Probing the hot intra-cluster medium with X-ray observations

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Herschel (1785)
Zwicky (1933)
Stars: < 5%
Hot gas: 1.1%
Dark matter: > 85%

\[ M_{500} \sim 1 - 1.5 \times 10^{14} \, M_\odot \sim 10^{47} \, \text{g} \]
\[ R_{500} \sim 1 - 2 \, \text{Mpc} \sim 10^{24} \, \text{cm} \]
Dark matter-driven gravitational coalescence

13.2 GYr; z=8.5
12.8 GYr; z=5.7
3.6 GYr; z=1.4
Today; z=0.0

Less structured homogeneous (on large scales)

More structured peaks, filaments voids

Time
Dark matter-driven gravitational coalescence

dark matter  
gas density  
gas shocks

$z = 2.0$

dark matter density  
gas density  
gas shocks

V. SPRINGEL
\( \rho, T, Z \)

\[ T \sim 0.5 - 15 \text{ keV} \]
\[ \rho_g \sim 10^{-1} - 10^{-4} \text{ cm}^{-3} \]
\[ Z \sim 0.3 \, Z_\odot \]
Thermal emission from the ICM

- Fully ionised H+He plasma with highly-ionised heavy elements
- Bremsstrahlung emission (continuum) + lines
- Imagery: gas density distribution
- Spectral shape: kT, Z
  - Need sensitivity > 10 keV

\[
\frac{dN(e)}{dE} \sim n_e n_i V \left[ g(E, T) T^{-1/2} e^{-E/kT} + \text{lines} \right]
\]
Probing formation
Morphological variety

EINSTEIN IMAGES FROM JONES & FORMAN (1984)
Shocks: example of A665

- Rankine-Hugoniot jump conditions for 1D shock (Landau & Lifshitz 1959)
- Independent measurements from density and temperature jumps
- Typical shock Mach numbers ~1-4

Dasadia et al. 2016 (Chandra, A665)
Shocks: $e^- -$ ion equilibrium

- Direct heating or adiabatic compression then equilibrium on $\sim$ Spitzer timescale?
- Deprojected temperatures in Bullet cluster suggest $e^-$ heated directly at shock

Markevitch 2006; Russell et al 2012 (Chandra)
Cold fronts

- Abrupt $kT$, $n_e$ jumps but no pressure jump $\rightarrow$ not a shock
- Gas sloshing in dark matter potential
Cold fronts
Cold front width in A3667

- Density jump width \(< 4 \text{kpc} \ll \text{Coulomb mfp } \lambda_e \approx 10-15 \text{ kpc}
- Diffusion and conduction \(\kappa \propto \lambda_e\) across front is suppressed
- Magnetic draping / barriers

\[ S_x, \text{cts s}^{-1} \text{arcsec}^{-2} \]

\[ r, \text{kpc} \]

VIKHLININ ET AL 2001
KH instabilities
KH instabilities

$10^4 M$

RISA BENDER, PHOTO TAKEN OVER DALLAS
Possible KH instabilities in A3667

- Sequential pattern identified in break radii
- Possible KH instabilities
- Set limit on viscosity of plasma

$> 10^{19}$ M

ICHINOHE ET AL 2017 (CHANDRA)
Gas motions
Turbulent power spectrum

\[ E(k) \]

Injection scale

Inertial range

\[ Q(k) \propto k^{-\alpha} \]

dissipation scale

Kolmogorov:

\[ E(k) \propto k^{-5/3} \]
Power spectrum tracers (simulations)

\[ A(k) = \sqrt{E(k)} k \]
Measured power spectrum (pressure)

Coma: Schuecker et al 2004, with XMM

Coma: Khatri & Gaspari 2016, with Planck(!) and Chandra

Coma: Schuecker et al 2004, with XMM

Chandra 1.67A_p^7
θ_max = 60'
-NGC4839 60'
40'
30'
20'
15'

A_p = [k^3 P(k)/(2π)]^1/2

k/(2π) = 1/λ (kpc^-1)
Density fluctuations

- Stratified atmosphere, local pressure balance $\Rightarrow$ entropy and density gradient

\[
\left( \frac{\delta \rho_k}{\rho} \right)^2 = \eta \left( \frac{V_k}{c_s} \right)^2 ; \eta = \sqrt{\frac{H_p}{H_s}} \sim 1
\]

- Valid in both large scale (buoyancy-dominated) and small-scale (turbulence-dominated) regimes

ZHURAVLEVA ET AL 2014
Density fluctuations - numerical simulations

ZHURAVLEVA ET AL 2014; GASPARI ET AL 2014
Density fluctuations - Perseus

\[ \frac{\delta \rho_k}{\rho} \sim 7 - 15\% \text{ on scales 6-30 kpc} \rightarrow \text{velocities } \sim 90-140 \text{ km s}^{-1} \]
Direct measurements
Line measurements

- Centroid (bulk)
- Intensity (abundance)
- Width (turbulence)
- Shape (los velocity structure)
Line broadening measurements (XMM RGS)

Sanders & Fabian 2013;
See EG OTA & Yoshida 2016 for bulk motion measurements with Suzaku
Direct velocity measurement with Hitomi

$\Delta E \sim 7 \text{ eV}$
Metallicity
Metallicity distribution and evolution

- Abundance outside core constant to large radius and high redshift
- Cool cores have central abundance peaks with redshift evolution
- Early enrichment + build-up due to BCG
Central AGN redistributes metals

- Entrainment of metals to larger radius
- Correlation with jet power

McNamara et al. 2011, Kirkpatrick et al. 2011 (Chandra)
The future
What’s needed

1. More throughput (photons)

2. Spatial resolution (microphysics, distant objects)

3. Spectral resolution (the third dimension)
The Athena+ Observatory

L2 orbit Ariane VI
Mass < 5100 kg
Power 2500 W
5 year mission

X-ray Integral Field Unit:
\( \Delta E: 2.5 \text{ eV} \)
Field of View: 5 arcmin
Operating temp: 50 mk

Wide Field Imager:
\( \Delta E: 125 \text{ eV} \)
Field of View: 40 arcmin
High countrate capability

Silicon Pore Optics:
2 m\(^2\) at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: \( 3 \times 10^{-17} \text{ erg cm}^{-2} \text{s}^{-1} \)

Barret et al., 2013 arXiv:1308.6784
Rau et al. 2013 arXiv:1307.1709
Unprecedented capability

Spectro-imaging at 2.5 eV resolution

Wide-field imaging

60 arcsec (22 kpc)

CROSTON, SANDERS ET AL 2013

A. RAU / T. DAUSER / J. WILMS / T. BRAND
1. Clusters are giant physics laboratories

2. X-ray observations hold the key to understanding many aspects of their formation and evolution

3. New instruments will enable major new advances
end