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Title: Excitation of Banded Whistler Waves in the Magnetosphere

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Excitation of Banded Whistler Waves in the Magnetosphere

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Abstract

Linear kinetic dispersion analysis and two-dimensional electromagnetic particle-in-cell simulations are performed to demonstrate a possible excitation mechanism of banded whistler waves in the magnetosphere. Whistler waves in the lower and the upper bands can be generated simultaneously by the whistler anisotropy instability driven by two bi-Maxwellian electron components with $T_{\perp}/T_{||} > 1$ at different $T_{||}$. Given ω_e/Ω_e, the ratio of the electron plasma frequency to the electron cyclotron frequency, $T_{||}$ of each electron component determines the properties of the excited waves. For typical magnetospheric condition of $1<\omega_e/\Omega_e<5$ in regions associated with strong chorus, upper-band waves can be excited by anisotropic electrons below ~1 keV, while lower-band waves are excited by anisotropic electrons above ~10 keV. The resultant lower-band waves are generally field-aligned and substantially electromagnetic. However, the excited upper-band waves generally propagate obliquely to the background geomagnetic field with quasi-electrostatic fluctuating electric fields.

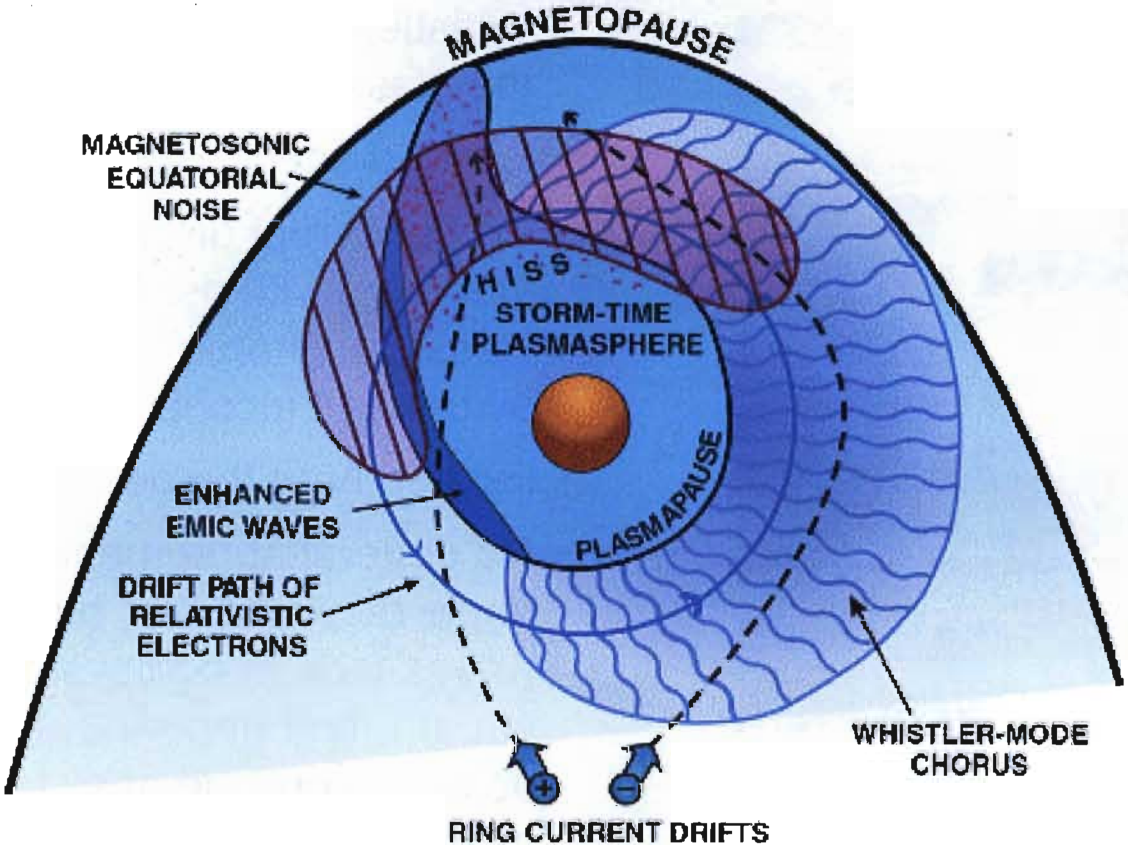
Outline

Introduction: Wave Overview

- The intensity and the structure of the trapped relativistic electron belts are controlled by a balance of acceleration, transport, and loss processes
- Wave-particle interactions play an important role in the pitch-angle scattering and the acceleration of radiation belt electrons
- Many wave modes can scatter relativistic electrons, e.g., EMIC waves, whistler waves, and magnetosonic waves

