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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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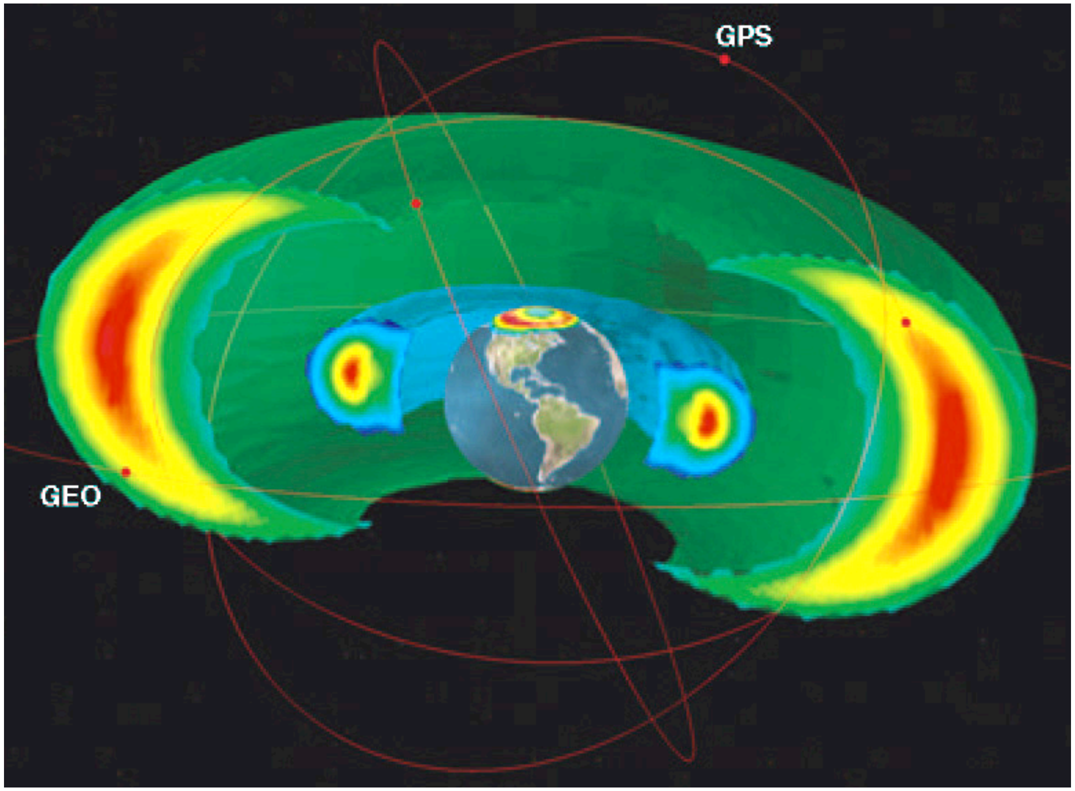
Outline

- Introduction
- Whistler Anisotropy Instability
- Excitation of Banded Whistler Waves
- Summary
- Future Work

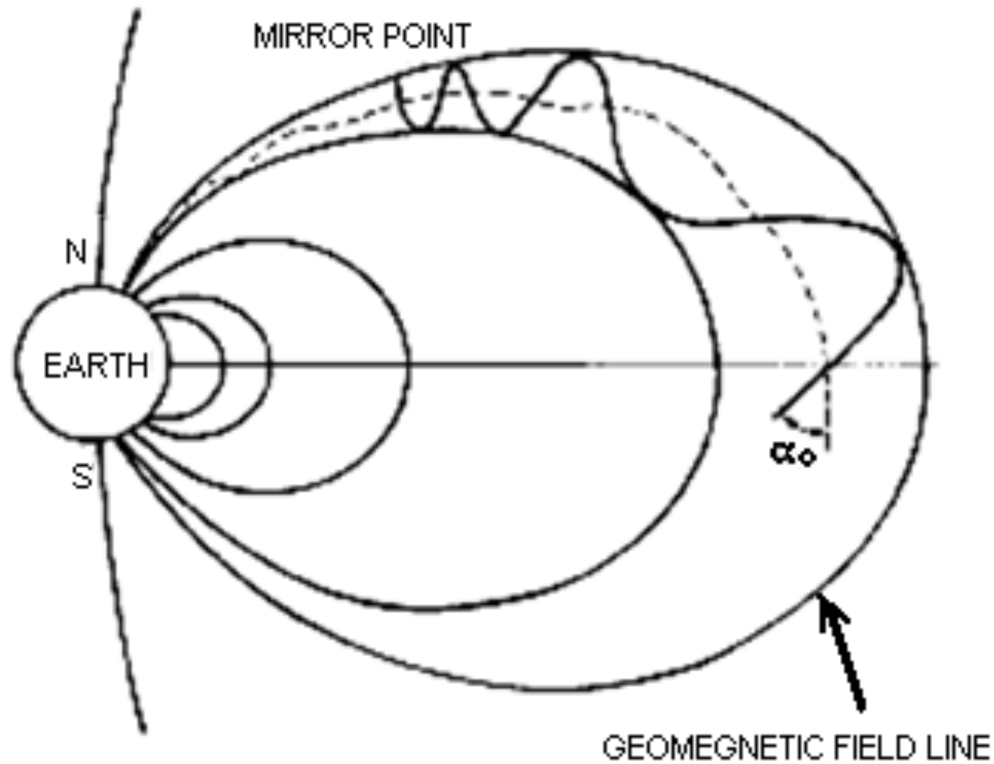
Introduction: Van Allen Radiation Belts

- Historic discovery in 1958 by the Explorer I mission under Dr. James Van Allen
- Torus of energetic charged particles trapped by the geomagnetic field around the Earth
- Two distinct belts: energetic electrons forming the outer belt and a combination of protons and electrons creating the inner belt
- Relativistic electrons (>~500 keV) are a serious threat to the operation of spacecraft



