A Tale of Two Instabilities: Buoyancy Instabilities in Galaxy Clusters
Ian Parrish, UC Berkeley

Collaborators: Jim Stone, Eliot Quataert

Heat Flux Driven Buoyancy Instability (HBI)

\[ \frac{d^2 T}{dr^2} + \frac{B_0}{r} \frac{dT}{dr} > 0 \quad \text{(unstable)} \]

- Most unstable for B parallel to g.
- Magnetic energy amplified by up to ~400.
- Driven field to horizontal: (\(B_0\)) \( \leq 4-5\)°
- Magnetic field in equipartition with kinetic energy.
- Steady state heat flux is less than 0.5% of the fiducial (Spitzer) value.

\[ Q = Q_0 \left( \frac{B_0}{B_{\text{Spitzer}}} \right) \]

Magnetic Field Angle

Heat Fluxes

MTI Qualitative Mechanism

- Long mean free path regime.
- Heat conduction dominated by anisotropic transport along magnetic field lines.
- Ideal MHD is supplemented by Braginskii equations for transport.

\[ \vec{V} = \vec{V}_T \]

Convective Stability in a Gravitational Field

- Classically: Schwarzschild Criterion: \( \frac{V}{c} > \frac{1}{2} \)
- Long MFP: Bulbus Criterion: \( \frac{\Omega}{c} \approx \frac{1}{2} \)

New Stability Criterion: The Magnetothermal Instability

Dispersive Relation/Validation

- Anisotropic Heat Flux \( Q_{\text{z}} = -\gamma_B \vec{B} \cdot \vec{V}_T \)

\[ \gamma_B \approx \frac{B_0}{B_{\text{Spitzer}}} \approx 0.5 \]

- Most unstable for \( \vec{B} \) perpendicular to \( g \).
- The instability can be stabilized by:
  - Strong magnetic fields exerting Alfvénic tension.
  - Isothermal conduction across magnetic field lines, shortening the driving, e.g., radiation.

Observables and Cosmology

- Turbulent Velocities: up to Mach 0.3-0.4, could have been measured with Sx.5.
- Magnetic Field Geometry: \( B_{\text{HBI}} \sim 4-5 B_0 \), could be explained by radial field.
- Temperature Profiles (neglect heating so far).
- SZ profiles and missing baryons?

Clusters & Cosmology

- Cluster Mass \( M_\text{vir} \approx 3.8 \times 10^{14} \)
- Initially radial fields, one-third Spitzer conductivity.
- Bremsstrahlung + X-line cooling (Tozzi & Norman fit).
- Cluster heats up, HBI becomes active, reducing conductivity: cooling catastrophe!

Simulation of HBI in Cluster Cores

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- Cluster heats up, HBI becomes active, reducing conductivity: cooling catastrophe.

With HBI, could live 115 Myr.

Without HBI, lifetime would be 0.6 Myr.

With HBI, could live 115 Myr.

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