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Cold-hot coupled waves in a flowing magnetized plasma

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ABSTRACT

- Nonlinear coupling between cold (fluid) and hot waves in a *time-varying plasma flow* is analyzed with the Vlasov equation.
- The kinetic analysis presents a generalized dispersion relation that involves resonances depending on cold and hot wave dispersions.
- Both the analytic solution and fully kinetic particle-in-cell (PIC) simulations demonstrate that the wave spectrum is nonlinearly determined by the wavenumbers of linearly independent waves.

BACKGROUND

- Rapid plasma transports are frequently observed in a variety of situations such as sawtooh crashes, tearing modes [2], the burst of edge-localized modes [3], ionospheric flows, and the explosion of coronal loops.
- These events involve time-varying plasma flows $\mathbf{u}_{s0} = \int \mathbf{v} f_{s0}\, \mathrm{d}\mathbf{v}/n_{s0} = \bar{\mathbf{u}}_{s0} + \tilde{\mathbf{u}}_{s0}(t)$ (species s with a distribution function $f_s = f_{s0} + f_{s1}$), then EM waves are excited by $\tilde{\mathbf{J}}_0 = \sum_s q_s n_{s0} \tilde{\mathbf{u}}_{s0}$.
- This work investigates the nonlinear wave-wave coupling, respectively, induced by $\tilde{\mathbf{J}}_0$ and $\mathbf{J}_1 = \sum_s q_s \int \mathbf{v} f_{s1}\, \mathbf{dv}$. A generalized dispersion relation is derived and the resulting wave spectra are studied.

METHODS & IMPLEMENTATION

(a) Kinetic analysis

- Zeroth order distribution function:

† v_T: thermal speed

$$f_{s0}(\mathbf{v},\mathbf{x},t) = \frac{n_{s0}}{\pi^{3/2} v_{Ts\perp}^2 v_{Ts\parallel}} \exp\left(-\frac{(\mathbf{v}_\perp - \mathbf{u}_{s0\perp})^2}{v_{Ts\perp}^2} - \frac{(\mathbf{v}_\parallel - \mathbf{u}_{s0\parallel})^2}{v_{Ts\parallel}^2}\right) \quad (1)$$

- First order distribution function (integration of the linearized Valsov Eq.):

$$\frac{\mathrm{d}f_{s1}}{\mathrm{d}t} = -\frac{q_s}{m_s}(\mathbf{E}_1 + \mathbf{v}\times\mathbf{B}_1)\cdot\frac{\partial f_{s0}}{\partial \mathbf{v}}$$

$$\Rightarrow \; f_{s1}(\mathbf{v},\mathbf{x},t) = -\frac{q_s}{m_s}\int_{t_0}^{t}(\mathbf{E}_1 + \mathbf{v}\times\mathbf{B}_1)\cdot\frac{\partial f_{s0}}{\partial \mathbf{v}}\,\mathrm{d}t' \quad (2)$$

- Equation of motion:

† bar : time-independent field
tilde: time-dependent field $\propto \exp(i\tilde{\mathbf{k}}\cdot\mathbf{x} - i\tilde{\omega}t)$

$$\frac{\mathbf{d}\mathbf{v}(t')}{\mathrm{d}t'} = \frac{q_s}{m_s}(\mathbf{E}_0 + \mathbf{v}(t')\times\mathbf{B}_0) \;\Rightarrow\; \mathbf{v}(t') = \mathbf{v}^* + \bar{\mathbf{u}}_{s0} + \tilde{\mathbf{u}}_{s0} \quad (3)$$

$\mathbf{v}^* = v_\perp(\hat{x}\cos\omega_c t - \hat{y}\sin\omega_c t)$: Cyclotron motion
$\bar{\mathbf{u}}_{s0}$: Time-independent flow
$\tilde{\mathbf{u}}_{s0}$: Time-dependent flow

Cold wave motion

$$\frac{\partial \tilde{\mathbf{u}}_{s0}}{\partial t'} = \frac{q_s}{m_s}(\tilde{\mathbf{E}}_0 + \tilde{\mathbf{u}}_{s0}\times\bar{\mathbf{B}}_0) \quad (4)$$

The time-dependent flow $\tilde{\mathbf{u}}_{s0} = \sum_{l,r}\tilde{u}_{s0lr}\hat{r}$ having the lth mode $\tilde{u}_{s0lr} \propto \cos[\tilde{\omega}_l(\tilde{\mathbf{k}}_l)t']$ is determined by the cold wave dispersion relation with the flow wavenumber $\tilde{\mathbf{k}}$. A general dispersion relation including the cold-hot coupled wave is obtained by combining $\mathbf{J}_1 = \sum_s q_s \int \mathbf{v} f_{s1}\, \mathbf{dv}$ (equation (2)) with Maxwell's equations (full analysis and results can be found in [1]).

(b) Particle-in-cell simulation (1-D periodic boundary condition) [4]

- As an example study, the perpendicular wave ($k = k_x$) spectrum is examined.
- A time-varying flow with a cold wave frequency $\tilde{\omega}(\tilde{k})$ is given by the initial EM fields and $\tilde{u}_{\mathrm{init}} \propto \cos(\tilde{k}x)$ satisfying equations (3)-(4).

