Enrico Fermi School – Varenna
Cool Cores and Mergers in Clusters
Lecture 3

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A85 Chandra (X-ray)

Cluster Merger Simulation
Cool Cores in Clusters

- Central peaks in X-ray surface brightness
- Temperature gradient, cool gas at center
- Radiative cooling time $t_{\text{cool}} < \text{Hubble time}$
- Always cD galaxy at center
- Central galaxies generally have cool gas (optical emission lines, HI, CO), star formation, and are radio sources
NGC 1275, Perseus (Conselice et al.)
Cool Cores in Clusters (cont.)

Original Theory:
• X-rays we see remove thermal energy from gas
• If not disturbed, gas cools & slowly flows into center
• Gas cools from $\sim10^8$ K $\rightarrow$ $\sim10^7$ K at $\sim100$ M$\odot$/yr

$$L_{\text{cool}} \approx \frac{5}{2} \frac{\dot{M}}{\mu m} kT$$
Cool Cores in Clusters (cont.)

Steady-state cooling of homogeneous gas

\[
\frac{1}{r^2} \frac{d}{dr} \left( r^2 \rho_v \right) = 0, \text{ mass conservation}
\]

\[
\rho_v \frac{dv}{dr} + \frac{dP}{dr} + \rho \frac{d\phi}{dr} = 0 \quad \text{momentum conservation}
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ r^2 \rho_v \left( \frac{v^2}{2} + \frac{5}{2} \frac{P}{\rho} + \phi \right) \right] = -L \quad \text{energy or entropy}
\]

\[
\dot{M} \equiv -4\pi \rho vr^2 = \text{constant}
\]

\[
v^2 \ll c_s^2 \quad \text{very subsonic}
\]

\[
P \approx \text{constant, isobaric}
\]
Bremsstrahlung cooling

\[ L \propto \rho^2 T^{1/2} \]

\[ T \propto r^{6/5} \sim r \]

\[ \rho \propto r^{-6/5} \sim 1/r \]

\[ I_X \sim 1/r \]

\[ L_X \sim r \]

Reasonable fit to X-ray surface brightness

\[ \dot{M} \sim 100 \, M_\odot /\text{yr} \]
The Cooling Flow “Problem”

• Where does the cooling gas go?
• Central cD galaxies in cooling flows have cooler gas and star formation, but rates are ~1-10% of X-ray cooling rates from images
• Both XMM-Newton and Chandra spectra → lack of lines from gas below ~$10^7$ K
High-Res. Spectrum (XMM-Newton)

Peterson et al. (2001)

Brown line = data, red line = isothermal 8.2 keV model, blue line = cooling flow model, green line = cooling flow model with a low-T cutoff of 2.7 keV
How Much Gas Cools to Low Temperature?

• Gas cools down to \(\sim 1/2-1/3\) of temperature of outer gas (\(\sim 2\) keV)

• Amount of gas cooling to very low temperatures through X-ray emission \(\leq 10\%\) of gas cooling at higher temperature

→ Cooling gas now consistent with star formation rates and amount of cold gas
Heat Source to Balance or Reheat Cooling Gas?

Heat source to prevent most of cooling gas from continuing to low temperatures:

• Heat conduction, could work well in outer parts of cool cores if unsuppressed
  • Works best for hottest gas $Q \propto T^{7/2}$, how to heat mainly cooler gas?
• Supernovae?
• Cluster dynamics (mergers, sloshing, …)?
• AGN = Radio sources
Radio Sources in Cooling Flows

- $\geq 70\%$ of cooling flow clusters contain central cD galaxies with radio sources, as compared to 20% of non-cooling flow clusters
- Could heating from radio source balance cooling?
A2052 (Chandra)

Blanton et al.
Radio Contours (Burns)
Other Radio Bubbles

Hydra A
Abell 262
Abell 133

McNamara et al.
Blanton et al.
Fujita et al.

Abell 2029
Abell 85

Clarke et al.
Kempner et al.
Morphology – Radio Bubbles

• Two X-ray holes surrounded by bright X-ray shells
• From deprojection, surface brightness in holes is consistent with all emission projected (holes are empty)
• Mass of shell consistent with mass expected in hole

X-ray emitting gas pushed out of holes by the radio source and compressed into shells
Buoyant “Ghost” Bubbles

Perseus

Abell 2597

Fabian et al.

McNamara et al.

• Holes in X-rays at larger distances from center
• No radio, except at very low frequencies (Clarke et al.)
Buoyant “Ghost” Bubbles (Cont.)

Abell 2597 – 327 MHz Radio in Green (Clarke et al.)

