Heat-flux driven instabilities in high-beta plasmas and their relevance for AGN feedback

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Outline

- Background – AGN feedback, role of conduction.
- PIC Simulations: Hot spot model and results.
- Unknown wave mode and questions.

AGN Feedback

- Gas surrounding central black hole in galaxy clusters can cool and accrete.
- Black hole can release jets, radiation, or winds back into intracluster medium (ICM) → heating or ejection of gas.
- Balance of cooling and heating thought to bring about thermodynamic stability.

Possible Roles of Conduction

1. Direct transport of heat into cluster core.
2. Effective way to thermalize energy in sound waves and shocks (e.g. from jets).
3. Inhibit local cooling of cluster gas.
4. Induces large-scale instabilities such as HBI and MRI.

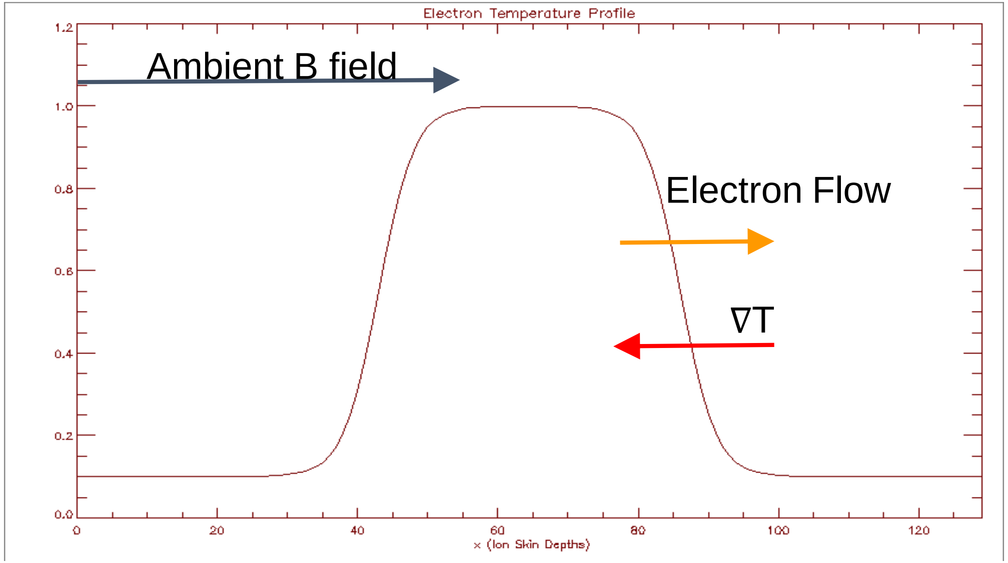
Modeling Conduction in ICM Plasmas

- Use 2D PIC simulations to study conduction-related microinstabilities.
- $\lambda_{mfp} \sim 10^{16}$m, in our simulations collisionless.
- $\beta = \frac{4\pi nT}{B^2/2} \sim 100$
- Weak, large-scale temperature gradients (~ 1 kpc, 10^{19} m).
- Heat fluxes, pressure anisotropies.

Starting Point

- Li, Drake & Swisdak (2012) studied transport of energetic electrons during solar flares.
- Initialize hot "pulse" of electrons on bed of cold ions in quasi-1D box.
- Buneman instability leads to electrostatic double layers. Electrons (and heat flux) confined.