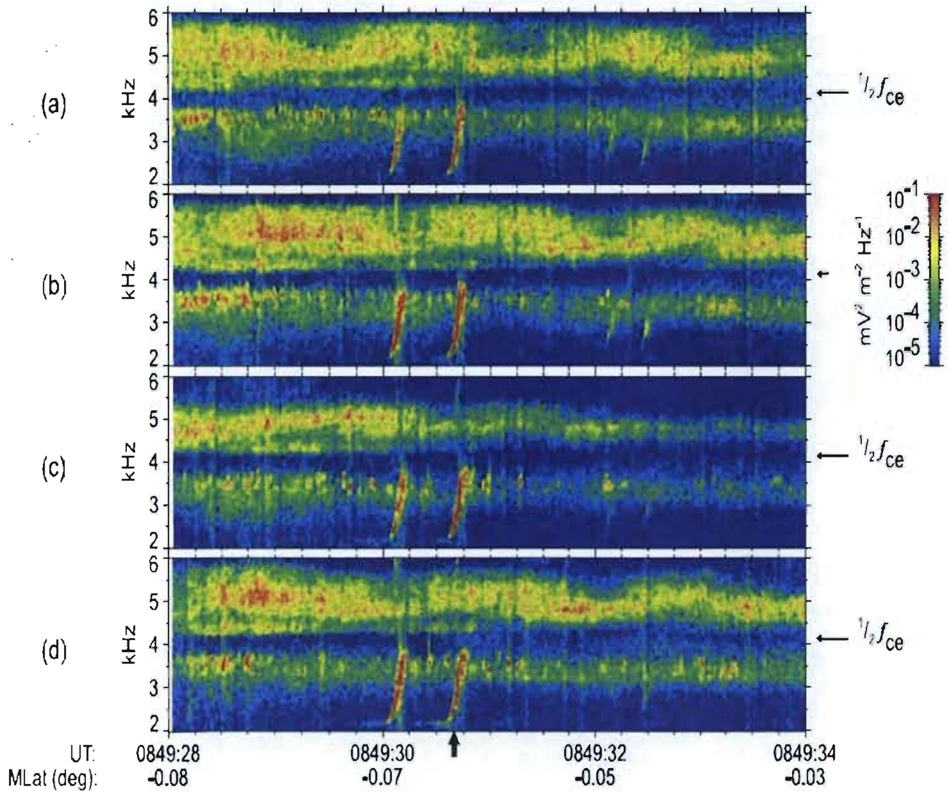
Wave Mode	EMIC Waves	Whistler Waves	Magnetosonic Waves
Free Energy	$T_{i\perp}>T_{i\|}$	$T_{e\perp}>T_{e\|}$	$\partial f(v_\perp)/\partial v_\perp>0$
Properties	$\omega<\Omega_p$, $k\lambda_i<1$, nearly parallel propagation	$\omega_p<\omega<\Omega_e$, $k\lambda_e<1$, oblique propagations are observed	$\omega\approx n\Omega_p$, $k\rho_i>1$, nearly perpendicular propagation
Electron Scattering	Mainly in pitch angle	Both in pitch angle and energy	Both in pitch angle and energy

Introduction: Wave Overview



- Schematic illustration of the wave distribution in the inner magnetosphere [*Thorne*, 2010]

Introduction: Chorus



- A chorus observation at L=4.4 on 18 April 2002 by the Cluster spacecraft [*Santolík et al.*, 2003]

- Whistler waves ($0.1\text{-}0.8\Omega_e$) outside of the plasmapause
- Banded spectra with a gap near $0.5\Omega_e$
- Composed of discrete narrowband wave elements with rising or falling tones (the classical "chorus") often accompanied by banded incoherent whistler waves
- Excited near the geomagnetic equator
- No general agreement on wave normal angle observations, but lower-band waves tend to be field-aligned near the equator and upper-band waves seem to be highly oblique at all latitudes [*Haque et al.*, 2010]
- Lower-band waves are stronger on average than upper-band waves [*Meredith et al.*, 2001]

Introduction: Banded Chorus Excitation

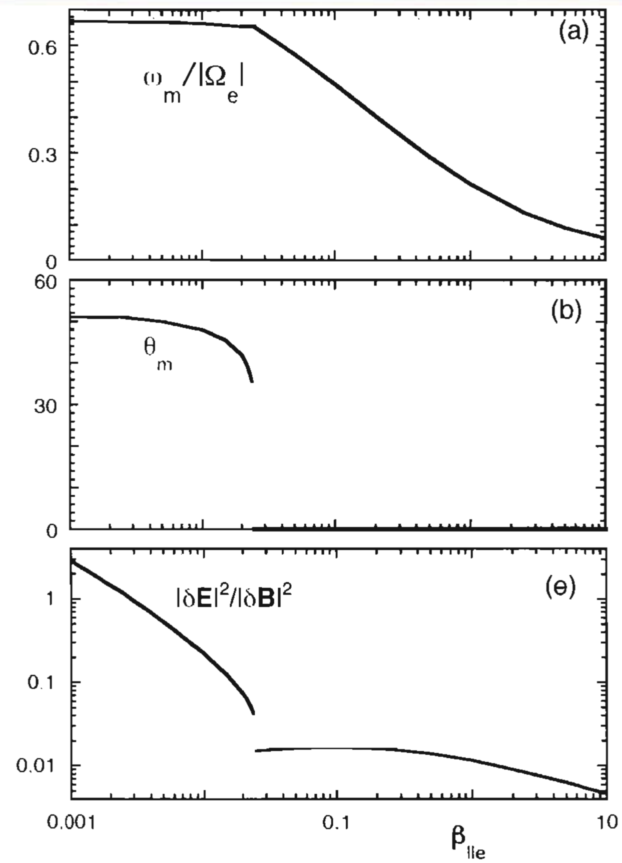
- We focus on the excitation of the banded incoherent whistler waves, while the discrete chorus elements can arise from these waves through nonlinear wave growth involving the inhomogeneity of geomagnetic field [*Omura et al.*, 2008]
- Lower-band waves are generated by whistler anisotropy instability driven by anisotropic electrons between a few and tens of keV [*Kennel and Petschek*, 1966]
- Upper-band waves and the banded structure?
  - + Landau damping [*Tsurutani and Smith*, 1974]
  - + Propagation effects [*Maeda et al.*, 1976]
  - + Different modes (whistler + ordinary) when $\omega_e < \Omega_e$ [*Curtis*, 1978]
  - + Upper-band waves are quasi-electrostatic and generated through an instability driven by anisotropic electrons of tens eV [*Hashimoto and Kimura*, 1981, *Hayakawa et al.*, 1984]
  - + Lower-band and upper-band waves trapped in ducts of enhanced and depleted cold plasma densities, respectively [*Bell et al.*, 2009]
  - + Nonlinear damping of a slightly oblique whistler wave propagating along the inhomogeneous geomagnetic field [*Omura et al.*, 2009]

