Chandra's Clear View of the Structure of Clusters

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Hydra A Cluster
(Kirkpatrick et al. 2009)

Bullet Cluster
(Markevitch et al. 2004)
Cool Cores, Radio Sources, & Feedback

Perseus (Chandra)

Fabian et al. 2011
Radio Bubbles

X-ray Cavities

Perseus (Fabian et al. 2000)
Radio Bubbles

X-ray Cavities Filled by Radio Lobes

Perseus

Radio (blue) on pressure structure map (Fabian et al 2006)
A2052 (Chandra)

Blanton et al. 2001
Radio Contours (Burns)
Other Radio Bubbles

- Hydra A
  - McNamara et al. 2000
- Abell 262
  - Clarke et al. 2009
- MS0735.6+7421
  - McNamara et al. 2005
- Abell 4059
  - Heinz et al. 2002
- MKW3s
  - Mazzotta et al. 2002
- Centaurus
  - Fabian et al. 2005
Morphology – Radio Bubbles

- Two X-ray holes surrounded by bright X-ray shells
- From de-projection, surface brightness in holes is consistent with all emission being projected (holes are empty of X-ray gas)
- 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. 2000

McNamara et al. 2001
Multiple Radio Bubbles

Perseus
Fabian et al. 2011

Abell 2597
Blanton et al. 2011

Hydra A Cluster
Wise et al. 2007
Buoyant “Ghost” Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies

Fabian et al.
Buoyant “Ghost” Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies
- Filled with very low frequency radio

Abell 2597
Abell 2052
Abell 262
327 MHz radio green
Clarke et al. 2005
327 MHz radio green
Clarke et al. 2009
Blanton et al. 2011
Buoyant “Ghost” Bubbles

Filled with very low frequency radio

Hydra A Cluster

330 MHz radio green
Lane et al. 2004
Buoyant “Ghost” Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies
- Filled with very low frequency radio

Old radio bubbles which have risen buoyantly

Give repetition rate of radio outbursts

($\sim 10^{7-8}$ yr)
X-ray Tunnels?

Continuous channels in X-ray, with steeper radio spectra at large distances

Abell 262

Red = Chandra
Green = low frequency radio
Clarke et al. 2009
Entrainment of Cool Gas

A133
Fujita et al. 2002; Randall et al. 2010

- Columns of cool X-ray gas from BCG center to radio lobe
- Gas entrained by buoyant radio lobe?
Entrainment of Cool Gas

M87/Virgo
Million et al. 2010, Werner et al. 2010
Temperatures & Pressures

In most radio bubbles:
- 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 ~20 times smaller than X-ray pressures in shells!??
Shocks Around Radio Bubbles

Some radio bubbles surrounded by shocks
→ supersonic expansion

MS0735.6+7421  Hydra A  Hercules A

McNamara et al 2005  Nulsen et al 2005a.b
X-ray Shells as Radio Calorimeters

Energy deposition into X-ray shells from radio lobes (Blanton et al. 2002; Churazov et al. 2002):

\[
\frac{1}{\gamma - 1} PV + PV + \text{(shock energy)} = \frac{\gamma}{\gamma - 1} PV = (2.5 \text{ to } 4) PV
\]

- \( E \approx 10^{59} \) ergs in Abell 2052, typical value
- Divide by repetition rate of radio (from buoyant bubbles) = radio jet kinetic power
Compare to Radio Luminosity

Radio emission is very inefficient

Can Radio Sources Offset Cooling?

Works in many cases, but perhaps not all

How Do Radio Sources Heat the Cooling X-ray Gas?

Enough energy, but how to get it into the cooling gas?

One possibility is sound waves and weak shocks from the radio source.
Ripples in Perseus

Fabian et al. 2006
Ripples in A2052

Unsharp Masked Chandra Image

Unsmoothed Chandra Image

Blanton et al. 2008, 2011
In some cases, association between X-ray filaments and filaments of cooler gas and dust (optical emission lines, CO, star formation)

Perseus

Fabian et al. 2011

Abell 2052

Blanton et al. 2011
Radio Bubbles and Shocks in Groups and Galaxies

NGC5813 Group

Randall et al. 2011

NGC4636

Baldi et al. 2009
Merging Clusters

MACSJ0717.7+3745

Ma et al. 2009
Cluster Mergers

- Clusters form by mergers
- Merger shocks heat intracluster gas
Cluster Mergers

• Clusters form by mergers
• Merger shocks heat intracluster gas
• Mergers may accelerate relativistic particles

Radio Relics
Abell 3667
Röttgering et al. 1997

Radio Halo
Coma
Govoni et al. 2001
Cold Fronts in Mergers

Merger shocks?

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

Abell 2142
(Markevitch et al. 2000)

Abell 3667
(Vikhlinin et al. 2001)
Contact discontinuity, cool cluster cores plowing through hot shocked gas  
(Vikhlinin et al. 2001)
Merger Cold Fronts & Merger Shocks

Diagram:
- hot, diffuse gas
- Cold Front
- cool, dense gas
- bowshock?
Merger Shock Fronts

1E0657-56 = Bullet Cluster

Markevitch et al. 2004

Abell 520

Markevitch et al. 2005
Double Merger Shock Fronts

Abell 2146 (unsharp mask)

Russell et al. 2010
Merger Kinematics

(Markevitch & Vikhlinin 2007)

Give merger Mach number $M$

- Rankine-Hugoniot shock jump conditions
  - Density, temperature, or pressure jump
    $$\frac{P_2}{P_1} = \frac{2\gamma}{\gamma+1} M^2 + \frac{(\gamma-1)}{\gamma+1}$$
  - Stagnation condition at cold front
  - Stand-off distance of bow shock from cold front

Find $M \approx 2$, shock velocity $\approx 2000$ km/s
Transport Processes – Thermal Conduction

(Ettori & Fabian 2000; Vikhlinin et al. 2001)

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

Is conduction generally suppressed in clusters?
Mergers: Test of Gravitational Physics

Bullet Cluster
1E0657-56

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

Gas behind DM ≈ Galaxies

(Markevitch et al. 2004
Clowe et al. 2004)
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 ≈ 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

(Randall et al. 2008)
“Sloshing” Cold Fronts

• Cold fronts in regular, cool core clusters
• Kinematics: lower Mach numbers

(Markevitch & Vikhlinin 2007)
“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
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- Due to gas sloshing due to passage of subcluster near core of main cluster

(Markevitch et al. 2001)
“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
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Abell 1644

(Johnson et al. 2010)
“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
- Kinematics: lower Mach numbers
- Due to gas sloshing due to passage of subcluster near core of main cluster
- One-arm spiral pattern toward subcluster often

Abell 2029
(difference image)

(Clarke et al. 2004)
Merger Shocks and Nonthermal Particles

Theory suggests relativistic particles (re)accelerated
• at merger shocks (radio relics)
• behind merger shocks (radio halos)
Merger Shocks and Nonthermal Particles

Chandra images support shock/radio connection

Bullet (Liang et al. 2000)

Abell 520 (Govoni et al. 2001)

Abell 754 (Macario et al. 2011)
Summary

- Chandra high resolution observations have transformed our view of clusters
- Cool cores - X-ray cavities, radio bubbles, and feedback
  - Low redshift analogs of high mass galaxy formation at high redshift
- Merging clusters, cold fronts, shocks
  - Physics of cluster formation, transport processes, and particle acceleration
  - Basic gravitational physics