Periodic Boundary

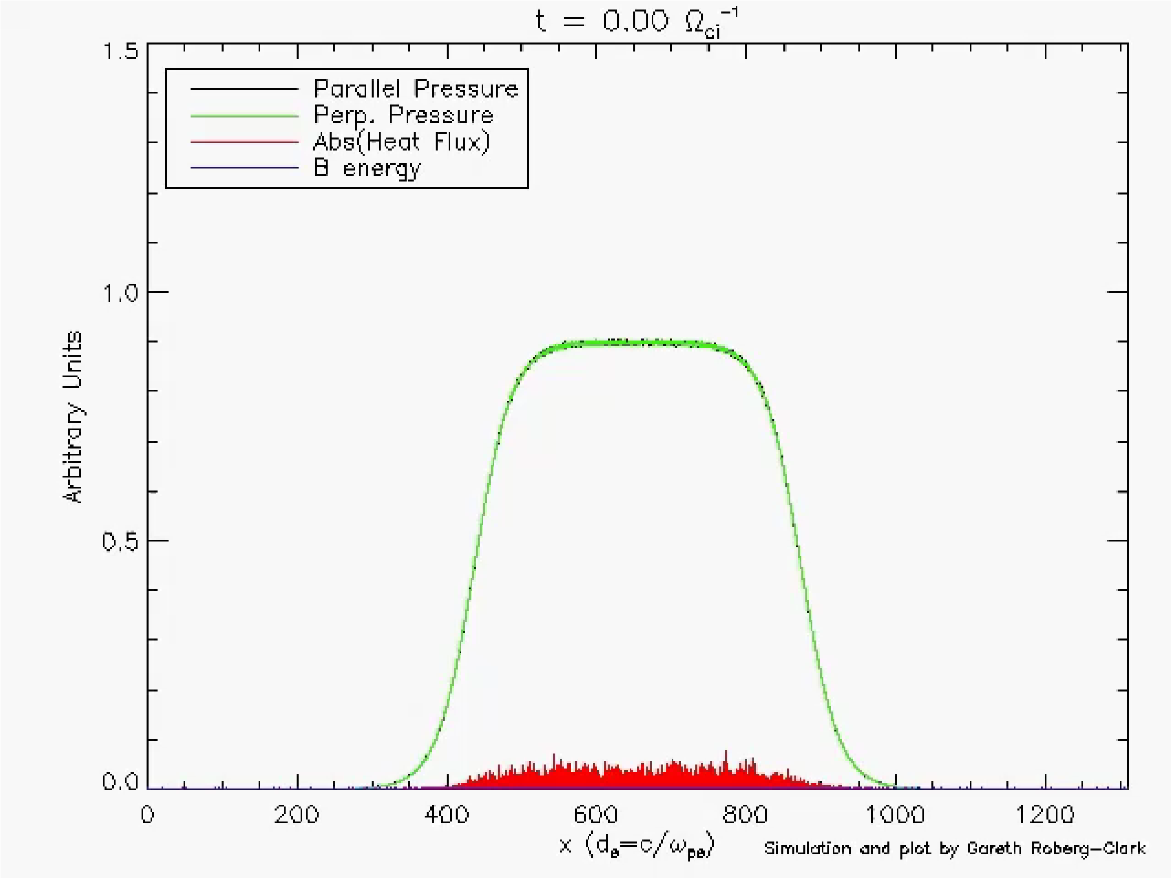


Periodic Boundary

Results from the initial model

- Increased β by reducing B - looked at β = 1,4,8,16. Found whistler waves – whistler anisotropy and heat flux instabilities.
- Firehose instability at β = 16.
- System passes mirror mode stability threshold at β = 8 and above.

