Lecture #30: Thermodynamics of Galaxy Clusters

I. Galaxy Clusters

A. Basic Properties:

1. Number of Galaxies $N \sim 50-1000$ galaxies
2. Total Mass $M_{tot} \sim 10^{14}-10^{15} M_{\odot}$
3. Composition: ~5% galaxies
   ~10% hot plasma (Intracluster Medium, ICM)
   ~85% dark matter
4. Velocity dispersion $\sqrt{\langle v^2 \rangle} \approx 300-1200$ km/s
5. Radius: a) $R \sim 1-3$ Mpc
   b) Core: $R_c \sim 100-200$ kpc
6. Generally, cluster observations provide some of the strongest evidence for the existence of dark matter

B. Properties of Intracluster Medium, ICM

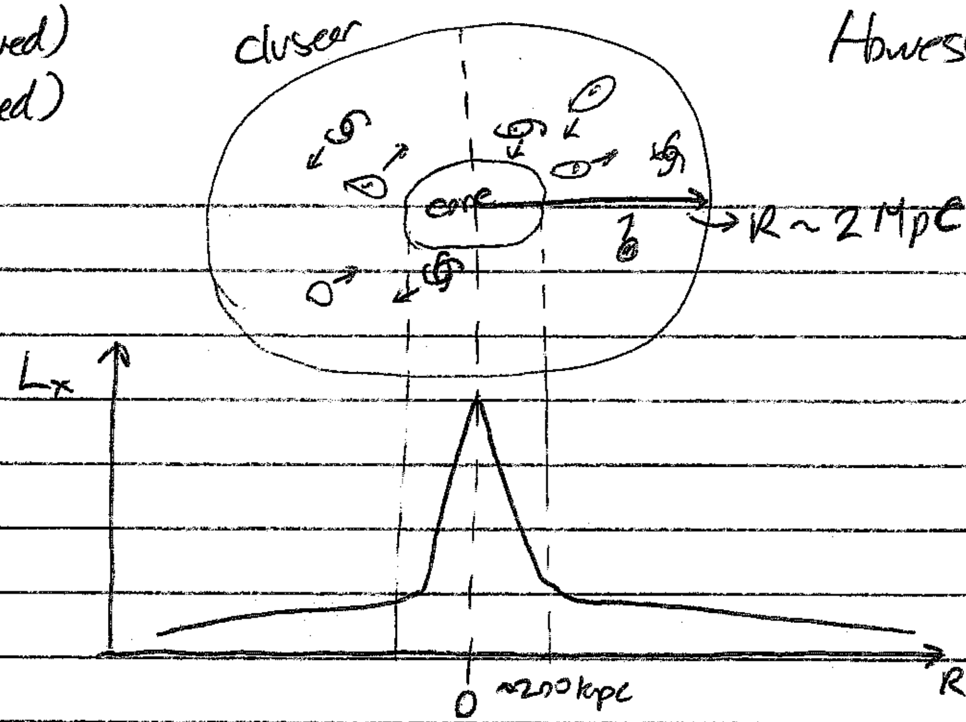
1. Density $n_e \sim 10^{-4}-10^{-2}$ cm^{-3}
2. Temperature $T \sim 10^7-10^8$ K
3. Mass $M_{ICM} \sim 10^{13}-10^{14} M_{\odot}$ ($> M_{galaxies}$)
4. X-ray Luminosity $L_x \sim 10^{43}-10^{45}$ erg/s
5. Radius $R_{ICM} \sim 1-2$ Mpc
6. Metallicity: Significant, from 0.3 to ~1 solar metallicity.
7. Quasi-hydrostatic equilibrium in gravitational potential
8. Gas is cooling slowly due to thermal bremsstrahlung radiation in X-rays

C. Cooling Flows in Clusters

1. X-ray emission is often (>50%) peaked at cluster core within 100-200 kpc.
2. High surface brightness in X-rays implies significant radiative cooling.

I. C. (Continued)

3.



