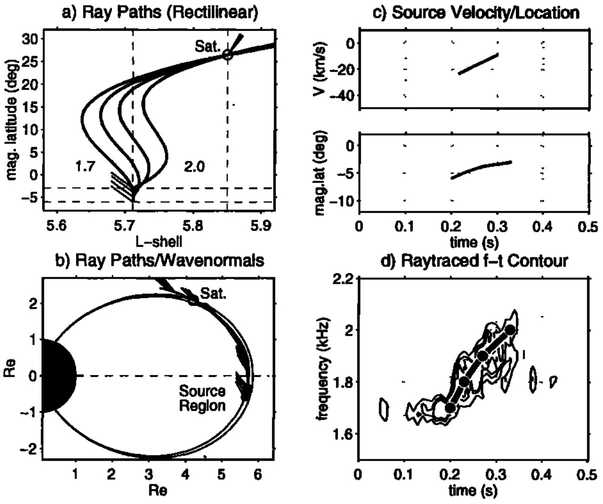

Figure 4. Raytracing results: a,b) paths and wave normals, c) source region location, d) f-t contour match.

Note that chorus did *not* occur during the previous dawn pass at ~1200 UT, Jan. 9 (however enhanced hiss is present inside the plasmasphere) or during the subsequent dawn pass at ~2200 UT, Jan. 10, consistent with the weak/northward IMF values at these times.

In passing we also note an intensification after A of Auroral Kilometric Radiation (AKR ~100-800 kHz), known to be associated with intense auroral precipitation during substorms.

Fig. 2b shows the event interval A-F in greater detail, with WIND/MFI B_z replaced by angle θ_{IMF} to show the correlated variations more clearly. Chorus is present with fluctuating intensity (to ~100 pT) during intervals A-B and C-D while ρV^2 remains strong and θ_{IMF} stays at or below ~-55° (dashed line) in both cases. Chorus is absent throughout B-C, as ρV^2 drops by more than a factor of 2 and θ_{IMF} jumps above -55°, and also after D, following a minor drop in ρV^2 as θ_{IMF} again climbs >-55°. By time E, although ρV^2 remains steady and θ_{IMF} again falls <-55°, here POLAR has entered the plasmasphere ($L <\sim 4.5$, c.f. Fig. 1b,c) where chorus is less likely to occur. Later, chorus is again seen after F as POLAR exits the plasmasphere.

We note the drastic drop in ρV^2 from ~4 to <2 nPa at time B has evidently allowed the magnetopause to relax to a location sunward of Geotail (dashed profile in Fig. 1a), as indicated by the simultaneous jump to northward (magnetospheric) values in the Geotail B_z data, which just prior had been tracking IMF features along with WIND (c.f. Fig. 2a).

Analysis

To link chorus occurrence to the magnetospheric perturbations induced by the magnetic cloud, we first use VLF raytracing to establish the location of, and wave characteristics within, the likely chorus source region.

Fig. 3a (bottom row) shows power spectral density for six 1/2 s HFWR snapshots from interval C-D, each showing typical rising chorus elements. Above each are the corresponding k-vector wave normal angles θ_k (calculated via Means' method [*Means*, 1972; *Hayakawa et al.*, 1990] with respect to local $\mathbf{B}_o$) shown both in color f-t format (middle row) and as $\theta_k(t)$ profiles (top row) for the indicated chorus f-t traces.

We select snapshot 05:50:28.6 UT as our representative chorus element, which rises from f_{lo}=1.7 kHz to f_{hi}=2.0 kHz in Δt~0.15 s (df/dt~2 kHz/s), with corresponding wave normal θ_k ~45° to ~15°. We adopt a dipole magnetic field model and cold plasma density profile consistent with the observed upper hybrid resonance frequency f_{uhr} [*Carpenter et al.*, 1981]; the profile labeled 97010 06 UT in Fig. 1c prevails during our event.

We then find the optimal set of rays which match the observed f-t behavior with minimum error between simulated $\hat{\theta}_k$ and measured θ_k wave normals at the satellite by iterating chorus source L-shell L_s, latitude λ_s and initial wave normal θ_{ks} while allowing for natural source region latitude drift and accounting for intrinsic $\partial f/\partial t$ at the off-equatorial locations [*Helliwell*, 1967].