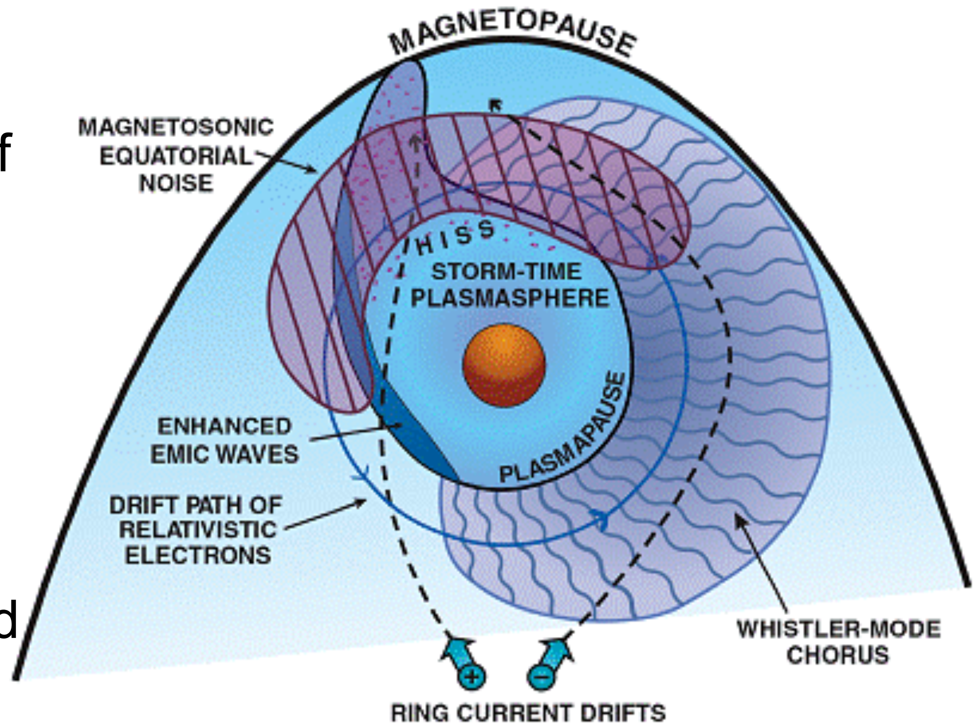
Introduction: Radiation Belt Dynamics

- Particle pitch angle α: $p_{||}/p = \cos(\alpha)$
- Particles with equatorial pitch angles $\alpha_E > \alpha_L$ are trapped due to magnetic mirroring
- Particles with $\alpha_E < \alpha_L$ encounter the atmosphere before mirroring, and consequently get lost
- α_L defines the size of "loss cone", which decreases with distance from the Earth



Introduction: Radiation Belt Dynamics

- The intensity and the structure of the trapped relativistic electron belts are controlled by a balance of acceleration, transport, and loss processes
- Relativistic electrons can be injected from the plasma sheet by geomagnetic storms
- Wave particle Interactions can scatter electrons into loss cone and remove them from radiation belts
- Many waves can scatter relativistic electrons, e.g., EMIC waves, whistler waves, and magnetosonic waves



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

Introduction: Overview of Waves

Wave	EMIC Waves	Whistler Waves	Magnetosonic Waves
Free Energy	$T_{i\perp}>T_{i\|\|}$	$T_{e\perp}>T_{e\|\|}$	$\partial f_i(v_\perp)/\partial v_\perp>0$
Properties	$\omega<\Omega_p$, $k\lambda_i<1$, nearly parallel propagation	$\Omega_{lh}<\omega<\Omega_e$, $k\lambda_e<1$, parallel as well as oblique propagation	$\omega\approx n\Omega_p$, $k\rho_i>1$, nearly perpendicular propagation
Fast Electron Scattering	Mainly in pitch angle	Both in pitch angle and energy	Both in pitch angle and energy
Simulation Model	Hybrid	Particle-in-cell	Particle-in-cell