4. Physics of the Cooling Flow

a. Strong X-ray emission in cluster core leads to a drop in the temperature of the plasma

b. The pressure gradient supporting hydrostatic equilibrium decreases

c. The weight of gas at larger radii causes a slow, subsonic inflow

d. This inflow has two effects:

   i) Increase in density of core

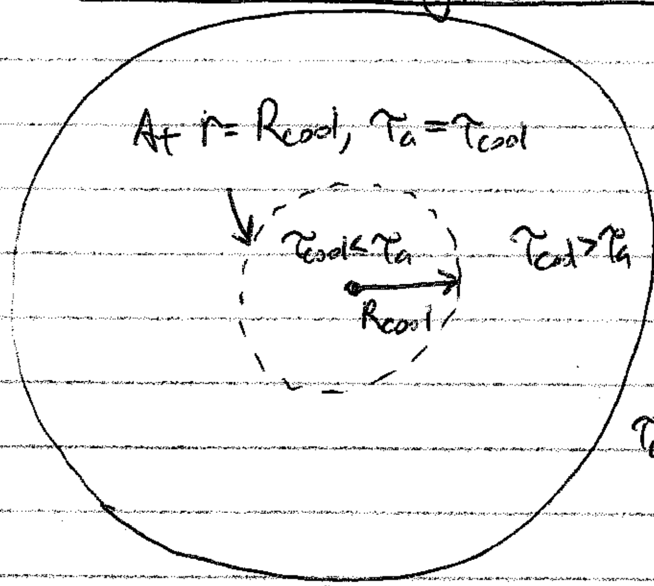
   ii) PdV work (driven by gravity) increasing temperature

e. Both of these effects serve to restore the pressure gradient somewhat

f. Ultimately, the system reaches a ~~state~~ of quasi-hydrostatic equilibrium, in which the radiative cooling in cluster cores is balanced by a slow inflow of gas ⇒ cooling flow.

I.C. (Continued)

5. <u>Timescales and Regions of Cooling Flow Clusters</u>



a. <u>Age of Cluster</u>: τ_a
Typically taken to be Hubble time, or age of the universe, $\tau_a \sim H_0^{-1} \sim 10^{10}$ y

b. At $r = R_{cool}$, the cooling time τ_{cool} by thermal bremsstrahlung is equal ~~τ_a~~, $\tau_a = \tau_{cool}$ at $r = R_{cool}$.

c. Within $r < R_{cool}$, $\tau_{cool} < \tau_a$, and so <u>a cooling flow</u> is expected in the cluster

d. Outside of $r > R_{cool}$, cooling is not important.

e. Note also that

$$\tau_a > \tau_{cool} > \tau_{grav}$$

for cooling core clusters, where τ_{grav} is the gravitational free-fall time. Thus, the gas is in <u>quasi-hydrostatic equilibrium</u>, with radiative cooling leading to a slow inflow for $r < R_{cool}$.

6. "<u>Mass Deposition</u>"

a. Inhomogeneities cause denser regions to cool more rapidly (higher X-ray flux from dense regions), so these rapidly cooling regions can "drop out" of the pressure balance, forming cold clouds or stars.

b. Therefore, cooling is expected to lead to a "deposition" of mass from the hot ICM into cold matter.

c. These leads to mass deposition rates $\dot{M} \sim 10-100\ M_\odot/y$

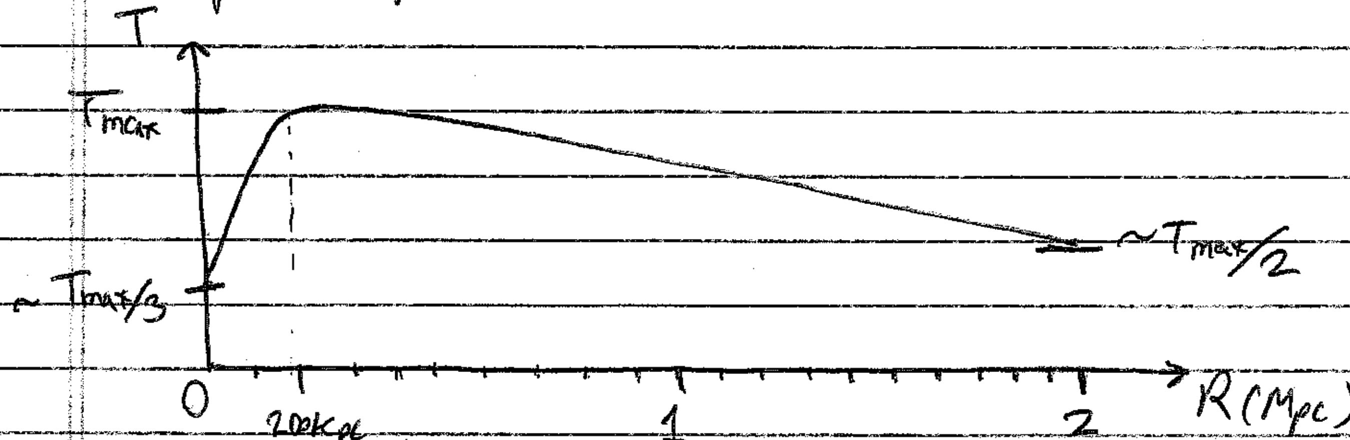
d. Generally $\dot{M}(r) \propto r$, so mass deposit occurs over a large volume, not just at center.