Introduction: Banded Chorus Excitation

- A recent case study by *Santolík et al.* [2010] shows that two anisotropic electron components at different $T_{||}$ can excite the waves in the lower and the upper bands simultaneously
- A 2D PIC simulation of *Schriver et al.* [2010] studied the same event. Only one bi-Maxwellian distribution ($T_{\perp}/T_{||}$=10 and $T_{||}$=300 eV) is used and it drives upper-band waves through whistler anisotropy instability. Obliquely-propagating lower-band waves are excited through nonlinear wave-wave coupling
- *Li et al.* [2010] carried out a statistical survey of the equatorial electron distributions (THEMIS) responsible for chorus excitation
  - + A gap of anisotropy for electrons of several keV
  - + Anisotropic electrons below ~ 1 keV and above ~10 keV are responsible for the excitation of the upper-band and lower-band waves, respectively
- A similar scenario was also proposed by *Horne et al.* [2003] where the gap of anisotropy for electrons of several keV was suggested to be due to rapid pitch-angle scattering by ECH waves

Introduction: Whistler Anisotropy Instability

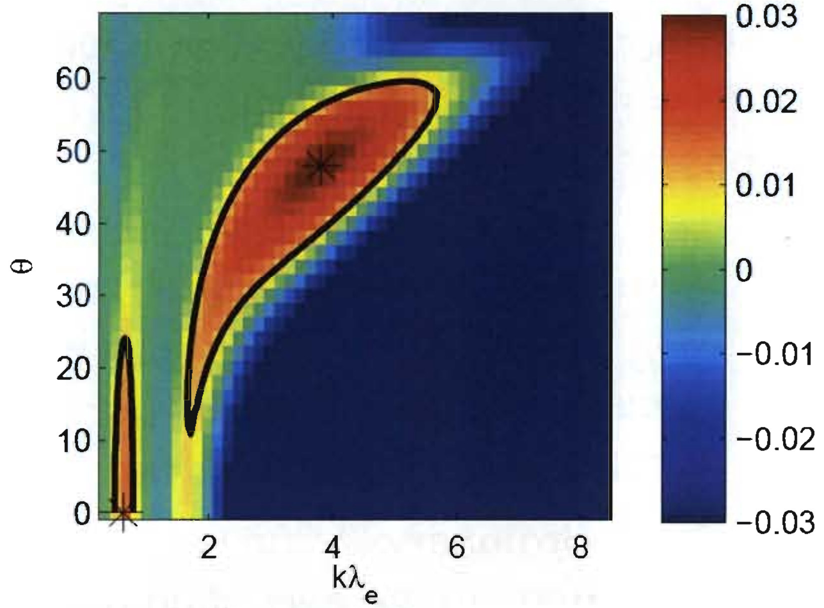
- Driven by anisotropic electrons with $T_{\perp}/T_{\|}>1$
- Properties of excited waves have a $\beta_{\|e}$ dependence ($\beta_{\|e}=n_e T_{\|e}/(B_0^2/2\mu_0)$) when $\omega_e/\Omega_e>1$ (see adjacent poster for details) :
  - + γ_m at parallel propagation and the excited waves are substantially electromagnetic when $\beta_{\|e}>\sim 0.025$
  - + γ_m at oblique propagation and the excited waves are quasi-electrostatic when $\beta_{\|e}<\sim 0.025$
  - + The frequency also shifts from below to above $0.5\Omega_e$
- The electromagnetic regime at $\beta_{\|e}>0.025$ corresponds to the excitation of lower-band waves [*Kennel and Petschek*, 1966], while the quasi-electrostatic regime at $\beta_{\|e}<0.025$ relates to the excitation of upper-band waves [*Hashimoto and Kimura*,1981]
- Banded whistler waves can be excited when two bi-Maxwellian electron components with $T_{\perp}/T_{\|}>1$ at different $T_{\|}$ are present