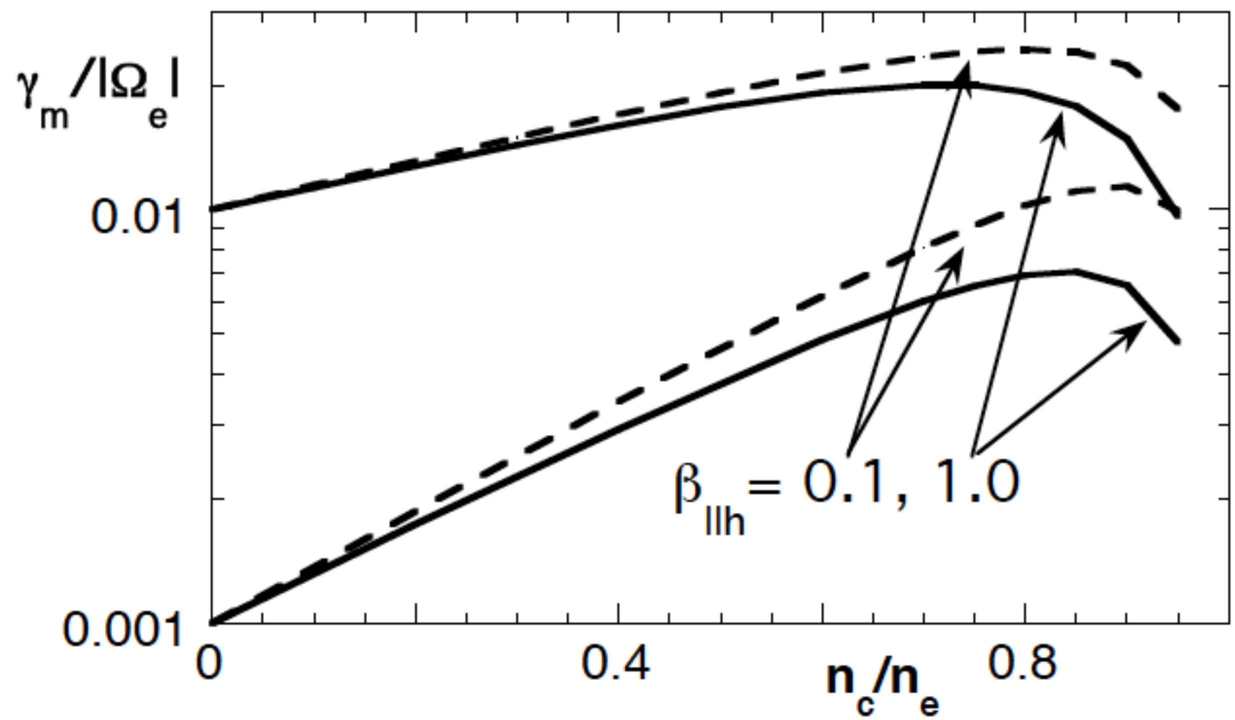
Whistlers: Linear Kinetic Theory

- Whistler anisotropy instability due to $T_{\perp e}/T_{||e} > 1$ is a likely source of enhanced "chorus" frequently observed in outer magnetosphere.
- Kinetic linear theory predicts instability grows at:
  - $\Omega_{lh} < \omega < \Omega_e$.
  - $kc/\omega_{pe} < 1$.
  - Maximum growth at propagation parallel to B_o.
- For a bi-Maxwellian electron velocity distribution, maximum growth rate:
  - Increases with increasing $T_{\perp e}/T_{||e}$.
  - Increases with increasing $\beta_{||e}$.
- For more realistic electron distributions, instability response gets more complicated.

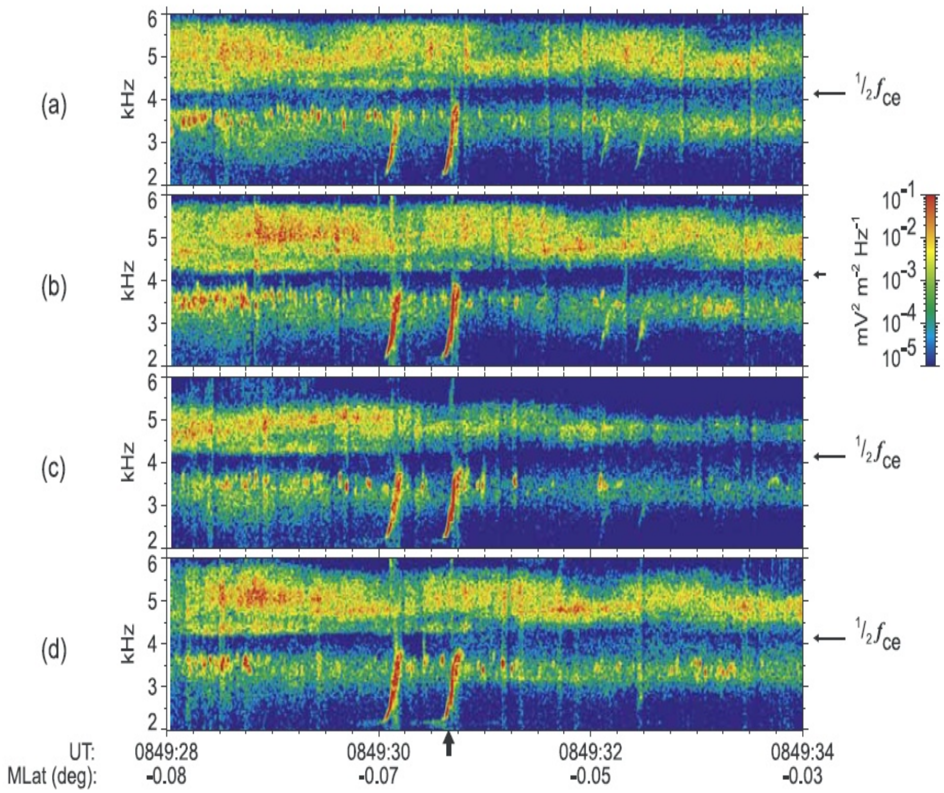
Whistler Anisotropy Instability: Cold Electrons Maximize Growth

- In plasmasphere, electron distribution usually consists of at least two components:
  - Hot, anisotropic, tenuous.
  - Cold, dense.

- Increasing cold electron density leads to growth rate maximum:



Banded Whistlers



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

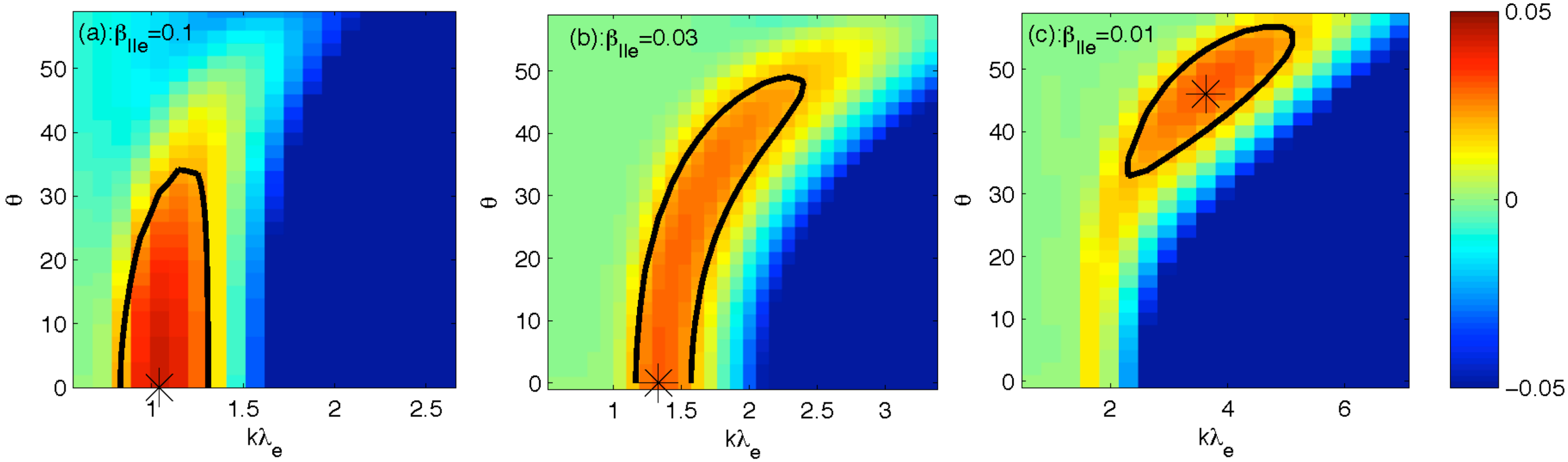
- Banded spectra with a gap near $0.5\Omega_e$
- Composed of discrete narrowband wave elements with rising or falling tones (the classical “chorus”) often accompanied by banded incoherent whistler waves
- Excited near the geomagnetic equator
- No general agreement on wave normal angle observations, but 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]