I. D. The Cooling Flow Problem

1. There are two major observational problems with the cooling flow cluster model:
   a. Drop in ICM temperature towards center is limited to a factor of 3, much smaller drop than cooling flow models predict
   b. There is no observational evidence of the cooled mass that results from the cooling flow.

2. The basic framework of the cooling flow problem:
   a. The cluster plasma loses significant thermal energy in x-rays.
   b. Efficient and distributed heat sources are difficult to construct
   c. The cluster plasma appears to cool most of the way, $T_{max}/3$
   d. There is no evidence for complete cooling.

3. Temperature profile observed (last decade: XMM Newton, Chandra)



E. Mechanism for Distributed Heating of ICM in Cluster Core

1. The identification of a distributed heating mechanism for the cluster core would:
   a. Explain the partial cooling of the core plasma.
   b. Resolve the "missing" cold mass. For $T_{central} \sim \frac{T_{max}}{3}$, $\dot{M} \sim 1-10\, M_\odot/y$

I. E. (Continued)

2. These smaller mass deposition rates are compatible with observed rates of star formation.

II. Heat-Flux-Driven Buoyancy Instability and Magnetothermal Instability

A. General

1. An important potential source for heating cluster cores is thermal heat conduction.
2. In a collisionless plasma, electrons carry most of the conductive heat flux ($Q_e \simeq \sqrt{\frac{m_i}{m_e}}\, Q_i$) and move almost entirely along magnetic field lines.
3. This anisotropic heat conduction caused by the magnetic field leads to important new buoyancy instabilities in plasmas:
   a. Heat-Flux-Driven Buoyancy Instability (HBI)
   b. Magnetothermal Instability (MTI)

B. MHD Equations with Gravity and Heat Conduction

1.a. $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underset{\sim}{U}) = 0$

b. $\rho \frac{\partial \underset{\sim}{U}}{\partial t} + \rho \underset{\sim}{U} \cdot \nabla \underset{\sim}{U} = -\nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{\underset{\sim}{B} \cdot \nabla \underset{\sim}{B}}{4\pi} - \rho \underset{\sim}{g}$ ← Gravity

c. $\frac{\partial \underset{\sim}{B}}{\partial t} = \nabla \times (\underset{\sim}{U} \times \underset{\sim}{B})$

d. $\rho T \frac{ds}{dt} = -\nabla \cdot \underset{\sim}{Q}$ ← Heat Conduction

2a. Entropy per unit mass $S = \frac{1}{\gamma - 1} \frac{k_B}{m_H} \ln\left(\frac{p}{\rho^\gamma}\right)$ (k_B: Boltzmann constant)

b. $\frac{d}{dt} = \frac{\partial}{\partial t} + \underset{\sim}{U} \cdot \nabla$, Convective derivative

II B. (Continued)