- The $\beta_{\|e}$ dependence of the whistler anisotropy instability for a fixed maximum growth rate of $\gamma_m/\Omega_e=0.01$ [*Gary et al.*, 2011]

Linear Kinetic Dispersion Theory

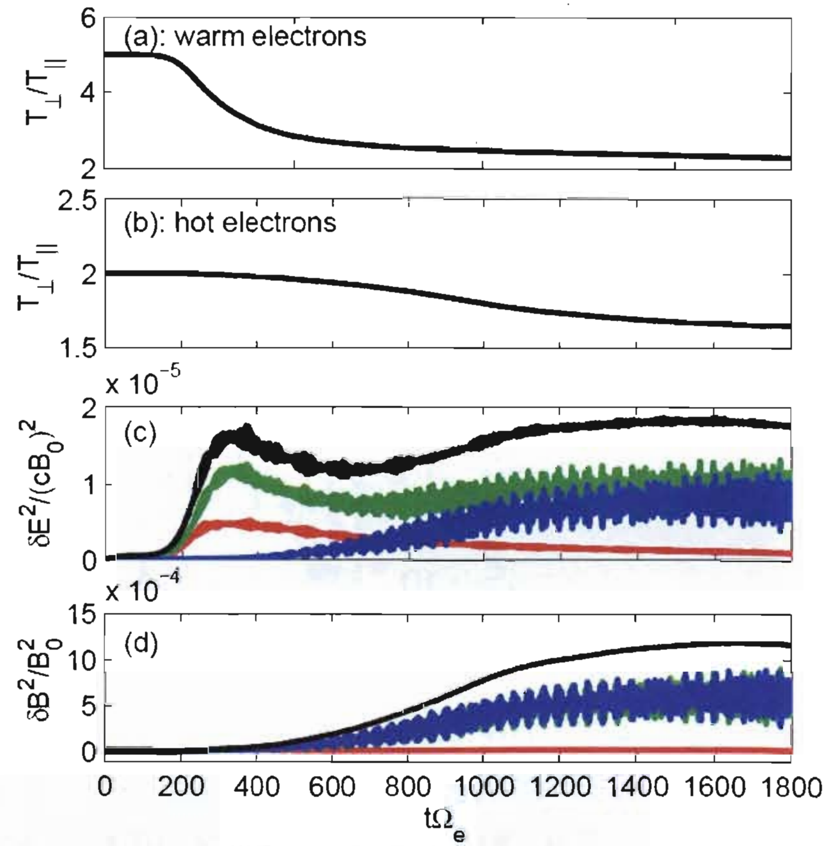
- Electrons: 90% of warm electrons with $T_\perp/T_{||}$=5 at $T_{||}$=160 eV and 10% of hot electrons with $T_\perp/T_{||}$=2 at $T_{||}$=16 keV
- ω_e/Ω_e=4 (1<ω_e/Ω_e<5 in regions associated with strong chorus [Li et al., 2010])
  - + $\beta_{||w}$=0.01 and $\beta_{||h}$=1 if $\beta_{||j}=n_0 T_{||j}/(B_0^2/2\mu_0)=(2T_{||j}/m_e c^2)(\omega_e/\Omega_e)^2$
- Hot electrons drive lower-band waves:
  - + ω_m/Ω_e=0.29, γ_m/Ω_e=0.016 at $k\lambda_e$=0.63 and $\theta=0^o$
  - + Substantially electromagnetic :$|\delta E_{||}|<<|\delta E_{\perp\perp}|\leq|\delta E_\perp|$ and $|\delta B_{||}|<<|\delta B_\perp|\leq|\delta B_{\perp\perp}|$
- Warm electrons excite upper-band waves:
  - + ω_m/Ω_e=0.69, γ_m/Ω_e=0.030 at $k\lambda_e$=3.8 and $\theta=48^o$
  - + Quasi-electrostatic :$|\delta E_{\perp\perp}|<<|\delta E_{||}|<|\delta E_\perp|$ and $|\delta B_{||}|\sim|\delta B_\perp|<|\delta B_{\perp\perp}|$



- Instability growth rate as a function of $k\lambda_e$ and θ (wave normal angle). The black contour lines are the contour of γ/Ω_e=0.01 [*Liu et al.*, 2011]