Banded Whistler 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]

Whistler Anisotropy Instability: Linear Theory

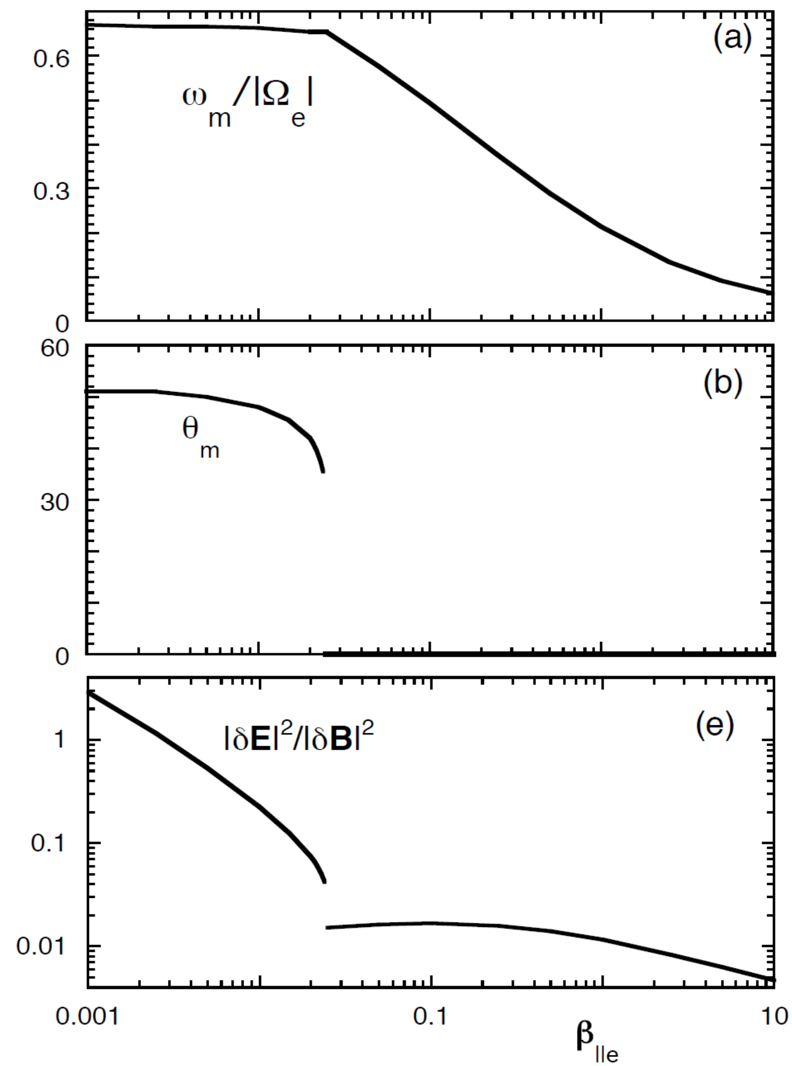
- Driven by anisotropic electrons with $T_\perp/T_\parallel > 1$
- Lead to whistler fluctuations over $\Omega_{lh} < \omega_r < \Omega_e$
- Properties of excited waves have a $\beta_{||e}$ dependence when $\omega_e/\Omega_e > 1$: ($\beta_{||e} = n_e T_{||e}/(B_0^2/2\mu_0) = (2T_{||e}/m_e c^2)(\omega_e/\Omega_e)^2$)



- The most unstable mode changes from parallel propagation to oblique propagation as $\beta_{||e}$ decreases

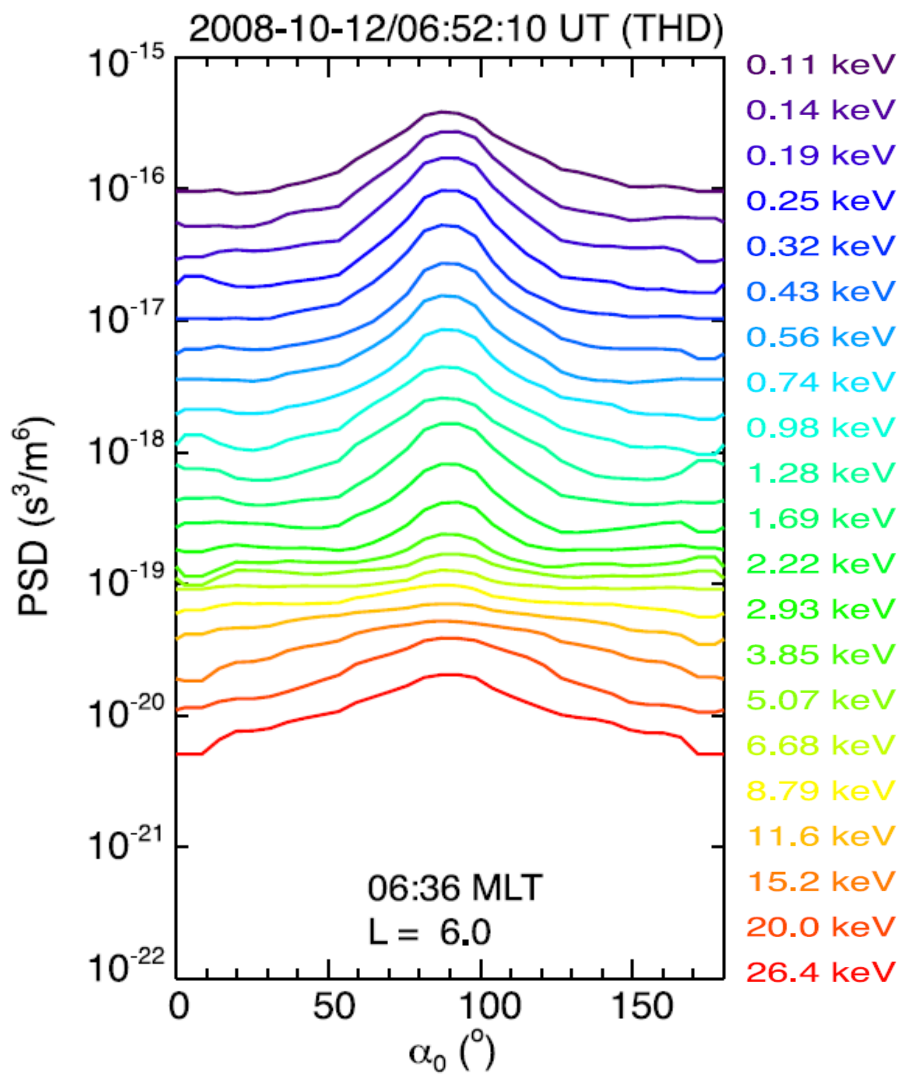
Whistler Anisotropy Instability: Linear Theory

