Waves in the ICM

Ellen Zweibel & Vladimir Mirnov
University of Wisconsin
Center for Magnetic Self-Organization

Overarching Questions

- How is energy propagated & dissipated in the ICM?
  - How do AGN couple to the ambient medium?
  - How do dynamical disturbances evolve?
- How do observations of acoustic & other disturbances constrain transport coefficients in the ICM?

Address these questions by studying waves, a complement to simulations.

Plan of this Talk

- Assumptions of our study
- Review of wave heating theory
- Formulation
- Driven waves
- Summary & future work

Lean heavily on Braginskii 1965

Assumptions

- Background medium is a hydrogen plasma with $T_e = T_i$ (easily modified).
- Global structure included through WKB
- Magnetic field is dynamically unimportant, but may affect transport through
  - its global orientation
  - small scale kinetic waves & instabilities

Review of Wave Heating Theory

Fabian et al. 2005

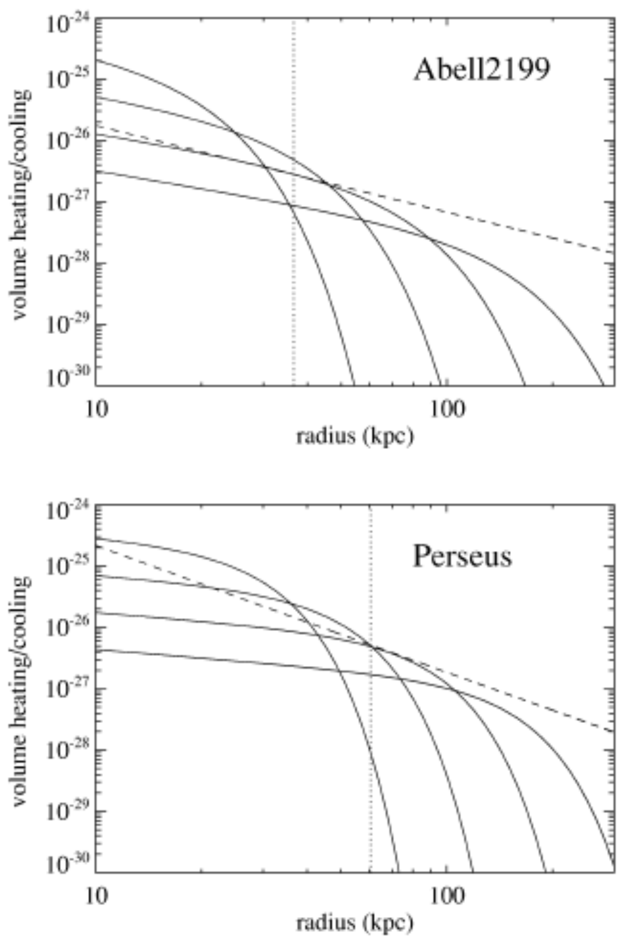
- Nearly adiabatic acoustic waves with frequency f in a medium with viscosity ν and conductivity κ are spatially damped at the rate

$k_i = 1/2\ell$ $$= \frac{2\pi^2 f^2}{c_s^3}\left[\frac{4}{3}\nu + \frac{\kappa}{\rho}\left(\frac{1}{c_V} - \frac{1}{c_p}\right)\right]$$

- The heating rate ε_{diss} at a distance r from a source with acoustic luminosity L is

$$\epsilon_{diss} = \frac{L_s(r)}{4\pi r^2 \ell} \qquad L_s(r) = L_{inj}\exp\left(-\int_{r_{in}}^{r}\frac{1}{\ell}\,dr\right)$$