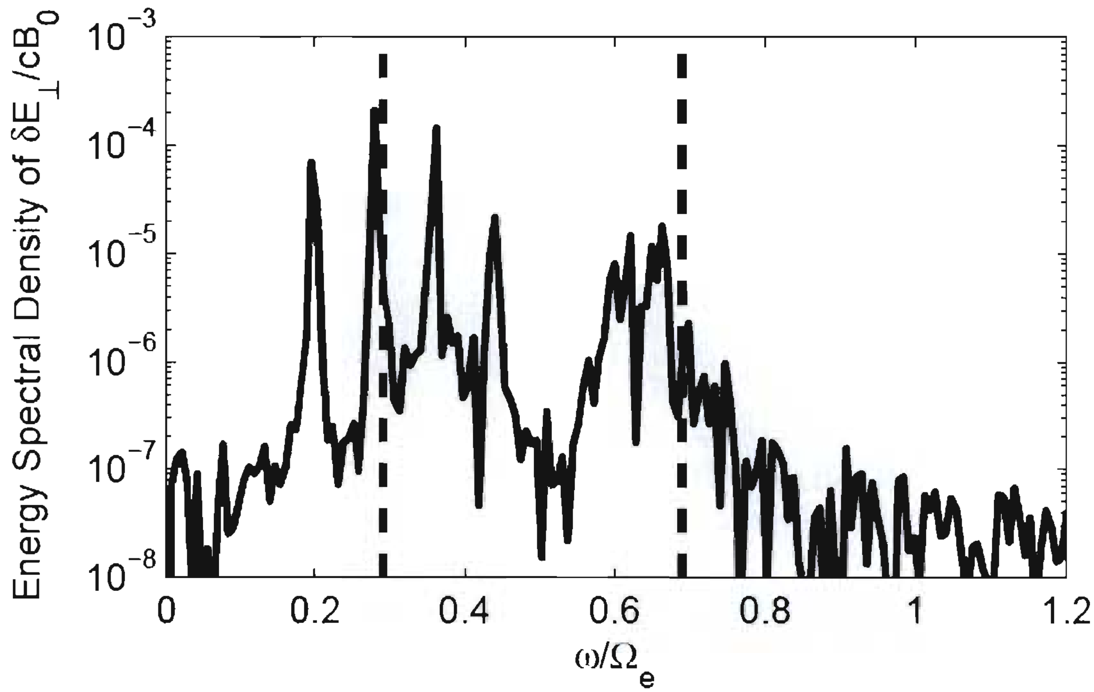
PIC Simulation

- 2D electromagnetic PIC simulation:
  - + $L_x=L_y=51.4\lambda_e$, $N_x=N_y=256$, $\Delta t\Omega_e=0.018$
  - + 9600 simulation particles per cell for each of the two electron components
  - + $\mathbf{B}_0$ is along x: x-||, y-⊥, z-⊥⊥
- The energy increase of δE around $t\Omega_e=200$ corresponds to the instability development driven by the warm electrons. The enhanced fluctuations are in the upper band and quasi-electrostatic
- The slight decrease of energy in δE after $t\Omega_e=300$ is due to Landau damping of the quasi-electrostatic fluctuations
- The energy increase after $t\Omega_e=600$ corresponds to the instability growth driven by the hot electrons. The enhanced fluctuations are in the lower band and predominantly electromagnetic



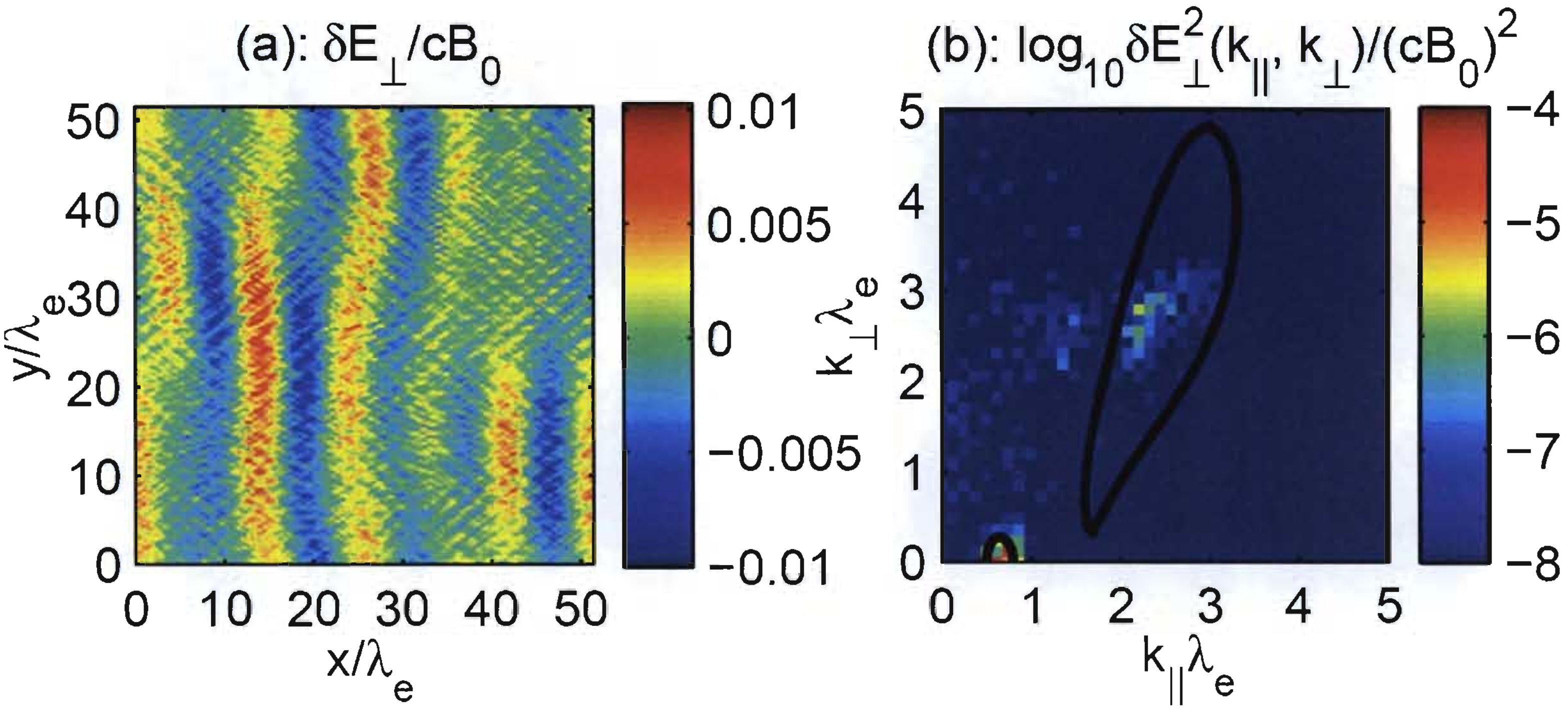
- Time evolution of $T_\perp/T_\parallel$ of the warm (a) and hot (b) electrons, as well as wave energies in different electric (c) and magnetic (d) field components (red-||, green-⊥, blue-⊥⊥, black-total) [*Liu et al.*, 2011]