- Two instability regimes:
  - + γ_m at parallel propagation and the excited waves are substantially electromagnetic when $\beta_{||e}$>~0.025
  - + γ_m at oblique propagation and the excited waves are quasi-electrostatic when $\beta_{||e}$<~0.025
  - + The frequency also shifts from below to above $0.5\Omega_e$
- Banded whistler waves can be excited when two bi-Maxwellian electron components with $T_\perp/T_{||} > 1$ at different $T_{||}$ are present



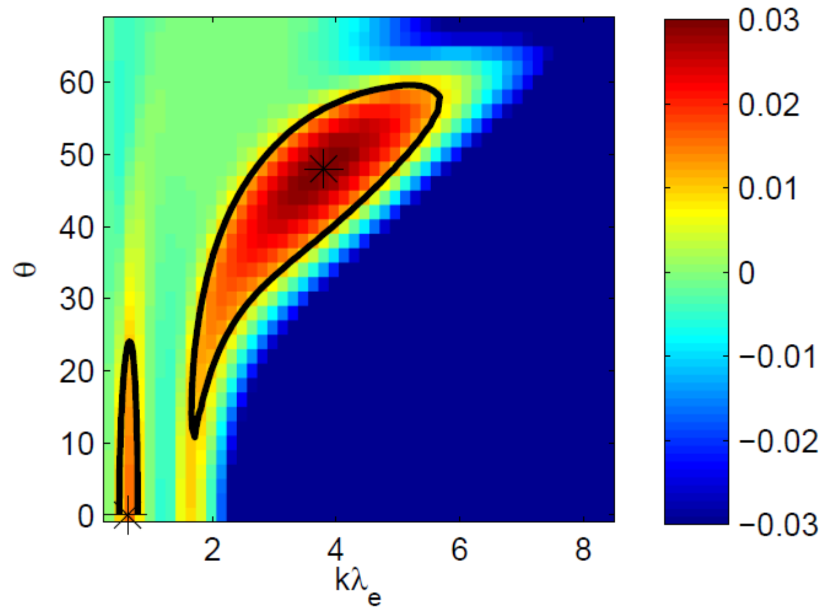
Banded Whistler Excitation: Observations

- *Santolík et al.* [2010] : two anisotropic electron components at different $T_{||}$ can excite the waves in two bands simultaneously
- *Li et al.* [2010] : a statistical survey of the equatorial electron distributions (THEMIS) responsible for chorus excitation



Banded Whistler Excitation: Linear Theory

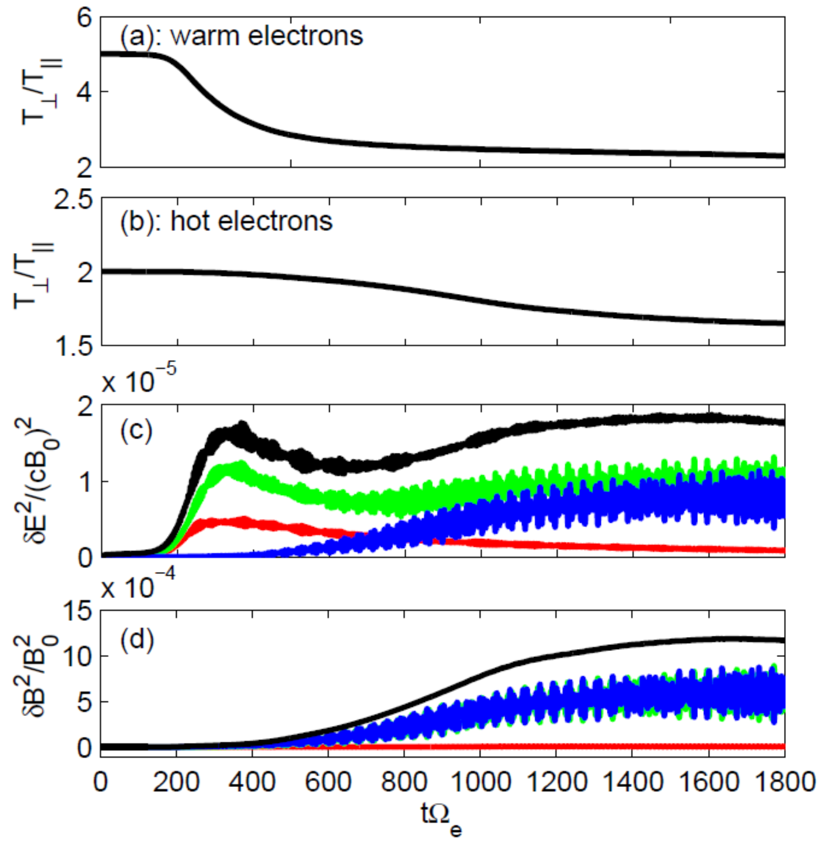
- Electrons: 90% of warm electrons with $T_\perp/T_{||}$ =5 at $T_{||}$=160 eV and 10% of hot electrons with $T_\perp/T_{||}$=2 at $T_{||}$=16 keV
- ω_e/Ω_e=4 ($1<\omega_e/\Omega_e<5$ in regions associated with strong chorus [Li et al., 2010])
  + $\beta_{||w}$=0.01 and $\beta_{||h}$=1 if $\beta_{||j}=n_0T_{||j}/(B_0^2/2\mu_0)=(2T_{||j}/m_ec^2)(\omega_e/\Omega_e)^2$
- 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 θ=0°
  + 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 θ=48°
  + 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]