$\boldsymbol{\beta = 4}$ Simulation



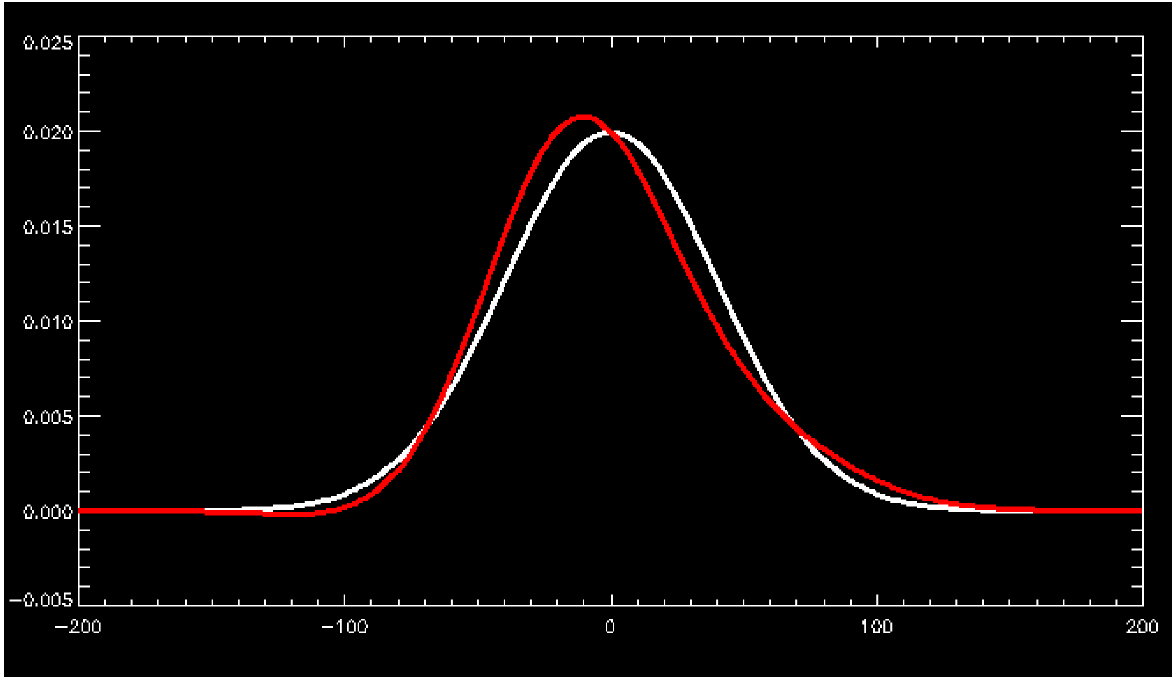
Whistler Heat Flux Instability

- Discussed in *Gary & Li* (1994) in context of the solar wind.
- Skewness of an electron distribution function (heat flux) leads to wave growth. We calculate:

$$\vec{q} = \frac{1}{2} m_e \int d^3v \, (v - V)^2 \left(\vec{v} - \vec{V}\right) f_e$$

- Marginally stable heat flux estimated to scale as $\frac{1}{\beta^{.9}}$ in solar wind (*Gary & Li 2000)*.

Heat flux distribution



- From Levinson & Eichler (1992)
- Assume collisions (Krook operator) and a T gradient; expand f to first order.
- Maxwellian in white.
- New distribution in red ($\varepsilon = 0.2$)

$$f_o(\boldsymbol{r},\boldsymbol{v}) = f_m\left[1 + \frac{\varepsilon}{2}\left(\frac{v^2}{v_T^2} - 5\right)\frac{v_n}{v_T}\right]$$

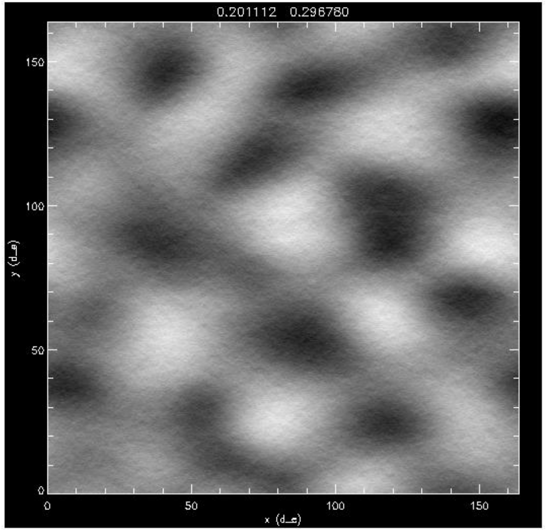
Here $\epsilon = (|\nabla T|/\nu T)v_T$, $v_T = (kT/m)^{1/2}$, and $v_n = -\boldsymbol{v}\nabla T/|\nabla T|$ is the component of the velocity along the direction of the thermal flux.

Simulations of heat flux distribution.

- Spatially homogeneous box, $\mathrm{B_o}||\nabla T$.
- Simulations <u>did not</u> produce whistler waves.
- Not sure why – is L&E derivation reliant on $f_e < 0$ portion?
- Reducing $\frac{m_e}{m_i}$ from $\frac{1}{100}$ to $\frac{1}{1600}$ produced a new wave mode.