PIC Simulation



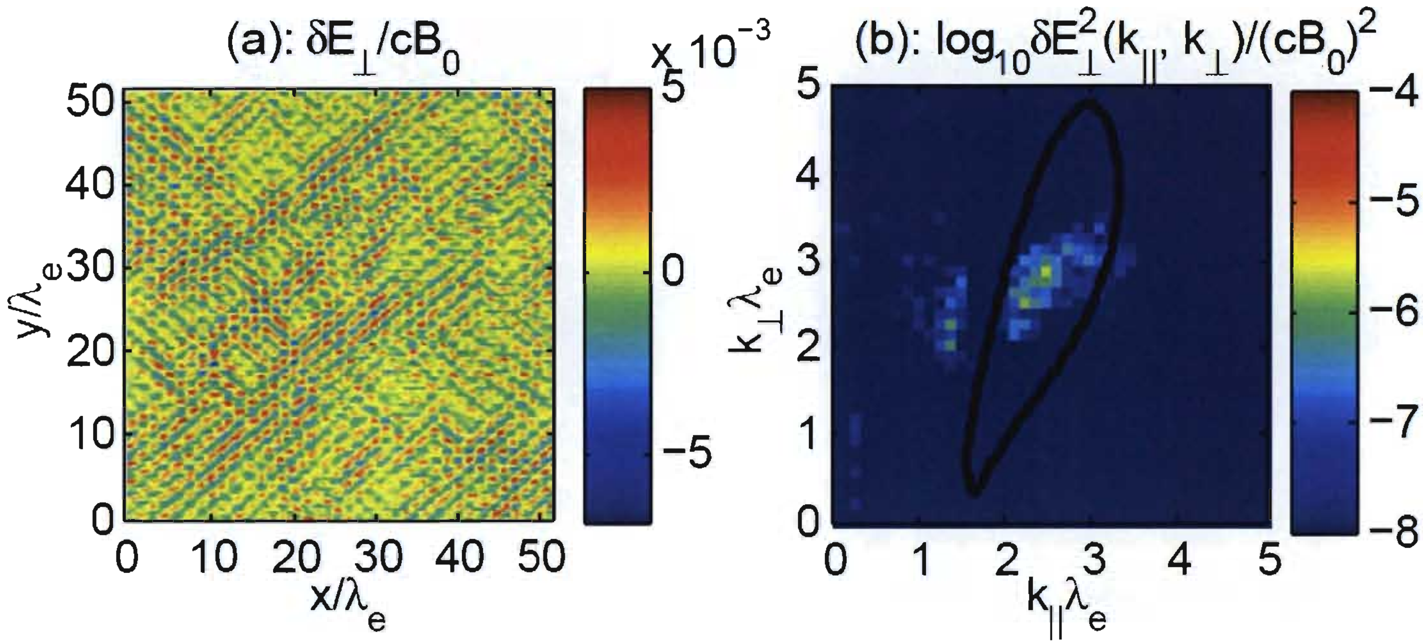
- Energy spectral density of $\delta E_{\perp}$ at $x=y=25.7\lambda_e$ from $t\Omega_e$=900 to 1800. The two vertical dashed lines mark the locations of the most unstable modes predicted by linear kinetic theory [*Liu et al.*, 2011]
- The four discrete spikes around the lower-band spectral peak are due to the limited size of the simulation domain, which allows only waves of $k=2n\pi/L$, n=0, 1, 2, …