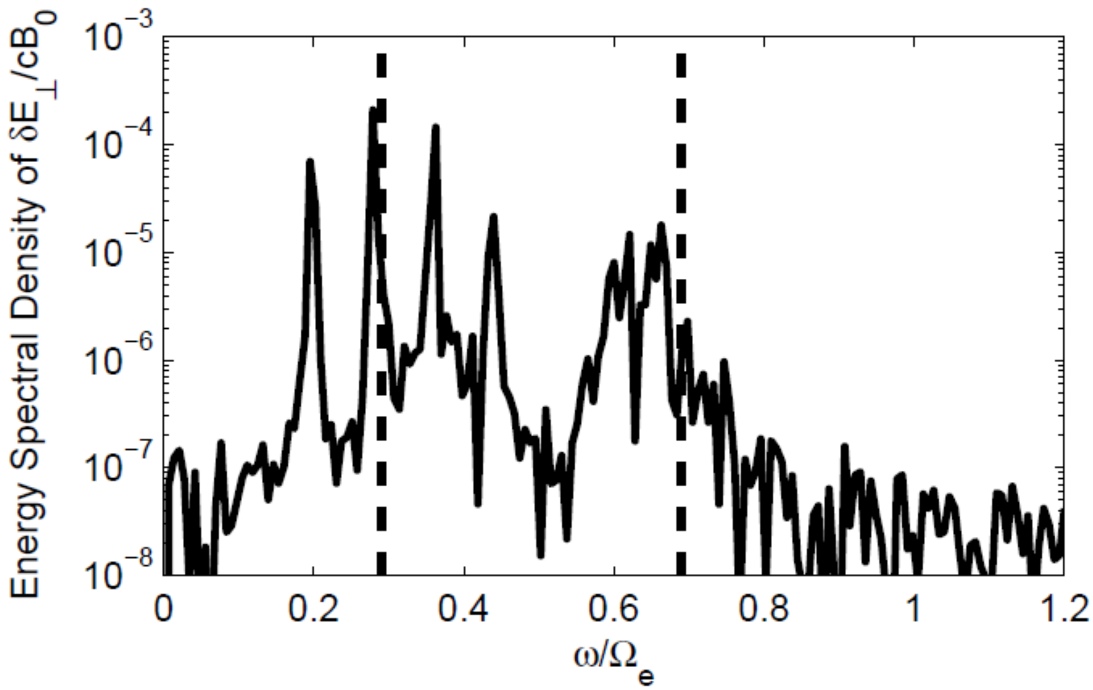
Banded Whistler Excitation: PIC Simulation

- 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



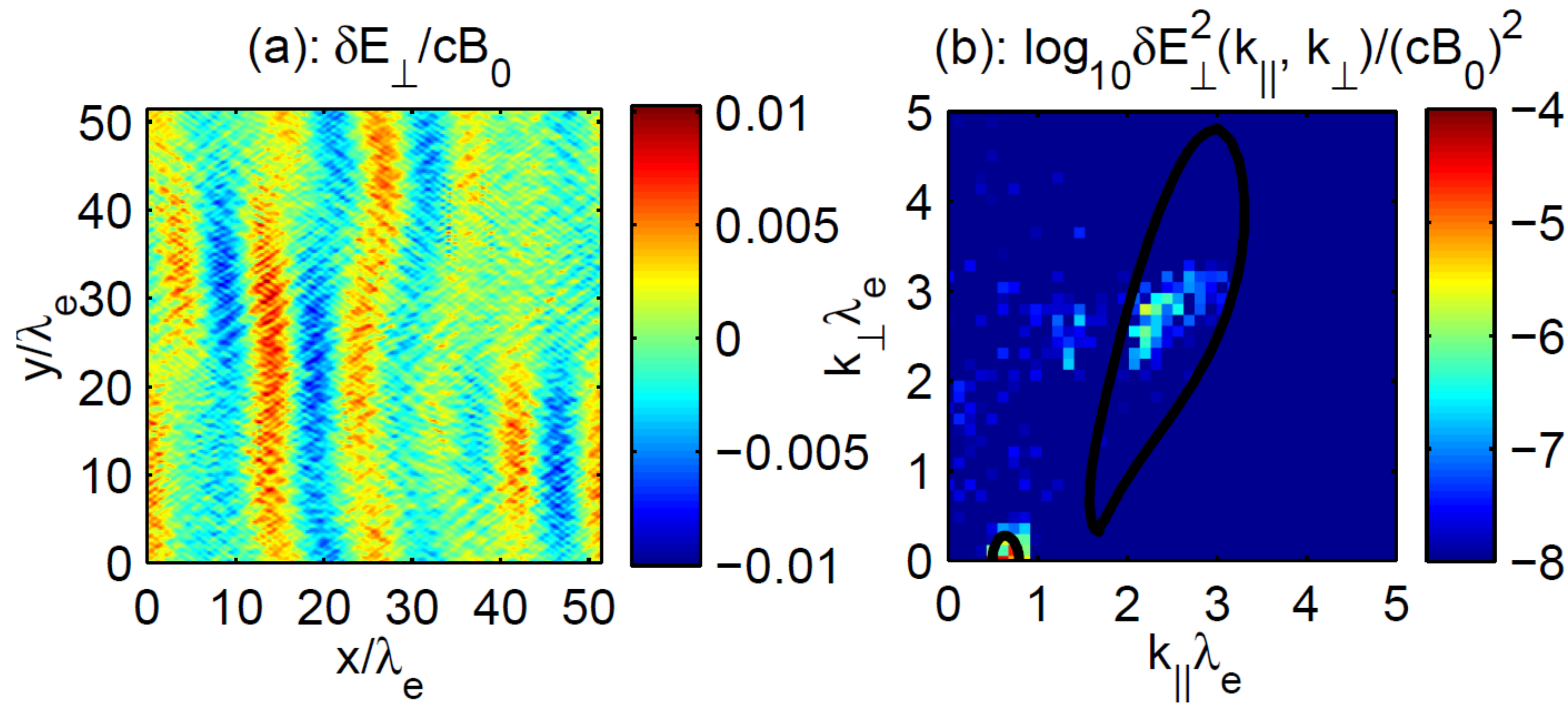
- Time evolution of $T_\perp/T_\parallel$ of the warm (a) and hot (b) electrons, as well as wave energies in different electric (c) and magnetic (d) field components (red-||, green-⊥, blue-⊥⊥, black-total) [*Liu et al.*, 2011]