Ghost bubbles have low frequency radio
Buoyant “Ghost” Bubbles

Holes in X-rays at larger distances from center
No radio, except at very low frequencies (Clarke et al.)
Old radio bubbles which have risen buoyantly
Temperatures & Pressures

- Gas in shells is cool
- Pressure in shells ≈ outside
- No large pressure jumps (shocks)
  Bubbles expand ≤ sound speed
  Pressure in radio bubbles ≈ pressure in X-ray shells
- Equipartition radio pressures are ~10 times smaller than X-ray pressures in shells!?
X-ray Shells as Radio Calorimeters

- Energy deposition into X-ray shells from radio lobes (Churazov et al.):

\[
\frac{1}{(\gamma-1)} PV + PdV = \frac{\gamma}{(\gamma-1)} PV
\]

- Internal bubble energy
- Work to expand bubble

- \( E \approx 10^{59} \) ergs in Abell 2052
- ~Thermal energy in central cooling flow, \( \ll \) total thermal energy of intracluster gas
- Repetition rate of radio sources \( \sim 10^8 \) yr (from buoyancy rise time of ghost cavities)
Can Radio Sources Offset Cooling?

• Compare
  – Total energy in radio bubbles, over
  – Repetition rate of radio source based on buoyancy rise time of bubbles
  – Cooling rate due to X-ray radiation

\[ L_{\text{cool}} = \frac{5}{2} \frac{\dot{M}}{\mu m} kT \]
Can Radio Sources Offset Cooling?

Works in most cases, but perhaps not all

(Birzan et al.):
Limit Cycle?

BH inactive → X-ray cooling

Stop BH accretion → BH accretes

Stop X-ray cooling → Radio jets

Heat X-ray gas → Stop X-ray cooling
"Feedback" and Galaxy Formation

If every large dark matter halo makes a galaxy
→ too many large galaxies

(Croton et al. 2006)
“Feedback” and Galaxy Formation

AGN feedback suppresses cooling and star formation in large galaxies.

Cool cores with radio bubbles = wonderful local labs to study the effects of AGN feedback on massive galaxy formation.
Major Unsolved Problem: How Do Radio Sources Heat the Gas?

Initial energy is kinetic energy of radio jets

- How is the gas heated?
  - Mixing of radio and X-ray plasma and direct particle heating?
  - Plasma waves?
  - Sound waves and shocks?
Ripples in Perseus

Fabian et al. 2006:
Major Unsolved Problem: How Do Radio Sources Heat the Gas?

Initial energy is kinetic energy of radio jets
- How to get heat preferentially into cooler gas?
- How is energy transported to larger radii without disrupting the cool core and abundance gradients?
- How do narrow jets heat gas in all directions?
  - Why don’t the jets just punch narrow channels in the gas?
    - Jet precession?
    - Cluster gas motions?
    - Wide jets or winds?
    - Instabilities?
Simulation of Multiple Outburst Jets

Jets form narrow channels

Vernaleo & Reynolds 2006
Enrico Fermi School – Varenna
Cluster Mergers

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A85 Chandra (X-ray)

Cluster Merger Simulation

$t=4.0$ Gyr
Cluster Formation from Large Scale Structure

Lambda CDM - Virgo Consortium
Cluster Formation (cont.)

Major mergers
Accretion

PS merger tree: Mass vs. time
Spherical Accretion Shocks

- Self-similar solution for spherical accretion of cold gas in E-dS Universe (Bertschinger 1985; earlier work Sunyaev & Zeldovich)
- Cold gas → very strong shocks
- Accretion shocks at very large radii (≥ r_{vir} ~ 2 Mpc)
- No direct observations so far

\[ \lambda \equiv \frac{r}{r_{ta}} \] (turn around radius)
Accretion Shocks (cont.)

- Growth of clusters not spherical
- Accretion episodic (mergers)
- IGM not cold
Accretion Shocks (cont.)

- Growth of clusters not spherical 40x40 Mpc
- Accretion episodic (mergers)
- IGM not cold

40x40 Mpc
(Jones et al)
Accretion Shocks (cont.)

- Mach numbers $M \equiv \frac{v_s}{c_s} \sim 30$
- $Y_\phi = \text{kinetic energy}, \ Y_{th} = \text{thermal energy}$
Accretion Shocks (cont.)

• Accretion shocks at large radii in very low density gas
• X-ray emission $\propto (\text{density})^2 \rightarrow$ very faint, never seen so far
• Radio relics?
• Eventually, SZ images? (SZ $\propto$ pressure)

Growth of LSS $\rightarrow$ most IGM is now hot, most baryons in diffuse, hot IGM
Mergers

- Clusters form hierarchically

Major cluster mergers are most energetic events in Universe since Big Bang

- Major cluster mergers, two subclusters, $\sim 10^{15}$ M$_\odot$ collide at $\sim$ 2000 km/s
- $E$ (merger) $\sim$ 2 x $10^{64}$ ergs
- $E$ (shocks in gas) $\sim$ 3 x $10^{63}$ ergs
Major Mergers
Thermal Effects of Mergers

- Heat and compress ICM
- Increase entropy of gas
- Boost X-ray luminosity, temperature, SZ effect
- Mix gas
- Disrupt cool cores
- Produce turbulence
- Provide diagnostics of merger kinematics
Merger with mass ratio of 3:1, offset merger (Ricker & Sarazin)

0.0 Gyr
\[ \log \rho_{\text{gas}} \]

0.0 Gyr
\[ \Delta s/1.5k \]
Merger Shocks

- Typical shock velocity 2000 km/s
- E (shock) $\sim 3 \times 10^{63}$ ergs
- Main heating mechanism of intracluster gas

Ricker & Sarazin
Merger Shocks (cont.)