PIC Simulation



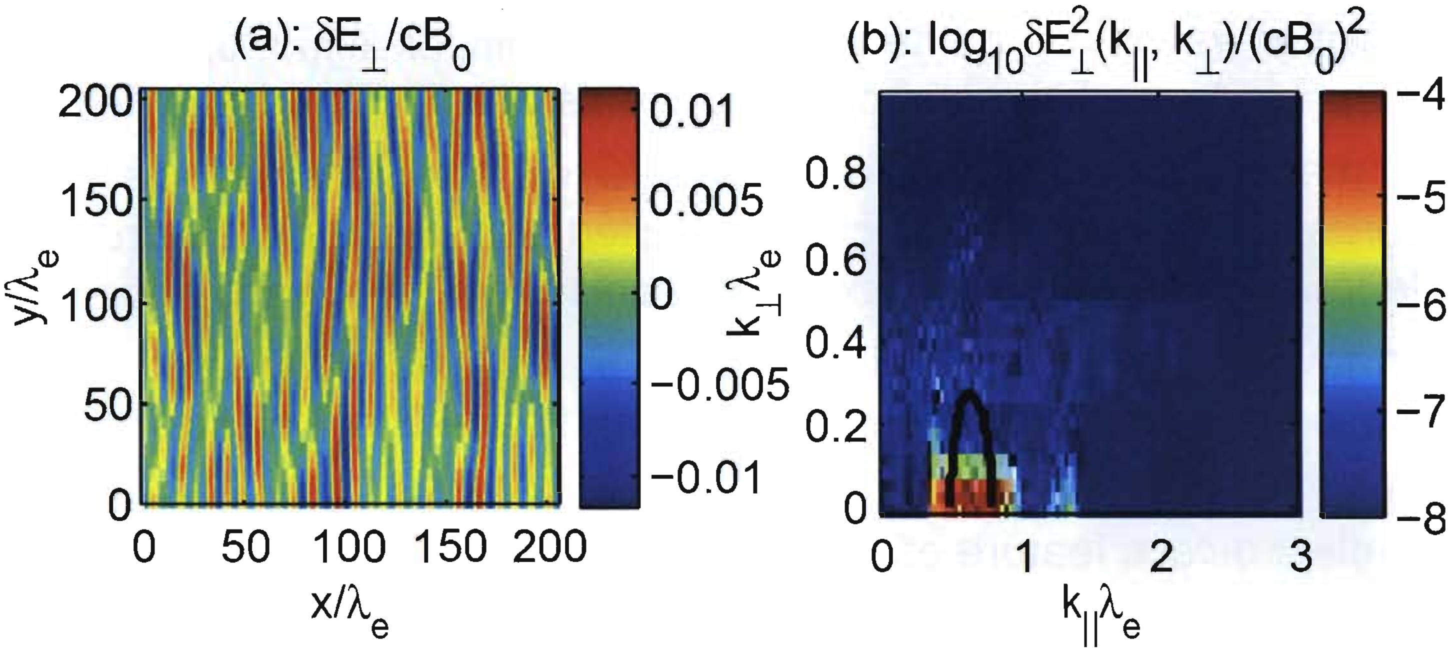
- The wave component $\delta E_\perp$ at $t\Omega_e$=1800: (a) The contour plot ; (b) The wave number power spectrum. The black contour lines represent the contour of γ/Ω_e=0.01 given by linear kinetic dispersion theory [*Liu et al.*, 2011]
- The superposition of short-wavelength obliquely-propagating waves on top of long-wavelength field-aligned waves
- The weak enhancement of waves around $k_{||}\lambda_e$=1.5 and $k_\perp\lambda_e$=2.5 suggests that the nonlinear wave-wave coupling mechanism in *Schriver et al.* [2010] operates weakly

Nonlinear Wave-wave Coupling



- The wave component $\delta E_\perp$ at $t\Omega_e$=1800 from a two-dimensional PIC simulation with only the warm electrons being anisotropic: (a) The contour plot ; (b) The wave number power spectrum. The black contour lines represent the contour of γ/Ω_e=0.01 given by linear kinetic dispersion theory
- The weak enhancement of waves around $k_{||}\lambda_e$=1.5 and $k_\perp\lambda_e$=2.5 suggests that the nonlinear wave-wave coupling mechanism in *Schriver et al.* [2010] operates: Obliquely-propagating lower-band waves are excited through nonlinear wave-wave coupling

Nonlinear Wave-wave Coupling



- The wave component $\delta E_\perp$ at $t\Omega_e$=1800 from a two-dimensional PIC simulation with only the hot electrons being anisotropic: (a) The contour plot ; (b) The wave number power spectrum. The black contour lines represent the contour of γ/Ω_e=0.01 given by linear kinetic dispersion theory
- The weak enhancement of waves around $k_{||}\lambda_e$=1.3 and $k_\perp\lambda_e$=0 reveals another wave-wave coupling mechanism: Parallel-propagating upper-band waves are excited through nonlinear wave-wave coupling