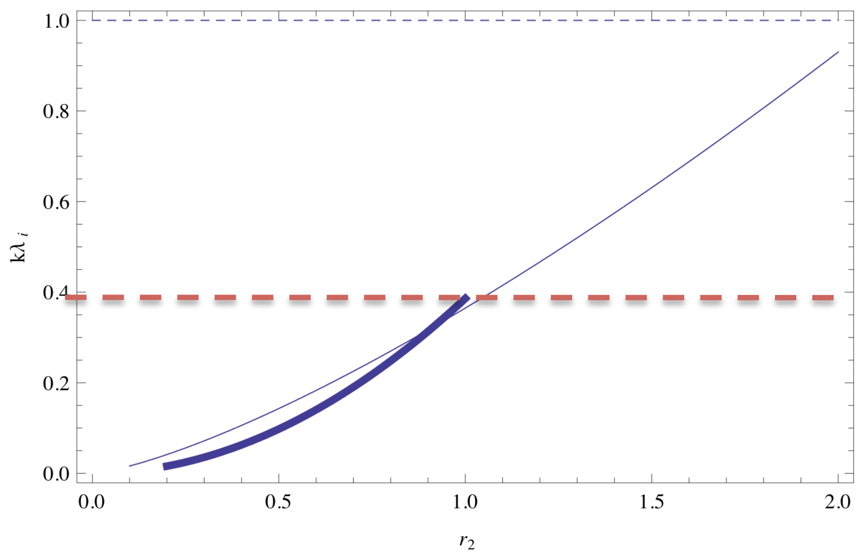
Balance Between Heating & Cooling



Fabian et al. 2005

- Comparison between radiative cooling & wave heating for wave periods (1,2,4,8)x10^7 yr and plausible luminosities. Electron thermal conduction is completely suppressed and ion viscosity is 1/10 the Spitzer value.

How Collisional is the ICM?



$k\lambda_\iota$ for a wavelength of 10 kpc plotted vs (r/100 kpc) for A2199 (light line) and Perseus (heavy line). Purple dashed line discussed at right.

- Fluid theory holds for small $k\lambda_{i.}$ As $k\lambda_i$ increases, collisional damping gives way to ion Landau damping. Above the purple dashed line the wave damps by a factor of *e* in less than one wave period (Kulsrud & Ono 1975).

Fluid Theory

Dissipative effects:

- Electron thermal diffusivity
- Ion viscosity
- Ion thermal diffusivity (*Ignored in F05; damping is 40% of viscous damping*).
- Electron – ion temperature equilibration (*Previously ignored; arises because e & i have different thermal diffusivities)*

Basic Equations

$$nM\frac{\partial \mathbf{u}_1}{\partial t} = -\nabla(P_{e1} + P_{i1}) - \nabla \cdot \pi_1,$$

$$P_{e1} + P_{i1} = 2n_1 T + n(T_{e1} + T_{i1}),$$

$$\frac{\partial n_1}{\partial t} = -n\nabla \cdot \mathbf{u}_1,$$

$$\frac{3}{2}\frac{\partial T_{e1}}{\partial t} = -T\nabla \cdot \mathbf{u}_1 + \chi_e \nabla^2 T_{e1} - 3\frac{m}{M}\frac{(T_{e1} - T_{i1})}{\tau_e},$$

$$\frac{3}{2}\frac{\partial T_{i1}}{\partial t} = -T\nabla \cdot \mathbf{u}_1 + \chi_i \nabla^2 T_{i1} + 3\frac{m}{M}\frac{(T_{e1} - T_{i1})}{\tau_e},$$

$$\pi_{1ab} = -0.96nMD_i\left(\frac{\partial u_{1a}}{\partial x_b} + \frac{\partial u_{1b}}{\partial x_a} - \frac{2}{3}\delta_{ab}\nabla \cdot \mathbf{u}_1\right) \equiv -\eta_0 W_{1ab}$$

Modified Transport

- Multiply transport terms by
  - ξ_e (electron conduction)
  - ξ_i (ion conduction)
  - ξ_v (ion viscosity)
  - ξ_{ei} (electron – ion temperature equilibration)