Case	$\bar{\mathbf{u}}_0$ (constant flow)	$\mathbf{k}\cdot\bar{\mathbf{u}}_0$ (Doppler-shift)	Remarks
(i)	0	0	Static plasma
(ii)	$0.02 v_{Te}\,\hat{y}$	0	Time-varying flow with a single $\tilde{k}$: $\tilde{\omega}(\tilde{k}) = 0.02\omega_{ce}$
(iii)	$0.02 v_{Te}\,\hat{x}$	$k_x \bar{u}_{0x}$	

Table A. Initial conditions with $\bar{\mathbf{B}}_0 = 2\hat{z}\,\mathrm{T}$, $n_{e,i} = 10^{19}\,\mathrm{m}^{-3}$, $T_{e,i} = 1\,\mathrm{keV}$

OUTCOME

- The kinetic analysis presents a *generalized plasma wave dispersion relation* that involves cold-hot coupled resonances at

$$\omega_{\mathrm{resonant}} = \sum_{l,r} m_{lr}\tilde{\omega}_l + n\omega_{cs} + k_\parallel v_\parallel, \quad -\infty \le n, m_{lr} \le \infty. \quad (5)$$

† r_L: Larmor radius

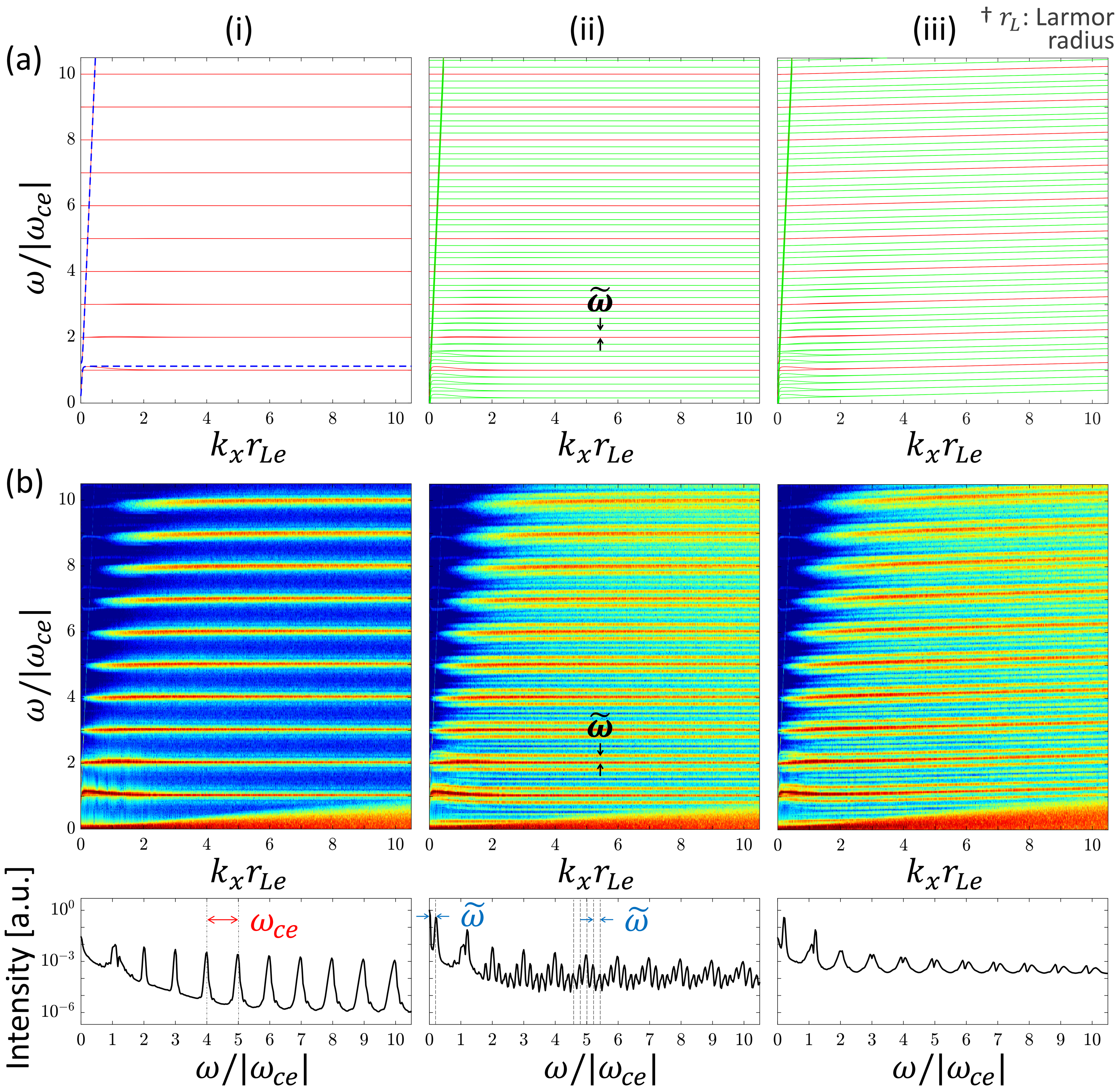

Figure A. Dispersion relations obtained from (a) kinetic analysis and (b) PIC simulations (electric field intensity on a logarithm scale). (i)-(iii) correspond to the cases in *Table A*. Frequency spectrums of the field intensity from the PIC are plotted in the bottom. In (a), the dispersions of cold (blue, dashed), hot (red only), and cold-hot coupled waves (red & green in (ii, iii)) are shown.

CONCLUSION

- Nonlinearly coupled harmonic waves are excited by the time-varying plasma flow.
- The spectrum is determined by $\tilde{\omega}$ via $\tilde{\mathbf{k}}$ (characteristic length scale of the flow) and $\mathbf{k}\cdot\bar{\mathbf{u}}_{s0}$ (Doppler effect).
- In experiments, it is expected that the plasma flow (current) results in a broad frequency spectrum by the excitation of cold-hot coupled waves (bottom panel of (ii)) and the Doppler effect (bottom panel of (iii)).
- The theory will be applied to the spectral interpretation of the transport processes in the laboratory and magnetospheric plasmas (e.g., MHD instability, magnetic reconnection, and turbulence).

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