Summary

- Banded whistler waves can be generated by the whistler anisotropy instability driven by two bi-Maxwellian electron components with $T_{\perp}/T_{||} > 1$ at different $T_{||}$
- For typical magnetospheric condition of $1<\omega_e/\Omega_e<5$ in regions associated with strong chorus, upper-band waves can be excited by anisotropic electrons below ~1 keV, while lower-band waves are excited by anisotropic electrons above ~ 10 keV
- Lower-band waves are generally field-aligned and substantially electromagnetic, while upper-band waves propagate obliquely and have quasi-electrostatic fluctuating electric fields
- The quasi-electrostatic feature of upper-band waves suggests that they may be more easily identified in electric field observations than in magnetic field observations.
- Upper-band waves are liable to Landau damping and the saturation level of upper-band waves is lower than lower-band waves, consistent with observations that lower-band waves are stronger than upper-band waves on average
- The oblique propagation, the lower saturation level, and the more severe Landau damping together would make upper-band waves more tightly confined to the geomagnetic equator ($|\lambda_m|<\sim 10^{o}$) than lower-band waves

References

- Bell, T. F., U. S. Inan, N. Haque, and J. S. Pickett (2009), Source regions of banded chorus, *Geophys. Res. Lett., 36*(L11101), doi:10.1029/2009GL037629.
- Curtis, S. (1978), A theory for chorus generation by energetic electrons during substorms, *J. Geophys. Res., 83*(A8), 3841.
- Gary, S. P., K. Liu, and D. Winske (2011), Whistler anisotropy instability at low β: Particle-in-cell simulations, *Phys. Plasmas, 18* (8), doi:10.1063/1.3610378.
- Haque, N., M. Spasojevic, O. Santolík, and U. S. Inan (2010), Wave normal angles of magnetospheric chorus emissions observed on the polar spacecraft, *J. Geophys. Res., 115*(A00F07), doi:10.1029/2009JA014717.
- Hashimoto, K., and I. Kimura (1981), A generation mechanism of narrow band hiss emissions above one half the electron cyclotron frequency in the outer magnetosphere, *J. Geophys. Res., 86*(A13), 11,148.
- Hayakawa, M., Y. Yamanaka, M. Parrot, and F. Lefeuvre (1984), The wave normals of magnetospheric chorus emissions observed on board GEOS 2, *J. Geophys. Res., 89*(A5), 2811.
- Horne, R. B., R. M. Thorne, N. P. Meredith, and R. R. Anderson (2003), Diffuse auroral electron scattering by electron cyclotron harmonic and whistler mode waves during an isolated substorm, *J. Geophys. Res., 108*(A7), 1290, doi:10.1029/2002JA009736.
- Kennel, C. F., and H. E. Petschek (1966), Limit on stably trapped particle fluxes, *J. Geophys. Res., 71*(1), 1.
- Li, W., R. M. Thorne, Y. Nishimura, J. Bortnik, V. A. J. P. .McFadden, D. E. Larson, J. W. Bonnell, O. L. Contel, A. .Roux, and U. Anster (2010), THEMIS analysis of observed equatorial electron distributions responsible for the chorus excitation, *J. Geophys. Res., 115*(A00F11), doi:10.1029/2009JA014845.
- Liu, K., S. P. Gary, and D. Winske (2011), Excitation of banded whistler waves in the magnetosphere, *Geophys. Res. Lett., 38*, L14108, doi:10.1029/2011GL048375.

References

- Maeda, K., P. H. Smith, and R. R. Anderson (1976), VLF emission from ring-current electrons, *Nature, 263*, 37.
- Meredith, N. P., R. B. Horne, and R. R. Anderson (2001), Substorm dependence of chorus amplitudes: Implications for the acceleration of electrons to relativistic energies, *J. Geophys. Res., 106*(A7), 13,165.
- Omura, Y., Y. Katoh, and D. Summers (2008), Theory and simulation of the generation of whistler-mode chorus, *J. Geophys. Res., 113*, A04223, doi:10.1029/2007JA012622.
- Omura, Y., M. Hikishima, Y. Katoh, D. Summers, and S. Yagitani (2009), Nonlinear mechanisms of lower-band and upper-band VLF chorus emissions in the magnetosphere, *J. Geophys. Res., 114*(A07217), doi:10.1029/2009JA014206.
- Santolík, O., D. A. Gurnett, J. S. Pickett, M. Parrot, and N. Cornilleau-Wehrlin (2003), Spatio-temporal structure of storm-time chorus, *J. Geophys. Res., 108*(A7), doi:10.1029/2002JA009791.
- Santolík, O., D. A. Gurnett, J. S. Pickett, S. Grimald, P. M. E. Décreau, M. Parrot, N. Cornilleau-Wehrlin, F. E.-L. Mazouz, D. Schriver, N. P. Meredith, and A. Fazakerley (2010), Wave-particle interactions in the equatorial source region of whistler-mode emissions, *J. Geophys. Res.*, 115(A00F16), doi:10.1029/2009JA015218.
- Schriver, D., M. Ashour-Abdalla, F. V. Coroniti, J. N. LeBoeuf, V. Decyk, P. Travnicek, O. Santolík, D. Winningham, J. S. Pickett, M. L. Goldstein, and A. N. Fazakerley (2010), Generation of whistler mode emissions in the inner magnetosphere: An event study, *J. Geophys. Res., 115*(A00F17), doi:10.1029/2009JA014932.
- Tsurutani, B., and E. Smith (1974), Postmidnight chorus: A substorm phenomenon, *J. Geophys. Res., 79*(1), 118.