Allows for modified transport relative to Spitzer/ Braginskii values

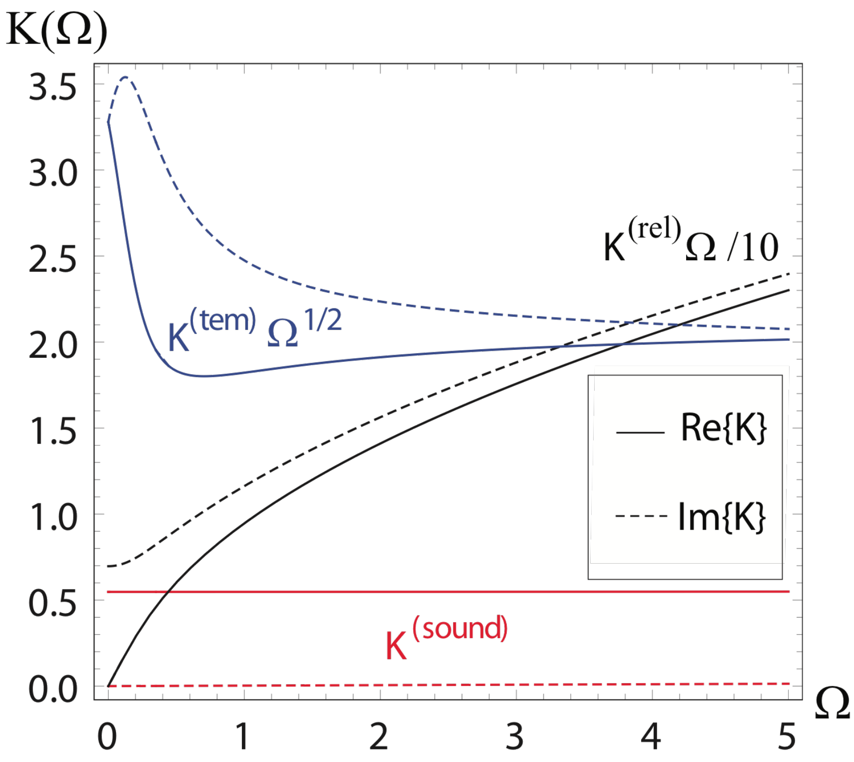
Three Modes ($\xi = 1$)

- Acoustic wave:
  - Nearly adiabatic for $k\lambda_i < (m/M)^{1/2}$
    - $\omega^2 \sim k^2 c_s^2$ ($c_s^2 = 10/3$ T/M)
    - weakly damped by all 4 dissipative processes, electron conduction the largest
  - Electrons become isothermal as $k\lambda_i \to (m/M)^{1/2}$
    - Electron conduction weakens relative to other processes
    - Electron – ion equilibration becomes important at the same $\kappa\lambda_\iota$
  - Ion Landau damping important for $k\lambda_i \to 1$
- Excited by pressure disturbances.

Three Modes...

- Heavily damped thermal wave
  - $k^2\chi \sim \omega$
- Heavily damped e - i relaxation wave
  - $k^2\lambda_i^2 \sim m/M$
- Excited by thermal perturbations or to satisfy boundary conditions.

Roots of Dispersion Relation



- Definitions:

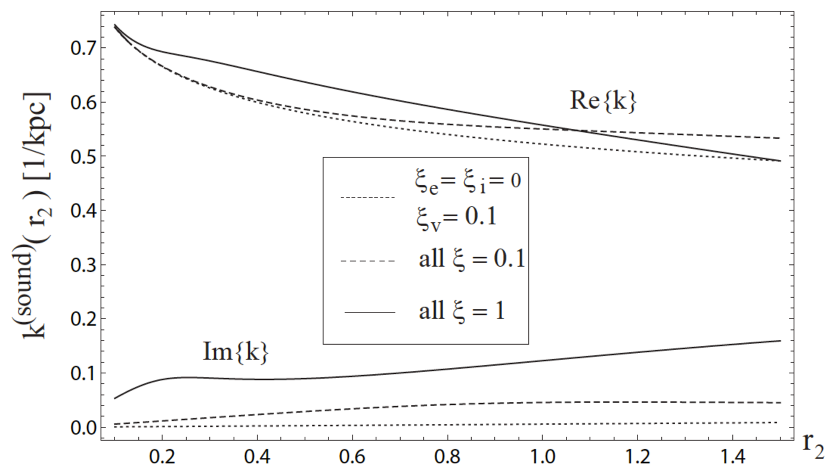
$$\Omega = \omega\tau_e(M/m)$$

$$K = kv_i/\omega$$

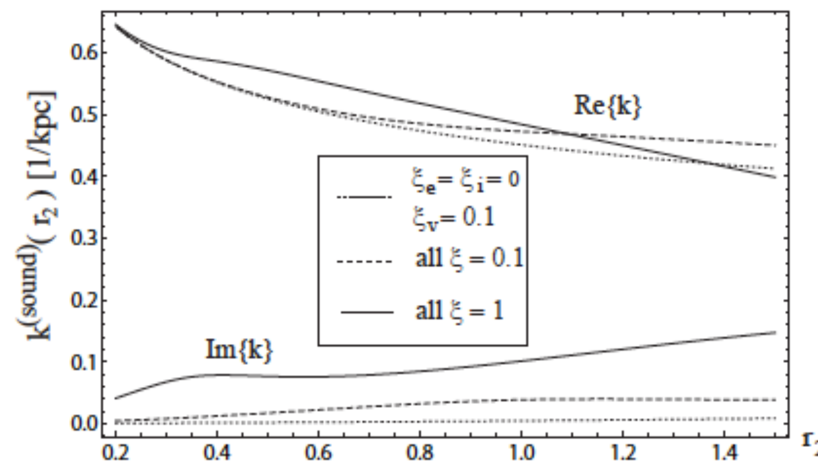
$$v_i = (T/M)^{1/2}$$

Local Damping Rates in the ICM

A2199



Perseus

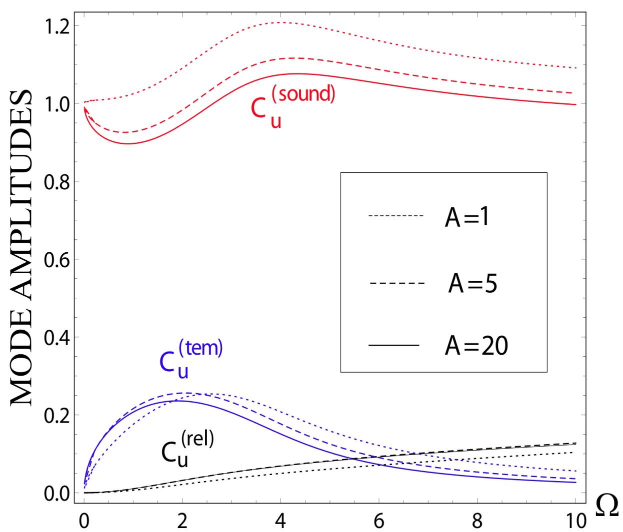


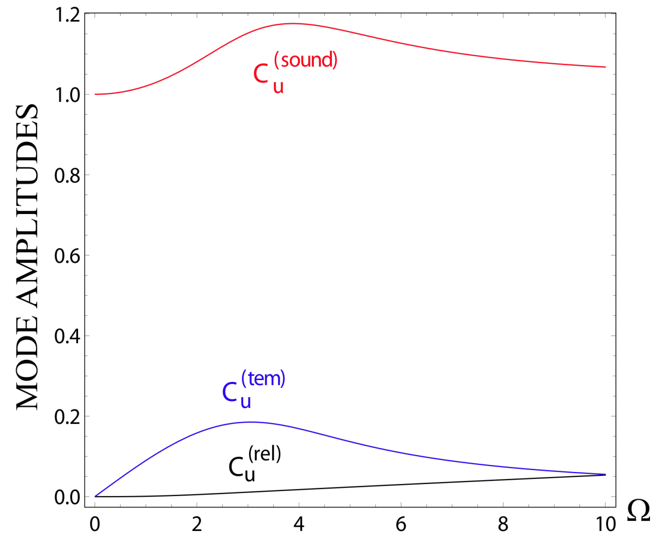
Only the acoustic damping rates are shown. Wave period is 10^7 yr

Driven Wave Problem

- Sphere oscillates at frequency ω about its equilibrium radius a with amplitude $a_1 << a$
- Impose boundary conditions on u_1 and a linear combination of T_{e1} & dT_{e1}/dr, T_{i1} & dT_{i1}/dr.
- In general, all 3 modes are generated.

Amplitudes





Amplitudes of driven modes for zero temperature perturbation (left) or zero heat flux perturbation (right), as functions of scaled frequency Ω and driver size parameter $A = \omega a/v_i$. Results in zero heat flux case are insensitive to A. We estimate A ~ 10 – 20 for 10^7 yr period waves from a 10 kpc source.

