What have we learned about clusters with XMM?

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I: Clusters are (more) complex objects (than we thought):
   the continuous hierarchical cluster formation

II: Clusters form a (more) regular population (than we thought):
   the self-similar collapse of the DM and the gas additional physics

(not exhaustive … > 100 XMM papers… )
• Primordial fluctuations (DM) that growth under the influence of gravity
  ==> the cosmic ‘web’: Voids, Filaments, Blobs: The clusters of galaxies

• Hierarchical clustering:
  - small structures collapse first
  - clusters are forming since $z \approx 2$ till now by merger/accretion along LS filaments

• The cluster population is an evolving population
  ==> provide powerful test of structure formation (Dark Matter and Gas)
  ==> can be used to constrain the cosmological parameters
Hierarchical Cluster Formation

• Is that true?
• Physics of merger events
• LSS Environment effects
Clusters forming via mergers

Shocks: major ICM heating source
Also Turbulence  [Schuecker et al, 04]
Formation history

Z=1.14

Hashimoto et al 04

Z=0.89

Maughan et al 04

Z=1.4

Mullis et al 05

∃: mergers

massive relaxed cluster

kT=11± 1 keV

clusters up to z=1.4
The complex merger physics

- Merger within merger (David & Kempner, 04)
- Cool trails
- Core Passage of shock wave due to minor merger (Churazov et al, 03)
- Cold front sub-structures (Briel et al, 04)

Reiprich et al, 04
The effect of LSS environment

Multiple ongoing mergers
Accretion along filament

Off-axis merger
=> Tidal torques

Substructure Occurrence Rate = 52 ± 7 %
Higher in denser environment
(from RASS: Schuecker et al, 01)
Detection of WHIM filaments in cluster vicinity?

- Sample of 14 clusters; in 3 clusters:
  - *soft excess* emission /hot ICM emission:
    + extended (5)
    + detection of OVII line at cluster z

  $\Rightarrow$ due to warm gas with $kT \sim 0.2$ keV

Clusters located in
- regions of enhanced soft XRB
- Super cluster environment

See also Nevalainen et al, 03; Finoguenov et al, 03; Fujimoto et al, 04; Bonamente et al, 05
The regular cluster population

Radial structure and scaling laws

• Do we understand the collapse of the Dark Matter?
• Does the gas simply follow the DM?
• Or there is additional (non gravitational) physics?
The cluster population

A wide range of global and morphological properties BUT

Correlations

Self-similarity expected in simplest formation models:
- close to virial equl. between (rare) major mergers
- self-similar collapse of DM (thus gas if grav. only)
Validity of the modelling of the (C)DM collapse

A universal total (DM) mass profile down to low mass with (cusped) shape as expected

See G. Pratt Talk

Pointecouteau, Arnaud & Pratt, 05
Also Pratt & Arnaud, 02,03; Pointecouteau et al, 04

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The ICM is NOT purely governed by gravitation

\[ L_X \propto T^2 \]

\[ S = T/n_e^{2/3} \]

Scaling laws not as expected

The entropy:
Key to the thermodynamical history:
grav. heating (shocks) => \( S \propto T \)
cooling ?
AGN, SN heating ?

\[ S \propto T \]
\[ S \propto T^{0.65} \]

Entropy excess
Higher at low T (M)
NB not due to wrong modeling of DM!
Gas history depends on both cooling and SN/AGN heating

Profiles scaled $S \propto T^{0.65}$

Self-similar down to 2 keV (more dispersion for groups); No flat entropy core
=> pure pre-heating models rejected  See G. Pratt Talk

See also: Sun et al 03,04; Pratt & Arnaud,03; Rasmussen & Ponman,04; Korsroshashi et al,04; Piffaretti et al, 05
The gas is cooling in the center

$kT$ drop in the center when $t_{\text{cool}} < t_H$

Tamura et al, 01

Kaastra et al, 04
No gas with temperature < T/2  (…but except A2597.. Moris & Fabian 05)
Isothermal locally  (Molendi et al 01 02; Matsushita et al 02)
‘Excess’ absorption seen previously is an artefact
Core properties not understood!
Balance between cooling and AGN heating? effect of conduction?

- X-ray cavities evacuated by radio source weak shocks and sound waves
- cool rims (no strong shocks) [see Blanton 03 review, but see McNamara, 05]
- cold front and sloshing gas [Markevitch et al, astro-ph/0208208]

See e.g. Bohringer et al, 02 Ghizzardi et al 04 (M87); Reiprich ed. [http://www.astro.virginia.edu/coolflow/]

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The overall picture provided by this study of the evolution of the cluster scaling relations is that within the statistical limits of the current data, the evolution of galaxy clusters out to \( z \approx 1 \) is described well by the self-similar model. "

See also Arnaud et al, 02, Lumb et al, 03, Sadat et al, 05; for Chandra: Vikhlinin et al, 02; Ettori et al, 04
Galaxy feedback: the ICM enrichment

Clarified: No resonance scattering: Fe measur. in center reliable *Gastaldello & Molendi, 04*
No abnormal low (< *) abundance in groups center *Buote et al, 02, 03*

Central Fe abundance peak (confirmed)
O/Fe increase with radius; Si/Fe and S/Fe flat

⇒ In center: production by cD (and long lived cool core *Bohringer et al, 04*) by SNI and SNII and massive star formation
⇒ In outer part: higher contribution from SNII AND even constraints on SNI/II yields (*Finoguenov et al, 02*)
No evolution of [Fe] abundance up to $z>1.1$
Consistent with early enrichment

Hashimoto et al 04
Conclusions

• As expected in the hierarchical CDM scenario for structure formation clusters are forming today and at high z by accreting matter/subclusters

• Importance of the LSS environment for cluster formation/dynamical state

• Merger of two clusters is a highly complex dynamical event

• Clusters do form a self-similar population down to kT~ 2keV and up to high kT and z
  
  modelling of the CDM collapse OK

• Self-similarity differs from purely gravitational model
  importance of cooling/galaxy feedback both in center and at large scale

  => Clusters good for cosmology
  => Gas physics still to be better understood …

More expected from statistical studies inc. archives and LPs….