Mystery Wave

Bx (Initial uniform Bx_0 + perturbations from waves)



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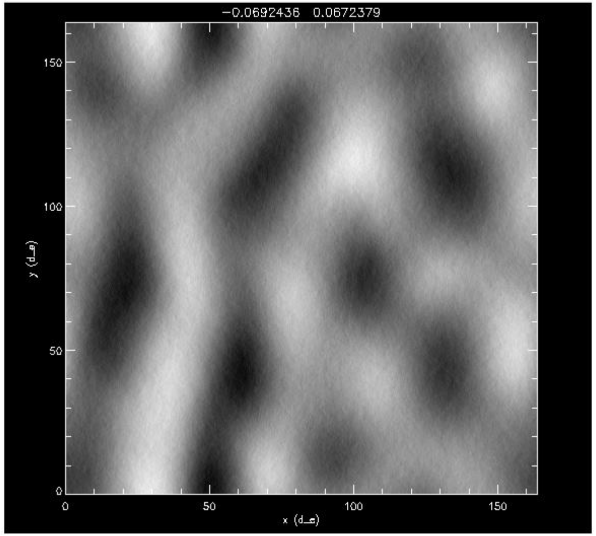
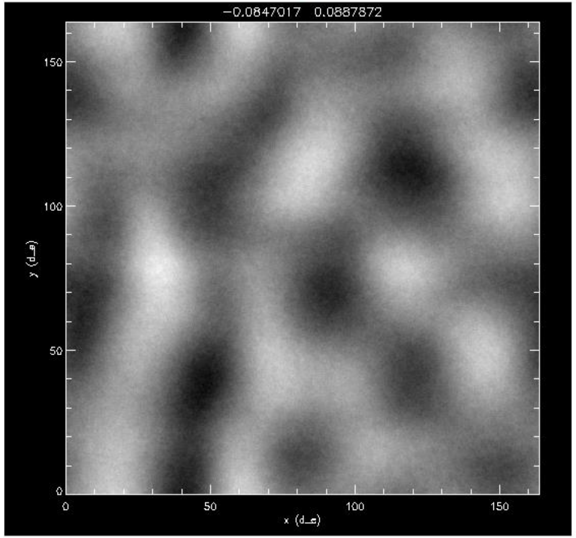


Bz



- Electric field was noisy and structure wasn’t brought out with smoothing.
- Polarization of B components unclear.

Mystery Wave (cont.)

- $\beta = 32$
- $kd_e = .08 - .16$
- $\frac{\gamma}{\Omega_{ce}} \sim 10^{-4}$
- $\frac{\omega}{\Omega_{ce}} \sim .016$
- Thought at first was an ion wave. Froze ions and wave still emerged – must be driven by electrons.
- Increasing heat flux – larger growth rate.

Mystery wave (cont.)

- As we decreased B_o, found that wavelength increased, growth rate decreased.
- At $B_o = 0$, box was probably too small to see waves.
- Ambient field definitely plays a role in the instability – probably not Weibel instability.
- Could this be an electron analogue to the gyrothermal instability?

Gyrothermal Instability Comparison

- From Scheckochihin et al., 2010.
- Alfvenic modes driven by heat flux and pressure anisotropies.
- Plugged in numbers from simulation
- Instability criterion satisfied but analytic growth rate higher by two orders of magnitude.
- Analytic frequency also higher than observed one.

$$\Delta = \frac{p_{\perp i} - p_{\parallel i} + p_{\perp e} - p_{\parallel e}}{p_{\parallel i}}, \quad \beta = \frac{8\pi p_{\parallel i}}{B^2}, \tag{21}$$

$$\delta = \frac{p_{\perp i} - p_{\parallel i} - (p_{\perp e} - p_{\parallel e})}{p_{\parallel i}} - \frac{2}{\beta}, \quad \Gamma_T = \frac{2q_{\perp i} - q_{\parallel i}}{p_{\parallel i} v_{\rm th}}, \tag{22}$$

but, in fact, only two matter because only the combination $\Delta + 2/\beta$ figures in equation (20) and δ will turn out not to be of much consequence. The resulting dispersion relation is

$$\left[\bar{\omega}^2 - \frac{k^2}{2}\left(\Delta + \frac{2}{\beta}\right)\right]^2 = \frac{k^4}{4}[(1-\delta)\,\bar{\omega} + k\Gamma_T]^2. \tag{23}$$