3. $\underset{\sim}{Q} = -\kappa_e \, \underset{\sim}{\hat{b}} (\underset{\sim}{\hat{b}} \cdot \nabla T)$ (For electrons with $\lambda_e \gg \rho_e$) — λ_e: mean free path, ρ_e: Larmor radius

a. $\underset{\sim}{\hat{b}} = \frac{\underset{\sim}{B}}{B}$

b. Thermal conductivity of free electrons, $\kappa_e = 6 \times 10^{-7} T^{5/2} \frac{\text{ergs}}{\text{cm K}}$ (Spitzer, 1962)

c. Taking κ_e = const (which it is not, strong T dependence),

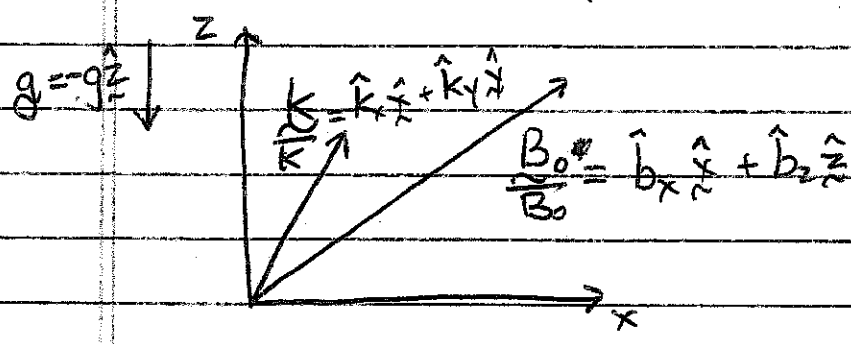
$$-\nabla \cdot \underset{\sim}{Q} = -\nabla \cdot \left[-\kappa_e \underset{\sim}{\hat{b}} (\underset{\sim}{\hat{b}} \cdot \nabla T) \right] = \kappa_e \frac{\partial^2 T}{\partial r_\parallel^2},$$

where $r_\parallel$ is <u>distance along field line</u>.

4. Note that thermal conduction has a diffusive effect on motions $\Rightarrow$ Conductivity can damp MHD waves, for example.

C. <u>Linear Dispersion Relation</u>

1. Consider a 2-D system



2. In the limit that the conductive time is much smaller than the Alfven wave crossing time and dynamical time of gravitational waves $\Rightarrow$ "Rapid Conduction Limit"

$$-\omega^2 + (\underset{\sim}{k} \cdot \underset{\sim}{v_A})^2 = \text{sgn}\left(\frac{\partial T}{\partial z}\right) \omega_{buoy}^2 \left[(2\hat{b}_z^2 - 1)(1 - \hat{k}_z^2) - 2\hat{b}_x \hat{b}_z \hat{k}_x \hat{k}_z \right]$$

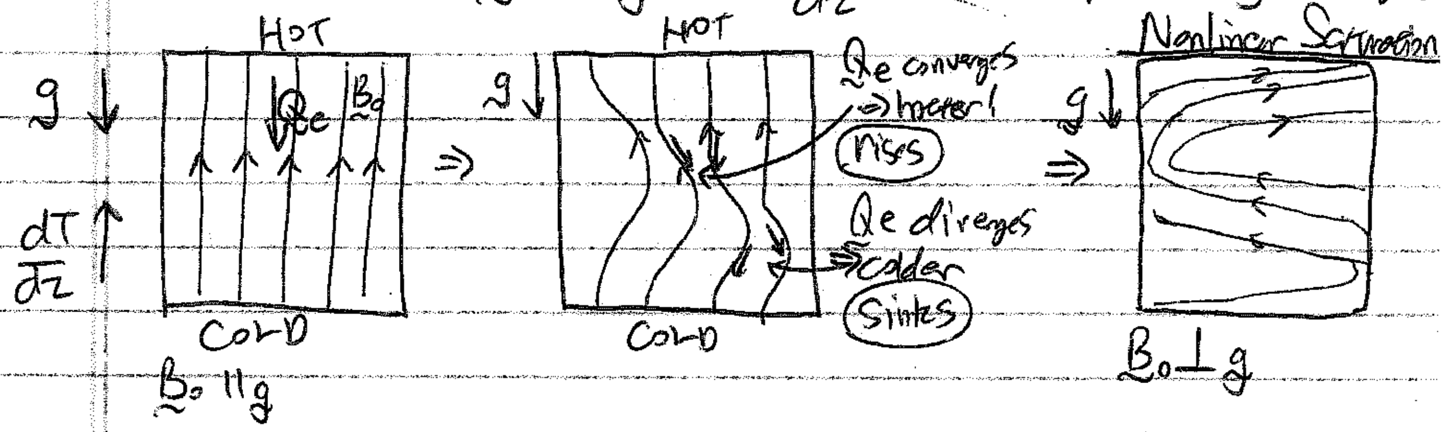
where $\omega_{buoy}^2 = \left| g \frac{\partial \ln T}{\partial z} \right|$ is characteristic buoyancy instability freq.