Banded Whistler Excitation: PIC Simulation



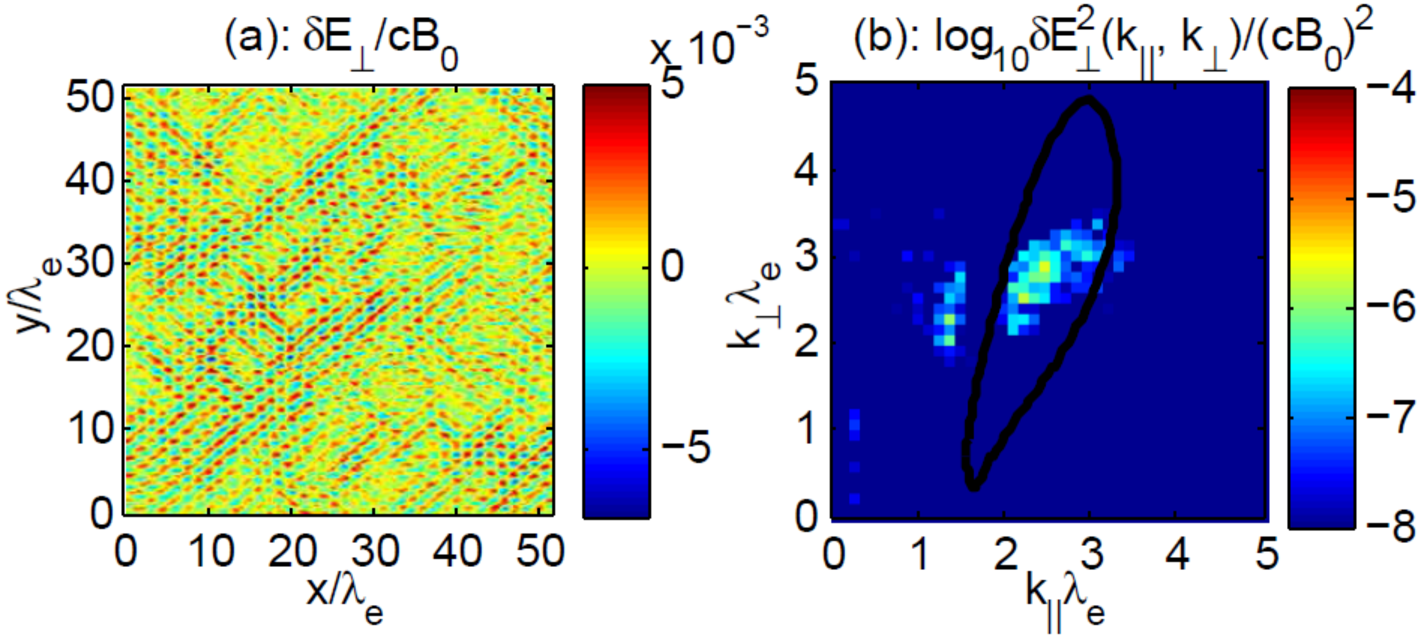
- Energy spectral density of $\delta E_{\perp}$ at $x=y=25.7\lambda_e$ from $t\Omega_e=900$ to 1800. The two vertical dashed lines mark the locations of the most unstable modes predicted by linear kinetic theory [*Liu et al*., 2011]
- The four discrete spikes around the lower-band spectral peak are due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

Banded Whistler Excitation: PIC Simulation



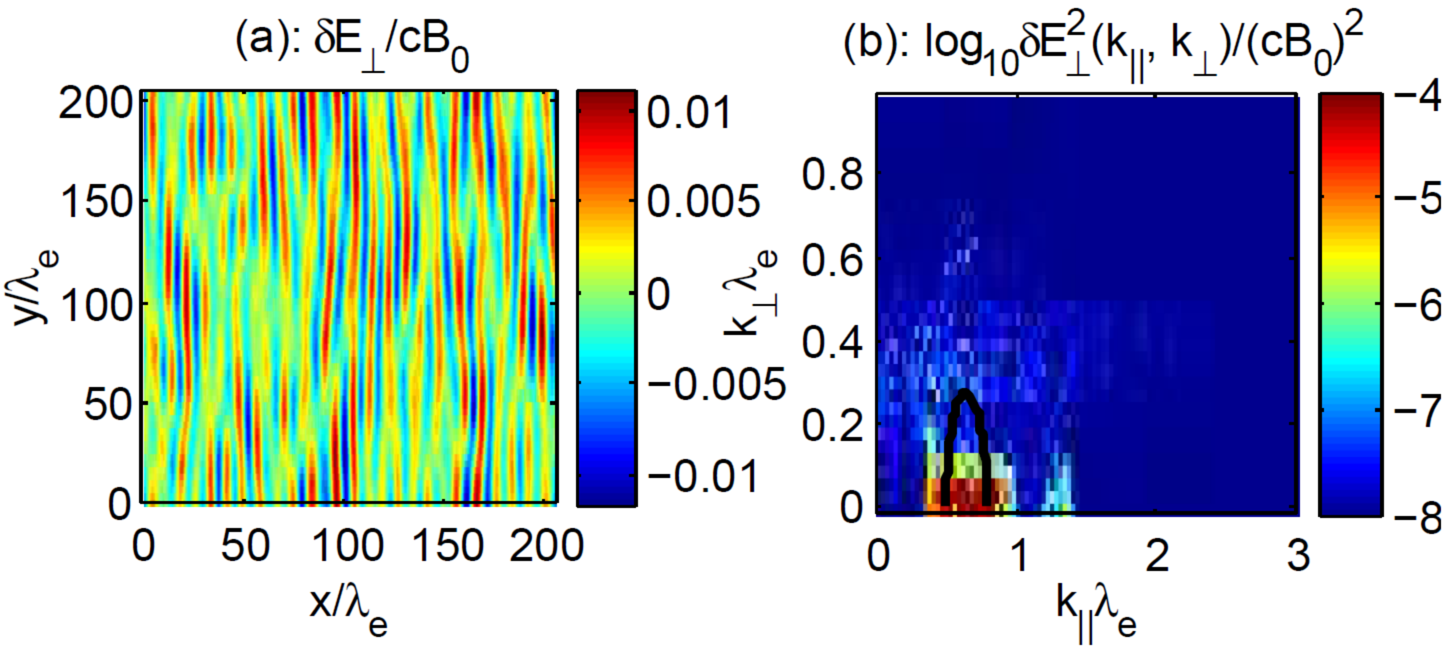
- The wave component $\delta E_{\perp}$ at $t\Omega_e$=1800: (a) The contour plot ; (b) The wave number power spectrum. The black contour lines represent the contour of γ/Ω_e=0.01 given by linear kinetic dispersion theory [*Liu et al*., 2011]
- The superposition of short-wavelength obliquely-propagating 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