• Although energetic, mainly weak shocks as cluster gas is already hot
• Mach numbers $\mathcal{M} \equiv v_s / c_s \sim 1.1-2$
Merger Boosts to $L_X$ & $T_X$

- Mergers temporarily boost
  - X-ray luminosity (factor of $\lesssim 10$)
  - Temperature (factor of $\lesssim 3$)
- Are the most luminous, hottest clusters mainly mergers?

Ricker & Sarazin
Turbulence and Mergers

- Merger simulations → turbulence in post merger shock regions of clusters
- $E_{\text{turb}} \approx 20\% E_{\text{therm}}$, decays following merger (Ricker & Sarazin)
- Explains radio halos in merging clusters?
Mergers Disrupt Cool Cores

Observed anticorrelation between mergers and cool cores
Not due to shocks – density gradient too big
Mainly due to ram pressure, changes in potential, instabilities, & mixing

Ricker & Sarazin
Cool Cores in Mergers

Cool cores $\rightarrow$ high density gas at bottom of deep potential well

Cool cores can survive for some time in mergers

Almost like a solid object moving through cluster

High density $\rightarrow$ prominent in X-ray images

Sharp front edge $\rightarrow$ very prominent in Chandra images

Ricker & Sarazin
Chandra: “Cold Fronts” in Mergers

Merger shocks?

No: Dense gas is cooler, lower entropy, same pressure as lower density gas

Abell 2142
Markevitch et al.
Cold Fronts (cont.)

Abell 3667

Contact discontinuity, cool cluster cores plowing through hot shocked gas

Vikhlinin et al.
Cold Front with Merger Bow Shock
Transport Processes – Thermal Conduction

Ettori & Fabian; Vikhlinin et al.

- Temperature changes by 5x in \( \lesssim 5 \text{ kpc} < \text{mfp} \)
- Thermal conduction suppressed by \(~100\times\)
- Kelvin-Helmholtz instabilities suppressed
- Due to transverse or tangled magnetic field?

Is conduction generally suppressed in clusters?
Merger Kinematics

Give merger Mach number $M$
- Rankine-Hugoniot shock jump conditions
- Mach cone angle
- Stagnation condition at cold front
- Stand-off distance of bow shock from cold front

Find $M \approx 1.1-2$, shock velocity $\approx 2000$ km/s
(Vikhlinin et al.)
Cold Front with Merger Bow Shock

1E0657-56

Markevitch et al.
Mergers: Test of Gravitational Physics

Bullet Cluster
1E0657-56
Markevitch et al.

Image = galaxies
Red = X-rays = gas
Blue = lensing mass = gravity

Gas behind DM ≈ Galaxies
Mergers: Test of Dark Matter vs. Modified Gravity

- Gas behind DM ≈ Galaxies
- DM = location of gravity
- Gas = location of most baryons
- Whatever theory of gravity, not coming from where baryons are

Require dark matter (not MOND)
Mergers: Test of Collisional Dark Matter

- Gas behind DM $\approx$ Galaxies
- Gas collisional fluid
- Galaxies collisionless particles
- Limit on self-collision cross-section of DM

$\sigma/m \text{ (DM)} \leq 1 \text{ cm}^2/\text{g} < 5 \text{ cm}^2/\text{g}$ required for cores in dwarf galaxies
Nonthermal Effects of Mergers: Particle Acceleration

Supernova remnants: shocks at
$\geq 1000 \text{ km/s} \rightarrow$
$\geq \text{ few } \% \text{ of shock energy} \rightarrow$
cosmic ray electrons

$E_{\text{CR,e}} \geq 10^{62} \text{ ergs}$

$E_{\text{CR,ion}} \geq E_{\text{CR,e}}$

Clusters
Cluster Radio Halos and Relics

Radio Relics
(shock acceleration?)

Radio Halo
(turbulent acceleration?)

Abell 3667
Röttgering et al.

Coma
Govoni et al.
A Few Questions About Clusters

- How do radio sources heat the intracluster gas?
  - Mechanism of heating?
  - How do jets produce large scale, isotropic heating?
- Is there a feedback loop between AGN and gas cooling?
- What determines the amount of cool gas and star formation in cool cores?
- What is the chemical and thermal history of the intracluster gas?
A Few Questions About Clusters

- How effective are transport processes in clusters?
  - Thermal conduction?
  - Viscosity?
  - Heavy element sedimentation?

- Can the intracluster gas generally be treated as a fluid?

- How do the morphological features in X-ray images relate to the dynamical history and state of the cluster?
  - Shocks and cold fronts
  - Sloshing
  - Bubbles
A Few Questions About Clusters

- How turbulent is the intracluster gas? Is it only very turbulent in merging clusters?
- What is the contribution of nonthermal matter to clusters?
  - Magnetic fields?
  - Relativistic particles
- How effective are merger shocks and turbulence at accelerating relativistic particles?
A Few Questions About Clusters

- Can we understand or measure or calibrate the physics of the gas in clusters well enough to use X-ray and SZ observations of clusters to do precision cosmology and measure dark energy?