II. C. (Continued)

3. Because term in [ ] can be positive or negative for any magnetic field direction $\hat{b}$, the plasma always has linearly unstable modes, for either sign of $\frac{\partial T}{\partial z}$.

D. Heat-Flux-Driven Buoyancy Instability (HBI)

1. Unstable for $\underset{\sim}{B}_0 \parallel \hat{g}$ and $\frac{dT}{dz} > 0$ (temp increasing with height)



2a. Perturbations in field lines lead to convergence and divergence of electron heat flux

b. Leads to heating and cooling of plasma

c. Hot regions rise, cool regions sink ⇒ buoyancy instability

3. a. Strong magnetic field can stabilize instability

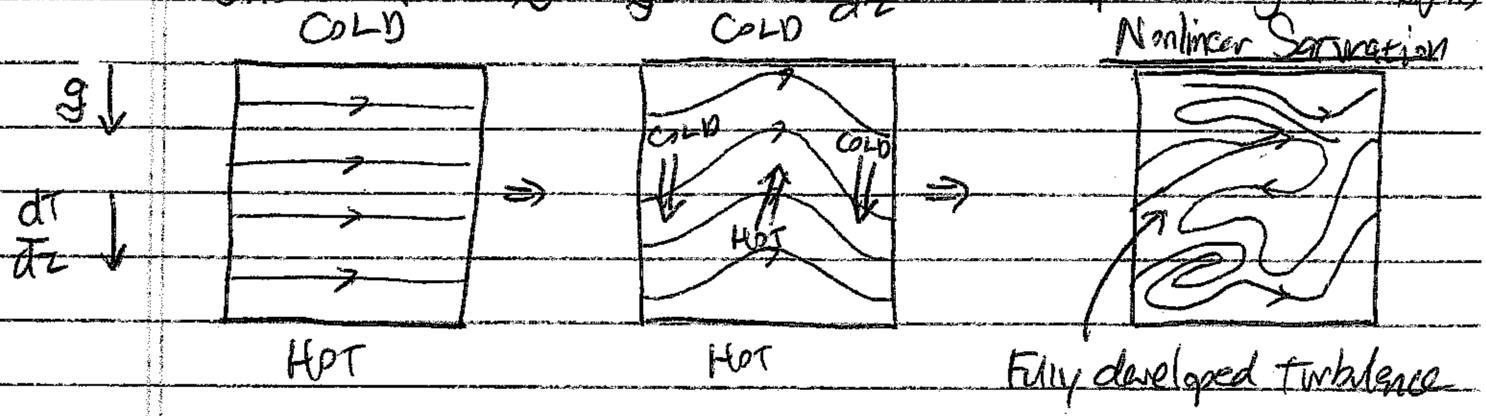
b. In a weak magnetic field, the magnetic field is dynamically insignificant (magnetic tension is subdominant), but the anisotropy in the heat conduction leads to instability.

4. Nonlinear Saturation:

a. Instability driven motions eventually re-orient the field so that $\underset{\sim}{B} \perp g$ ⇒ No heat flux ⇒ no instability