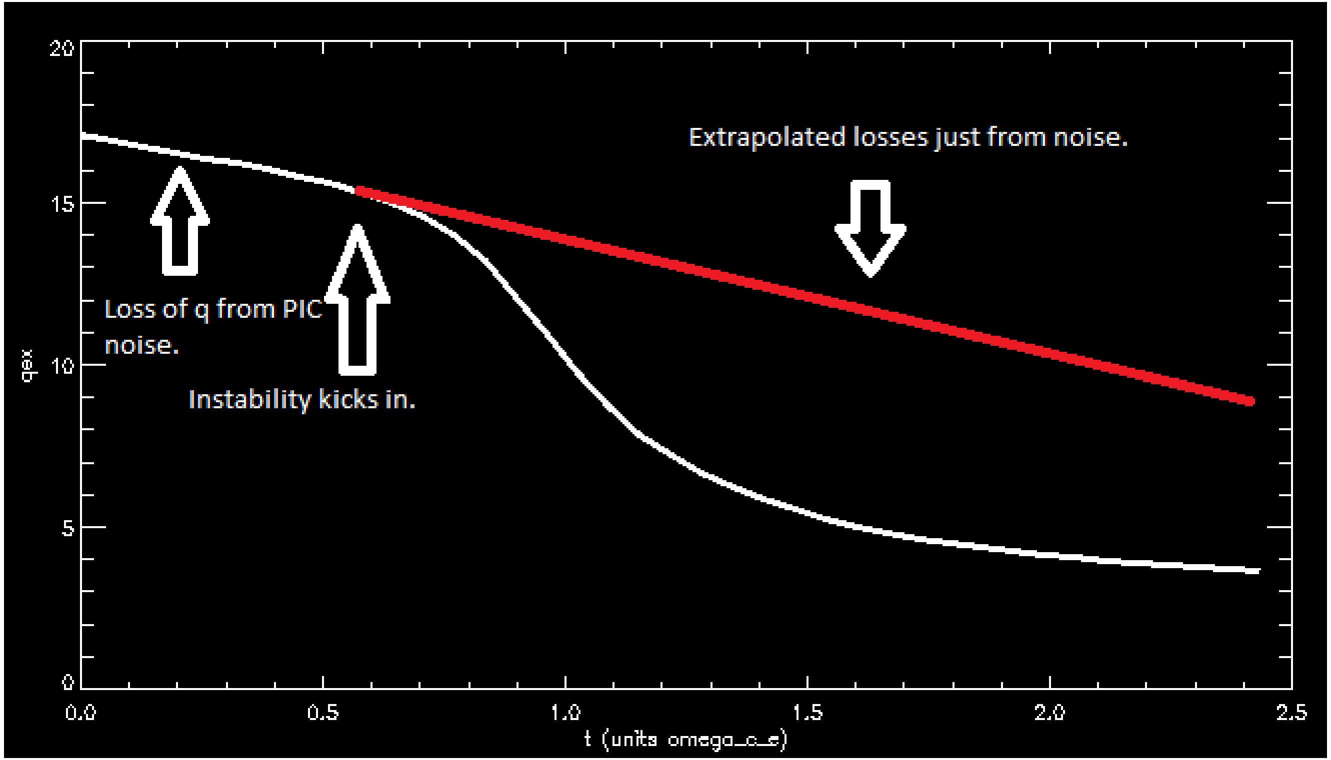
This has four roots of which two can be unstable:

$$\bar{\omega} = \pm\frac{k^2}{4}(1-\delta) + \frac{i|k|}{\sqrt{2}}\sqrt{-\left(\Delta + \frac{2}{\beta}\right) \mp k\Gamma_T - \frac{k^2}{8}(1-\delta)^2} \tag{24}$$

Questions about new instability

1. Could this be a so-called electron GTI? How would we confirm this?
2. How could the wave impact conduction in the ICM?
3. What are the nonlinear dynamics?
4. What if PIC collisions eliminate instability prematurely?

Time plot of heat flux



References

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- 3. Gary & Li, 2002, ApJ, 529, 1131-1135
- 4. Levinson & Eichler, 1992 ApJ 387: 212-218
- 5. Scheckochihin et al., 2010, Mon. Not. R. Astron. Soc. 405, 291-300