Fig. 4 shows the resulting source region spans -6° to -3° along L_s=5.71, with initial θ_{ks} at oblique angles for rays reaching the satellite (L=5.85, λ=26.5°) with the correct f-t (Fig. 4d) and wave normals (Fig. 4a,b). Close inspection of Figs. 4a,c shows f_{lo}=1.7 kHz starts farthest south and remains the most field aligned of all rays (~4° latitude), which may explain the persistent background enhancement at f_{lo} (c.f. Fig. 3) and provide a clue to chorus triggering. At higher f, rays start closer to the magnetic equator and depart the source field line ever more quickly, until at f_{hi}=2.0 kHz, the immediate departure greatly diminishes opportunity for cumulative wave/particle interaction, which may explain why the element terminates at this frequency.

We comment that the solution varies smoothly about these optimum values, indicating robustness both to measurement error and to small perturbations in the actual physical parameters. Conversely, no appreciably different set was found to match these data; however, this does not preclude chorus emission at some other θ_{ks} whose rays do not reach this satellite location.

With wave characteristics specified in the source region, the total kinetic energy for 1st-order gyroresonant electrons E_{res} is found directly, albeit parametric in equatorial pitch-angle α_{eq}, to match resonant $v_{\|}$ [*Inan and Bell*, 1991]. We chose two extrema, α_{eq}=3.3° (loss cone at L=5.7), and α_{eq}=60° (transverse yet mirroring beyond $|\lambda_{s,max}|$~6.0°), and one midrange α_{eq}=30°value. These results are listed in Table 1.

Discussion

In Table 1 the *range* of $\hat{\theta}_k$ is not as wide as measured (θ_k), nonetheless the *mean* values agree well and would readily match a more common θ_k~uniform chorus case.

E_{res} ranges 11-84 keV over f and α_{eq} for these θ_{ks}. For comparison, had θ_{ks}=0, E_{res} would be ~5% less. From theoretical expectations, midrange pitch-angles (~30°) participate most strongly in wave/particle energy exchange [*Carlson et al.*, 1990], so that E_{res} is most likely in the range 14-30 keV.

Table 1. Raytracing and E_{res} Results.

Source Region			Satellite		E_{res}(keV), α_{eq}=		
f(kHz)	λ^o_s	θ^o_{ks}	$\hat{\theta}^o_k$	θ^o_k	3.3°	30°	60°
1.7	-6.0	-47	33	45	22	30	84
1.8	-4.9	-46	31	35	17	23	65
1.9	-3.8	-46	28	25	13	18	50
2.0	-3.0	-46	24	15	11	14	39

Indeed, particle data at POLAR/HYDRA ($E \leq 20$ keV) [*Scudder, private communication*] show variations in transverse (to $\mathbf{B}_o$) electron flux which track the chorus pattern well for $E \sim 10$-20 keV, but not well at other energies. We expect detailed examination of the velocity-space distributions will reveal the precise correlation between specific pitch-angle anisotropy and these chorus emissions.

This association of chorus in direct response to sudden magnetosphere compression/relaxation and small, quick variations in θ_{IMF} is significant. Although in many cases chorus evidently arises from eastward drifting electrons injected from the tail during substorms driven by strong southward IMF B_z, in the present case there is insufficient time (~30 min required, c.f. [*Tsurutani and Smith*, 1977]) for such particles to either drift to the dawn meridian so quickly or to halt their drift so promptly.

The fast response suggests instead some combination of in-situ acceleration, fast radial transport and/or convection from the plasma sheet as the operative mechanism. In this regard we note that the concurrent drop in *Dst* (Fig. 2a, time A) may indicate a connection between chorus electron and ring current energization, the latter attributed largely to enhanced convection electric fields which arise quickly and regularly in response to magnetic cloud southward IMF B_z [*Chen et al.*, 1997].

Summary

The impact of the magnetic cloud of Jan. 10, 1997 caused the immediate generation of intense chorus emissions observed near the dawn meridian in quick (<60 s) response to incremental southward IMF turnings during intervals of sufficient solar dynamic pressure. Analysis indicates that these chorus emissions were generated near the magnetic equator by gyroresonant electrons having $E \sim 10$-100 keV, with $E \sim 14$-30 keV most probable from theoretical and observational considerations. Judging from the fast response, these electrons were most-likely accelerated by IMF-induced large-scale electric fields either in-situ or very close by with concurrent fast radial diffusion and/or convection.

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