II. E. Magnetothermal Instability (HBI)

1. Unstable for $\underset{\sim}{B} \perp g$ and $\frac{dT}{dz} < 0$ (temp decreasing with height)



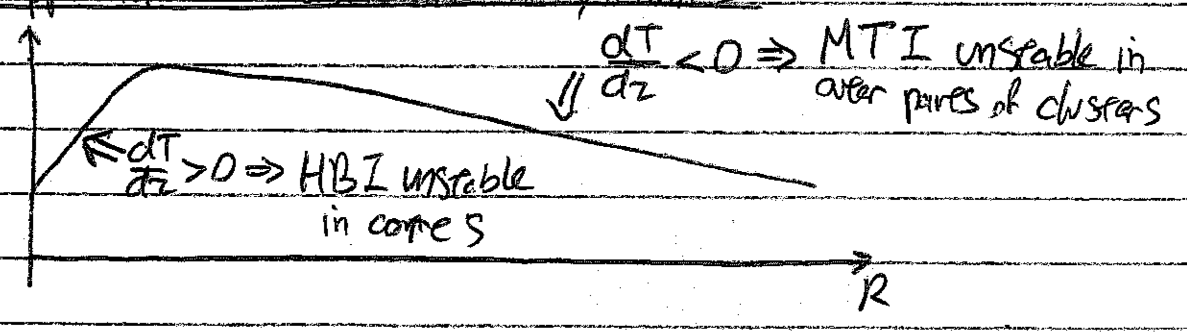
2.a. Upwardly displaced fluid elements are warmer than their surroundings, and continue to rise ⇒ buoyancy instability

3. Again, a strong magnetic field can stabilize the instability, but in a weak field the anisotropic conduction leads to an instability criterion $\frac{dT}{dz} < 0$ (for HD, instability for $\frac{ds}{dz} < 0$)

4. Nonlinear Saturation:
   a. MTI does not saturate to a quiescent state, but may drive vigorous turbulence convection with $\frac{U}{C_s} \sim \mathcal{O}(1)$
   b. Creates average $\underset{\sim}{B}$ and $\underset{\sim}{U}$ that are isotropic with respect to vertical & horizontal direction.
   c. Can also saturate by diminishing temperature gradient.

III. Application to Cluster Thermodynamics

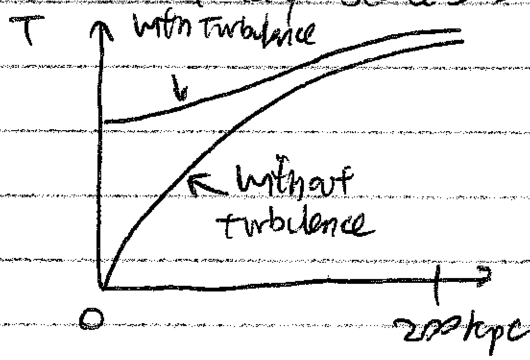
A.



III. (Continued)

B. <u>HBI in Cluster Cores</u>

1. HBI will arise if there is a radial conductive heat flux (heat flowing from hotter regions at $r \gtrsim 200$ kpc to cooler core at $r \lesssim 200$ kpc)
2. HBI will saturate by reoriented magnetic field to eliminate radial component of $\mathbf{B}$. $\Rightarrow \mathbf{B} \perp g$
3. But, this will shut off heating of the cluster core by conduction $\Rightarrow$ Makes the cooling flow problem worse.
4. <u>Turbulence to the rescue</u>:
   a. If there is a moderate level of turbulence, it can inhibit the nonlinear saturation of the HBI, leading to stable steady states of cluster cores



   b. Turbulence may be driven by
      i) "Stirring" by motion of cluster galaxies through ICM
      ii) Active Galactic Nuclei (AGN) in central cluster galaxies

C. <u>MTI in Outer Parts of Galaxy Clusters</u>

1. MTI grows on $\lesssim 10^9$ y timescales
2. Can drive vigorous, sustained turbulence if thermal gradient is maintained
3. MTI may provide up to 30% of pressure support beyond $r > 500$ kpc.

IV. References:

1. Reviews of Observations of Cooling Flow Clusters
   a. Fabian, Annu. Rev. Astron. Astrophys. (1994), 32:377.
   b. Peterson & Fabian, Physics Reports (2006) 427:1.
2. MTI theory: Balbus, ApJ (2000) 534:420.
3. HBI theory: Quataert, ApJ (2008) 673:758.
4. Nonlinear Saturation of HBI & MTI:
   McCourt, Parrish, Sharma, Quataert, MNRAS (2011) 413:1295.
5. Application to Galaxy Clusters:
   a. Parrish, Quataert, & Sharma, ApJ Lett (2010) 712:L194.
   b. Parrish, McCourt, Quataert, & Sharma, MNRAS (2012) 419:L29