Plasma physics in the intracluster medium from the smallest to the largest scales

Aurora Simionescu
Einstein Fellow
KIPAC/Stanford
Outline

- AGN - ICM interaction
- cold-fronts (and shocks)
- what are the thermodynamic properties at the virial radius?

Disclaimer: this is an overview, not a review talk
AGN feedback

filaments: X-ray bright; low temperature; metal rich
shocks: high temperature; high pressure
cavities: radio bright; X-ray faint
Temperature map of M87 / Virgo (nearest cluster)

Simionescu et al. 2007
120ks XMM

Million et al. 2010
574ks Chandra
Cool gas is metal rich

Simionescu et al. 2008
$Z \sim 2.2$ solar,
$M \sim 5 \times 10^8 \, M_{\text{sun}}$
$M_{\text{Fe}} \sim 1.5 \times 10^6 \, M_{\text{sun}}$

Simionescu et al. 2008
Conduction suppression in the azimuthal direction?

Simionescu et al. 2008
Conduction and no turbulence?

Metallicity (Solar)  
Million et al. 2010  

$kT$ (keV)
My cartoon picture of magnetic fields in M87

\[ B = 1 \mu G \]

\[ B = 5 \mu G \]
Astro-H

high spectral resolution calorimeters can:

- test multiphase structure
- measure the abundances of the different gas phases separately
- measure the turbulent line broadening and line shift of each component separately
Outline

- AGN - ICM interaction
- cold-fronts (and shocks)
- what are the thermodynamic properties at the virial radius?
Cold fronts in Virgo

Our work will concentrate on the Virgo cluster which is described in more detail in Section... 

In addition to the edges in brightness and temperature, temperature maps show spiral or arc-shaped cool regions inside the actual fronts. In X-ray brightness residual maps, an excess corresponding spatially to the structure in the temperature map is found. 

For some clusters, even a corresponding structure in metallicity maps is seen. X-ray brightness maps can be obtained more easily than temperature or metallicity maps; a spiral-shaped excess wrapped around the cluster core is often regarded as an indicator for ongoing sloshing. 

Observations of medium depth do not allow the derivation of temperature and metallicity maps but of radial profiles of these quantities across the edge. For this purpose, the observational data is binned into circular or elliptical rings of a certain azimuthal length, resulting in an azimuthally averaged profile. Such profiles display a steep gradient at the radius of the edge. 

1.3 The CFs in the Virgo cluster

Simionescu et al. (2010) have presented XMM and Suzaku observations of a pair of CFs in the Virgo cluster: one CF is located about 50 kpc NW of the cluster center; the other in the SE about 50 kpc from the cluster center. In Figure 1, we present two versions of residual X-ray brightness maps. The top panel shows the residuals w.r.t. the azimuthally averaged brightness. The bottom panel shows residuals w.r.t. a double-β profile fit to the observed X-ray brightness same as in Simionescu et al. 2010—but with a colour scale consistent to this paper.

1.4 Aims

Previous work has shown that the sloshing scenario can in principle explain the known observed characteristics of the resulting CFs in Virgo: the radius, contrast of X-ray brightness, temperature, metallicity across the edge, and morphology in maps depend on several parameters:

- characteristics of subcluster: mass, size, pericentre of orbit, velocity along orbit
- age: time since pericentre passage
- our line of sight: the orbit and orbital plane of the subcluster

Our aims are as follows:

- Test the sloshing scenario quantitatively. We show that we can find a reasonable set of parameters to reproduce the observations well. Thus, we can constrain the merger history.
Chandra LP of the M87 cold front

- what is the width of the fronts?
- do KH instabilities develop at the cold fronts?
- is there an underlying rotational/spiral flow associated with these fronts?
- is there a magnetized depletion layer?
Outline

- AGN - ICM interaction
- cold-fronts and shocks
- what are the thermodynamic properties at the virial radius?
Projected temperature and metallicity profiles:

- Excellent agreement with Chandra data
- Detailed profiles spanning 3 decades in radius
- Profiles between \( r_{500} \) and \( r_{200} \) resolved for the first time
- Metallicity profile measured for the first time until the virial radius
Deprojected thermodynamic profiles:

- Shallow decline of electron density at large radii.
- Entropy appears to flatten at large radii compared to the expected power-law pressure at large radii.

Pressure at large radii greater than predicted by numerical simulations (fitted to XMM data inside $r_{500}$ by Arnaud et al. 2010).
Gas mass fraction profile towards the NW:

- Good agreement with previous observations and numerical simulations at $r<0.4r_{200}$
- $f_{\text{gas}}$ value matches cosmic mean at $r\sim r_{500}$
- $f_{\text{gas}}$ exceeds cosmic mean at large radii ($r>0.6-0.7r_{200}$)
- Most likely cause: the gas is clumpy

Bottom panel shows the first measurements of the gas clumping factor
Corrected thermodynamic profiles:

Correcting for clumping (red lines) brings measurements into agreement with expected trends.

Other mechanisms, e.g. $T_e \neq T_i$ would explain entropy flattening but not explain pressure and $f_{\text{gas}}$ profiles.
Virgo pilot project:

Urban et al. 2011
The Perseus Key project:

How do the thermodynamic profiles vary with azimuth/ LSS environment? Is the NW arm "special"?
Perseus 8 arms Sx

Preliminary!

urban et al. in prep
Large scale “sloshing”?

Perseus
(Simionescu et al. 2012)

Virgo
(Simionescu et al. 2010)
The Perseus cluster

on large scales

Simionescu et al. 2012
Large scale “sloshing”?

what merger parameters can trigger such large-scale motions?

does the coherence of the “spiral” from ~10 kpc to >1 Mpc imply anything about viscosity of ICM?

how does the cool core survive such a merger?
Large scale motions in cool core vs. non-cool core clusters

Warning: at least some degree of cosmic coincidence is definitely involved
The Coma Large project:
In the entropy these edges look just like cold fronts - if you can have sloshing outside the cool core in CCC, what happens when you “slosh” a non-cool core cluster?
Is the Coma cluster underweight?

Density at intermediate radii along relaxed E/NW directions smaller than expected average kT probably boosted by merger and is not a good proxy for cluster mass/size.

Is virial radius of Coma smaller than expected?
Summary:

- AGN contribute to metal transport; this may induce turbulence and may affect geometry of B-fields; conduction is most likely anisotropic in cluster cores.
- Cold fronts / large scale motions may extend further out in radius than we thought.
- Gas in the outskirts may be clumpy, and/or NFW model may be less accurate than we thought.
- The virial radius of Coma may be smaller than we thought – biases in boosting kT due to merger?