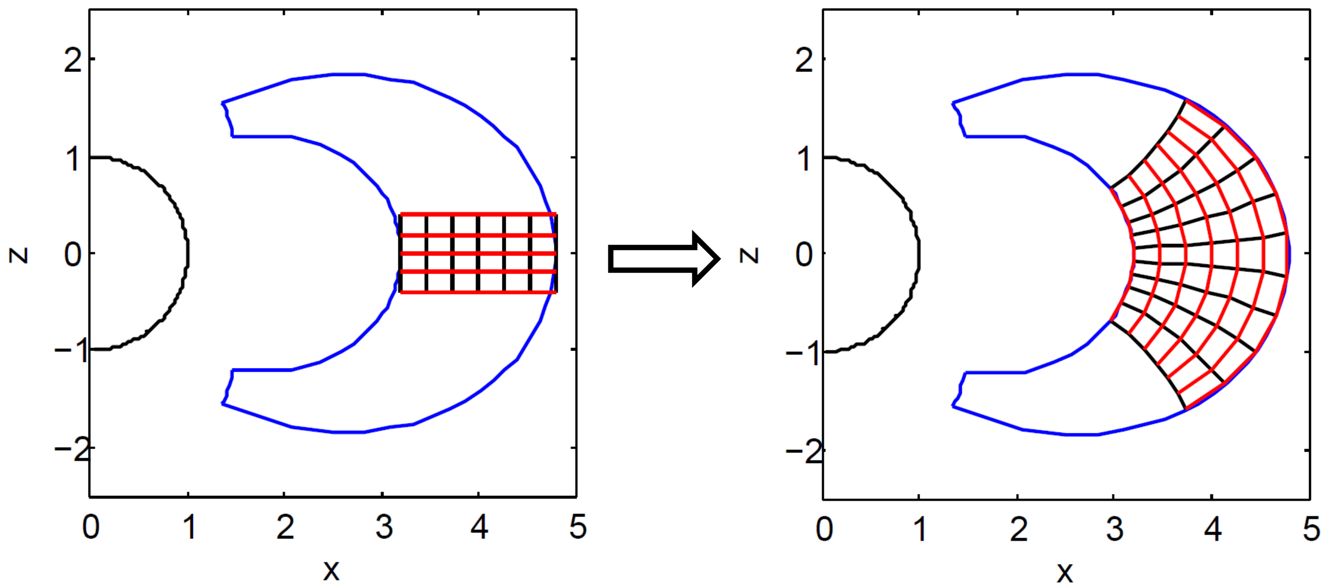


- The wave component $\delta E_{\perp}$ at $t\Omega_e$=1800 from a two-dimensional PIC simulation with only the hot electrons being anisotropic: (a) The contour plot ; (b) The wave number power spectrum. The black contour lines represent the contour of γ/Ω_e=0.01 given by linear kinetic dispersion theory
- 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

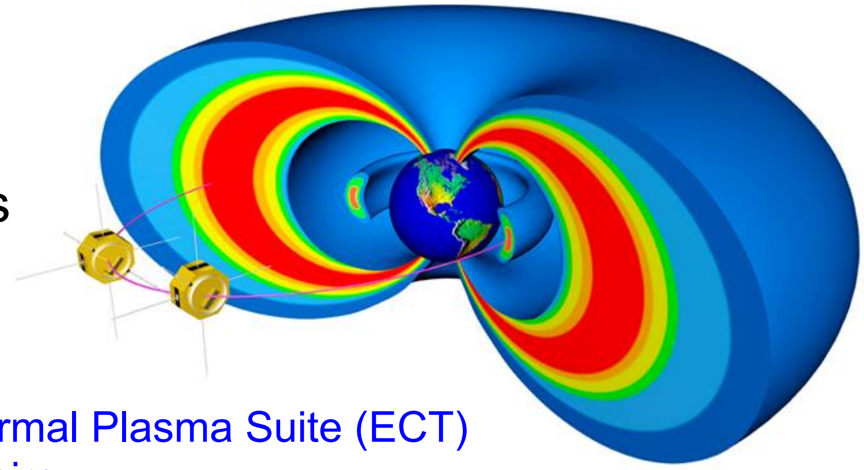
- Banded whistler waves can be generated by the whistler anisotropy instability driven by two bi-Maxwellian electron components with $T_\perp/T_{||} > 1$ at different $T_{||}$
- For typical magnetospheric condition of $1<\omega_e/\Omega_e<5$ in regions associated with strong chorus, upper-band waves 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

Future Work: Banded Chorus Simulation



- The present simulations use Cartesian coordinates and represent only the vicinity of the geomagnetic equator
- New simulations using curvilinear orthogonal coordinates are underway:
  - + The effects of inhomogeneous $\mathbf{B}_0$ on wave generation and wave propagation will be investigated
  - + Test particle computations would subsequently produce bounce-averaged diffusion coefficients

Future Work: RBSP Mission



- Date of launch: August 15, 2012
- Two craft make identical measurements in the radiation belts through both space and time
- Instruments onboard:
  - Energetic Particle, Composition, and Thermal Plasma Suite (ECT)
    PI: H. Spence, University of New Hampshire
  - Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS)
    PI: C. Kletzing, University of Iowa, Iowa City
  - Electric Field and Waves Suite (EFW)
    PI: J. Wygant, University of Minnesota, Minneapolis
  - Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE)
    PI: L. Lanzerotti, New Jersey Institute of Technology
  - Relativistic Proton Spectrometer (RPS)
    PI: National Reconnaissance Office