Wave generation and heat flux suppression in astrophysical plasma systems

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Outline

• The intracluster medium and roles of thermal conduction

• New boundary condition for PIC code (hot/cold plate) used to study transport in collisionless plasmas

• Part 1: Theory of scattering by large-amplitude whistler turbulence; thermal conduction scaling inferred from 2D PIC simulations

• Part 2: Going to lower beta – extending scaling law for conduction to solar wind / corona (Double layers).
The Intracluster Medium

- Central region of cluster of galaxies typically houses a luminous, compact center (Active Galactic Nucleus or AGN).
- AGN can house supermassive black hole [\(\sim 10^9\) solar mass], which accretes matter and expels jets of relativistic plasma.
- Surrounding plasma (ICM) is diffuse, hot, with weak magnetic field.
- ICM is dynamic: turbulence, shocks, magnetic dynamo, and radiation, often in X-ray (Bremsstrahlung).
Intracluster Medium (Parameters)

- \( \beta = \frac{4\pi nT}{B^2/2} \sim 100 \)

- \( B \sim 10^{-6} G, k_B T \sim 1 - 10 \text{ keV}, n = 10^{-2} \text{cm}^{-3} \)

- Mean free path: \( 10^{18-19} m \) (100 pc)

- \( \frac{T}{vT} \sim 10^{21} m \) (global radial T profiles). Size of cluster: \( 10^{23} m \) or larger

- Weakly collisional – strongly magnetized.

- \( \rho_e = v_{Te}\Omega_e^{-1} \sim 10^7 m \) (\( \sim \) npc), \( \Omega_e = \frac{eB}{m_e c} \sim 1 \text{ Hz} \), \( v_{Te} = \sqrt{\frac{2T_e}{m_e}} \).
Thermal conduction

Relevant to many phenomena in high-energy astrophysics:

• **Thermodynamic stability of galaxy clusters with cool cores** in which radially inward heat conduction can occur [e.g. Binney & Cowie 1981]

• Existence of discontinuities in temperature and density (**cold fronts**) [e.g. ZuHone & Roediger 2016]

• Stability of **optically radiating filaments** in cluster outskirts [Fabian et al. 2008]

• **Thermalization (damping) of sound waves** [e.g. Reynolds et al. 2015, Fabian et al. 2005, Zweibel et al. 2018]

• Large-scale fluid **instabilities**:
  • Heat flux driven buoyancy instability (HBI) [Quataert 2008, Avara et al. 2013]
  • Magnetothermal instability (MTI) [Balbus 2000, Parrish et al. 2008]
Cool Core (Relaxed) Cluster Profiles

Gas density and temperature profiles derived from X-ray Chandra observations
(Giacintucci et al. 2017)
Thermal conduction (continued)

• Heat transport described at large (collisional) scales by classical (Spitzer 1962) theory of thermal conduction. This is the usual Fick’s Law of Diffusion of the form:

\[ \mathbf{q} = -\alpha \nabla T \]

• Does thermal conduction follow the above form in a collisionless plasma?

• Transport, heating, and thermal equilibrium at kinetic scales not fully understood. Some theories consider feedback on large (e.g. ICM) scales by kinetic instabilities [e.g. Sheckochihin et al. 2005, Kunz et al. 2011, Rincon et al. 2015].

New Boundary Conditions

- Apply sustained electron temperature gradient via hot and cold plate boundary conditions.
- Reinject particles from hot and cold thermal reservoirs when they hit the boundaries.
- Background $B$ allowed to evolve freely.
- 2D domain, freeze ions.
- See also Komarov et al. 2018 for a very similar setup.
$T_{exx} = \langle m_e v_x^2 \rangle$
Steady state results

(a) Whistler turbulence resonantly scatters electrons [e.g. Karimabadi et al. 1992, GRC et al. 2016, Dalena et al. 2012]. Scattering is effective because of large amplitudes.

(b), (c) Spatial modulation of temperature and heat flux. Steady state is reached by $t = 800 \Omega_e^{-1}$

\[
\Omega_e = \frac{eB}{m_e c}
\]
Temperature and heat flux

\[ T_{exx} = \langle m_e v_x^2 \rangle \]

\[ q_{ex} = \frac{1}{2} \langle m_e v_x v^2 \rangle \]
Variation in steady state with system parameters

- Heat flux largely insensitive to imposed temperature gradient
- Follows linear scaling with $1/\beta$ (inset)
Scattering by whistlers (heat flux instability)

- Anisotropic distribution functions are robustly unstable to a whistler instability at high $\beta$. The anisotropy often involves a heat flux (Levinson & Eichler 1992, Gary & Li 2000).
- Resonant instability, with energy conservation in the frame of a single parallel whistler.
- Pitch angle scattering ($\mu$-non-conservation) with a characteristic bounce frequency and trapping width for deeply trapped particles.
Scattering by whistlers (heat flux instability)

- For parallel whistlers, resonance happens with backward-moving electrons (primary cyclotron resonance).
- Not good for reducing heat flux – those particles move in same direction as wave! (Mentioned in Pistinner & Eichler 1998)
Off-angle whistlers

• Oblique propagation introduces resonances at multiple harmonics of the cyclotron frequency:

\[ \omega - k_x v_x - n\Omega = 0 \]

• \( n \) is an integer or half-integer

• See Smith & Kaufman (1976), Karimabadi et al. (1990, 1992)

• For a large amplitude wave the resonances overlap, causing irreversible diffusive behavior – effective at reducing heat flux
Simulation particle trajectories

- Diffusion in pitch angle occurs rapidly. Large range of energies.