Calculate Heating from Entropy Production

The entropy transport equation is

$$\frac{\partial S}{\partial t} + \nabla \cdot \left(S\mathbf{u} + \frac{\mathbf{q_e} + \mathbf{q_i}}{T} \right) = \theta T,$$

where $\mathbf{q}_e$ & $\mathbf{q}_i$ are the electron & ion heat fluxes, and θT is the entropy production rate. For acoustic waves, this is equivalent to F05 to first order in k_i/k_r.

$$T\theta_v = -\frac{1}{2}\xi_i \pi_{ab} W_{ab},$$

$$T\theta_{ic} = \frac{n\xi_i \chi_i}{T} |\nabla T_{i1}|^2,$$

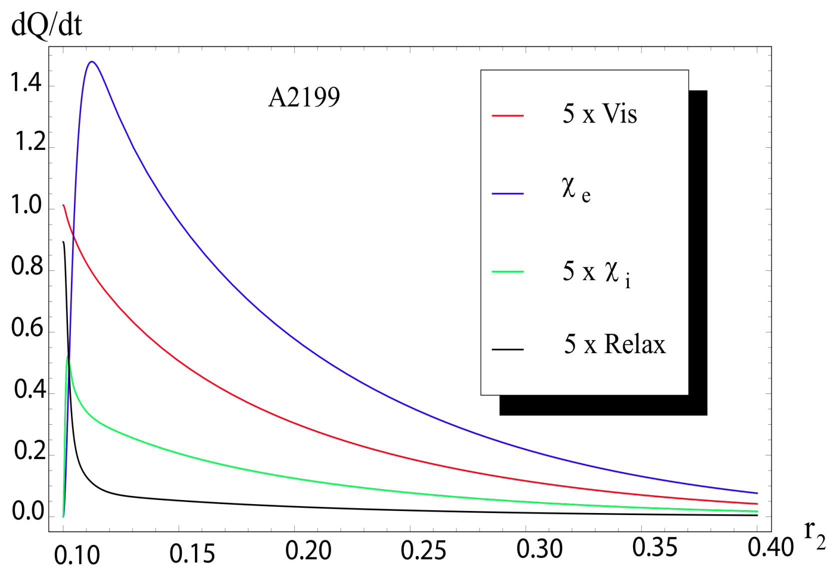
$$T\theta_{ec} = \frac{n\xi_e \chi_e}{T} |\nabla T_{e1}|^2,$$

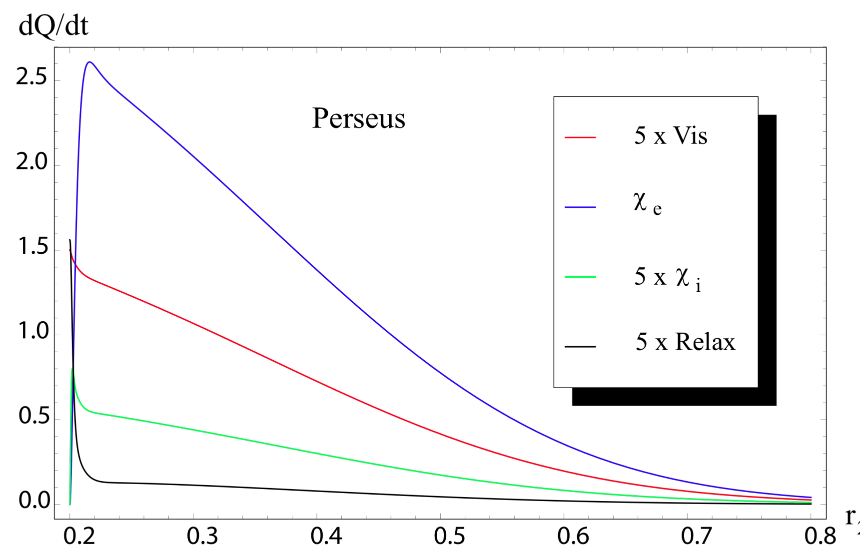
$$T\theta_{ei} = 3\xi_{ei} \frac{m}{M} \frac{n}{T\tau_e} (T_{e1} - T_{i1})^2,$$

Ion viscosity,
electron thermal conduction

Ion thermal conduction,
electron – ion equilibration

Heating Rates





Amplitude at source normalized to unity, driving period is 10^7 yr, $\omega a/v_i >> 1$ zero heat flux at source, all transport processes set to 1/10 their Spitzer values. Electron thermal conduction dominates, little heating beyond ~ 50 kpc, a boundary layer near the source.

Summary

- We developed a general treatment of low frequency collision dominated waves in high β plasmas,
  - valid for cluster cores
  - suitable for boundary value problems.
- Especially when 2 damping methods are included, we agree with Fabian et al 2005 that without strong suppression of transport, waves cannot propagate.
  - heated boundary layer forms around sources
  - a horizontal magnetic field would address this
- Outside cluster cores waves are collisionless & damping is even stronger; working on a separate theory.