Nonlinear wave-particle and wave-wave interactions in the outer radiation belt: physical mechanisms and observational effects

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The key processes for RB formation and dynamics are the same as in many astrophysical objects: radial diffusion and local angular particles acceleration/scattering.
Quasi-|| Chorus

NL GENERATION

temperature anisotropy of 10-50 keV electrons

1-5 keV electrons streams

NL INTERACTION EFFECTS

~100 keV electrons at Lat ~ 20-30° with
\[ \Delta E_\perp \sim 100 \text{ keV} \]

~1-10 keV electrons at the equator
\[ \Delta E_\parallel \sim 5-50 E_0 \text{ keV} \]

DETECTABLE EFFECTS OF NL WAVE-PARTICLE INTERACTIONS

- Transverse acceleration
- Microbursts
- Parallel acceleration of 1-10 keV to 10-50 keV
- Suppressing the anisotropy of 10-50 keV in a statistical pattern and blocking generation of parallel chorus
- Modification of \( E_\parallel \) waveform

Oliven & Gurnett, 1968; Rosenberg, 1981
Kersten et al., 11; Tsurutani et al., 13
Crew et al., 16
Breneman et al., 17; Mozer et al., 17
Shumko et al., 18 (under review)
Effects of Electron Acoustic Mode for Chorus

Magnetic and electric field waveforms (a,b) captured aboard Van Allen Probe A on April 24, 2013 and their dynamic spectra (c,d). Panel (e) presents the summary spectra of magnetic (the dashed curve) and electric (parallel component) field wave perturbation. The zoom of the wave perturbations are shown in panels (f) and (g) for the magnetic and electric field respectively. (h) - electron distributions along (the solid curve) the magnetic field and perpendicular (the thin curve) are presented.
Magnetic (a) and electric (b) field perturbations. The electron distribution function is shown in panel (c), and its parallel and transverse slices are presented in panel (d) with the solid and thin black curves respectively.
The results are presented in normalized units based on the electrons since they dominate the dynamics:

- the magnetic field to $B_0$,
- time to the inverse electron cyclotron time $\omega_{ce}^{-1}$
- lengths to the electron skin depth $d_e$
- velocities to the electron Alfvén speed $c_{Ae} = B_0/(4\pi m_e n_0)^{1/2}$
- temperatures to $m_e c_{Ae}^2$.
- grid scale of 0.05$d_e$.

- Other parameters of the simulations are a mass-ratio $m_i/m_e = 200$, which is sufficient to separate the dynamics of the two species, and speed of light $c = 5c_{Ae}$, which yields a ratio of the electron plasma frequency $\omega_{pe}$ to $\omega_{ce}$ of five.

- The initial electron parallel temperature $T_{exx} = 0.025$ is uniform while the perpendicular temperature $T_{eyy} = T_{ezz}$ is from 0.1 to 0.4 in the center of the domain, $|x-L_x|/L_x < 1/12$
\[ \Omega_c \text{t} = 0.000 \]

\[ B_z \]

\[ E_x \]

\[ T_{\text{exx}} \]
The power spectrum of the parallel electric field perturbation is presented in panel (k) with the solid black curve. Magnetic field spectrum is shown by the dashed curve.

<= Magnetic and electric field waveforms from the PIC simulation. The summary spectra of magnetic (the dashed curve) and electric (parallel component) field wave perturbation.
Effects of Electron Acoustic Mode: PIC calculation

The electron distribution function in the parallel and transverse velocity domain captured at point #1 and the corresponding field-aligned electron distribution function (for $v_\perp = 0$)

Dynamics of the electron distribution function in the $x$-$v_\parallel$ domain. Whistler parallel electric field modulates the resonance beam, which leads to generation of the electron acoustic mode with following steepening, overturning and mixing the hot beam.
Effects of Electron Acoustic Mode: PIC calculation
The rapid decay of the burst amplitude with growth of magnetic field is in a good agreement with the approximate dependence

$$e \varphi + T_{tr0} \frac{B}{B_0} \sim \text{const}$$

with $T_{tr} = T_{tr0} B / B_0$ shown by the red and blue solid curves respectively.
Conclusions

we report the first direct observation of the electrostatic electron acoustic wave generation triggered by the electromagnetic whistler mode in the presence of the resonance electron beam:

➢ The process which has been thought of as the nonlinear electrostatic steepening of whistler waves is, instead, the coupling of the whistler with the electron acoustic mode.
➢ This plasma wave mode conversion is thought to be important for the energy transport to smaller scales and for plasma heating in space and laboratory plasma systems.
➢ The mechanism has been confirmed by a self-consistent numerical simulation that fully reproduces all steps of the process.