- Some diffusion occurs in energy (perpendicular to circular contours)

- Whistlers propagate with slow phase speed compared to thermal speed (indistinguishable from origin in parallel velocity)
Diffusion in space

- Scattering in real space (left) is also very fast (order cyclotron period).
- Spacetime plot (right) shows diffusive nature of trajectories.
Propagation speed of whistlers

- Spacetime plot (left) of fluctuations reveals mostly uniform translation of waves to towards cold plate.
- Power spectra have a peak near $k\rho_e \sim 1$ even when $\beta$ changes.
Dispersion relation

• Linear theory sufficient: gives phase speed of waves.

\[ \omega = k^2 \rho_e^2 \Omega_e / \beta_e \]

\[ k \rho_e \sim 1 \]

\[ \frac{\omega}{k} \sim \frac{v_{Te}}{\beta_e} \]
Whistlers as scattering centers

- Imagine a whistler wave as a “bucket” that traps particles and convects their energy down the temperature gradient.

- Levinson & Eichler [1992] commented on a possible scaling:

\[
q \parallel = \alpha n_0 \frac{\omega}{k} T_{eh} \sim n_0 m_e \frac{v_{Te}^3}{\beta_{e0}} = v_{Te} \frac{B_0^2}{8\pi}
\]

- See also Gary et al. [1994], Pistinner & Eichler [1998].
Whistlers as scattering centers (continued)

Simulation results seem to confirm this scaling:

\[
q_{\parallel} = \alpha n_0 \frac{\omega}{k} T_{eh} \sim n_0 m_e \frac{v_{Teh}^3}{\beta_{e0h}} = v_{Teh} \frac{B_0^2}{8\pi}
\]

| Table 1 |
|---|---|---|---|
| \(L_x\) | \(\beta_{e0h}\) | \(T_{ec}/T_{eh}\) | \(q_{ex,f}/(n_0v_pT_{eh})\) |
| \(L_0 = 82 \rho_{e0h}\) | 64 | 1/2 | 3.44 |
| \(L_0/2\) | 64 | 1/2 | 3.30 |
| \(2L_0\) | 64 | 1/2 | 3.26 |
| \(L_0\) | 32 | 1/2 | 3.46 |
| \(L_0\) | 128 | 1/2 | 3.19 |
| \(L_0\) | 64 | 1/4 | 2.56 |
Confirmation in solar wind observations:

\[ q_{\parallel} \sim \frac{v_T n T}{\beta} \sim T^2 B_0^2 \]

- \( q \) is suppressed below the free-streaming value
  \[ q_0 = \frac{3 n_0 v_{Te} T_e}{2} \]
- Tong et al. [arXiv 2018] confirm that maximum heat flux scales as \( 1/\beta_{core,\parallel} \) for \(~2 \) to \(~6 \)
- Further results suggest it works for \( \beta \to 10^2 \)
- What happens in our simulations at lower \( \beta \) (order unity or less)?
Part 2: (lower $\beta$) Double Layers

- Imagine the hot/cold plate system again.
- Hot electrons quickly stream in the direction of heat flux, leaving a net positive charge.
- Resulting electric field pulls in return current electrons from cold side to cancel charge.

~ Charge neutral on both sides
Double Layers (continued)

- Sets up oscillations in the ions, launching a double layer (DL) in the return current direction [see Buneman 1958 for instability, Li et al. 2012, 2013, 2014 for PIC simulations]
- DL is basically a moving parallel-plate capacitor
- DL reflects hot electrons and accelerates cold return current: suppresses heat flux
New PIC simulations

• Same setup as before, but with hot/cold temperature ratio of 10 and stronger magnetic field (lower $\beta$)

• Mobile ions

• Whistlers and double layers (DLs) act together to suppress heat flux for a range of $\beta$

• DLs were not there previously because (a) ions were immobile and (b) even if they weren’t, whistler scattering would reduce return current driver.
Beta 1 vs. 16: Transition from whistler to DL heat flux
Spacetime diagrams of DLs \( (E_x) \)
Electron distributions, phase space and $T_e, T_i$ ($\beta = 1$)

- DL Potential reflects hot electrons (a).
- Cold electron beam visible (bright yellow)
Whistlers, DLs, and elongated magnetic structures ($\beta = 1$)
DLs and elongated magnetic structures ($\beta = 1/4$)
Heat flux and saturated amplitudes

\[ \beta = \frac{q}{f_d L} = \frac{q_0}{T_{ef}} \]

\[ \propto 1/\beta_{eh} \]

\[ (\delta B^2/\langle B \rangle^2)^1/2 \]

\[ (\delta B^2/\langle B \rangle^2)^1/2 \]

\[ T_{ef}/T_{ec} = 10 \quad + \quad T_{ef}/T_{ec} = 2 \]
Conclusions

• Heat flux instability strongly suppresses thermal conduction at high $\beta$ via oblique whistlers, where the steady state follows $q \sim 1/\beta$.

• Confirmation in solar wind data.

• At lower $\beta \sim 4$, whistlers become subdominant and heat flux levels off to constant fraction of free-streaming value.

• Possible signatures to look for in observational data related to solar wind or corona?
Image Sources

• Black hole accretion (slide 3, picture 1):

• Perseus Cluster (slide 3, picture 3):
  https://www.nasa.gov/chandra/multimedia/perseus-cluster.html

• Double Layer (slide 24): http://www.everythingselectric.com/double-layers-plasma/