Core Structure and Thermal Evolution of X-ray Clusters

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Motivation

$L_X - T$ relation of galaxy clusters

- $L_X$ depends on both $n_{\text{gas}}$ and $T_{\text{gas}}$
  
  \[ L_X \propto n_{\text{gas}}^2 T_{\text{gas}}^{1/2} \]

→ Physical status and evolution of the ICM

- Inconsistency between the self-similar model ($T^2$) and the observations ($T^3$, significant scatter)

Related observational results

- Connection between $L_X - T$ and cluster core radius (Ota & Mitsuda 2002)

- ‘Universal temperature profile’ in cooling-flow clusters (e.g. Kaastra et al.)

→ Cooling in the core may have much impact on $L_X - T$

Observational approach to core structure and thermal evolution of the ICM
Temperature profiles of CF clusters

\( T_{\text{min}} \sim (0.3-0.4)T_0 \)

\( \dot{M}_{\text{spec}} \sim \dot{M}_{\text{prof}} / 10 \)
Agenda

1. Review on a uniform X-ray analysis of a large number of ROSAT & ASCA distant clusters (Ota 2001; Ota & Mitsuda 2002, 2004)

2. $L_X-T$ relation and thermal evolution of ICM
   - $L_X-T$ and its connection to fundamental X-ray parameters in the light of radiative cooling
   - $L_X-T\beta$ and X-ray morphology
   - Discussion on the thermal evolution
     - Possibility of “quasi-hydrostatic state” of gas in regular clusters

$\Omega_M = 0.3, \Omega_\Lambda = 0.7, H_0 = 70 \text{ km/s/Mpc}$
1. A uniform X-ray analysis of distant clusters with ROSAT & ASCA

Ota (2001)
Ota (2001); Ota & Mitsuda (2004)

- analyzed ROSAT & ASCA data on 79 distant clusters with 0.1<z<0.82 under β-model
- Note: In $L_X$-$T$ analysis, we use 69 clusters (0.1<z<0.56) excluding high-z clusters with large uncertainties and 3CR clusters.

cf.
45 nearby, z<~0.1
(Mohr et al. 1999)
28 highz, 0.4<z<1.3
(Ettori et al. 2004)
Spatial analysis and spectral analysis

Spatial analysis with ROSAT HRI
- Isothermal $\beta$-model fitting $\rightarrow \beta, r_c, S_0(n_e0)$
- Double-$\beta$ gives significantly (marginally) better fit to 9 (7) regular clusters
- X-ray morphology. 69$\rightarrow$41 Regular + 28 Irregular

Spectral analysis with ASCA GIS(r<6') & SIS(r<3')
- Raymond-Smith model $\rightarrow T$; emission-weighted temperature, $L_x$; bolometric luminosity within $r_{500}$

See OM04 for the complete catalogue and scaling relations ($M_{\text{gas}}, M_{500}, f_{\text{gas}}, r_{500}, T, L_x, r_c, \beta, Z, ...$)
Surface brightness fitting

Single $\beta$-model

Double $\beta$-model
X-ray properties of the sample

⭐ Redshift dependence
- **No clear z evolution** in $T$, $\beta$-model parameters at $z<0.5$
- $L_X-T$ is steeper at $z>0.3$? but not statistically significant $\Rightarrow$ we perform the analysis regardless of $z$

⭐ Density structure
- Two distinct peaks at 50 and 200 kpc in $r_c$ histogram
- Coincidence with two $r_c$ values of double-$\beta$ clusters
- $r_c$ is correlated with X-ray morphology, $n_{e0}$, presence of cD galaxy, $L_X-T$ etc.
  - Significant difference between $r_c <100$ and $r_c>100$ kpc. $\Rightarrow$ Two classes of cluster type? Different stages of evolution?
Temperature vs redshift

No clear redshift evolution.
**β-model parameters vs redshift**

* Very large dispersion
* Systematic difference between Regular/Irregular clusters
* Less clusters with $r_c \sim 100$ kpc
Redshift dependence of $L_X-T$

cf. Ettori et al. 2004 reported a steep slope of $3.72 \pm 0.47$ for high-z clusters ($0.4 < z < 1.3$)

$L_X \propto T^{2.75^{+0.85}_{-0.71}}$ for $0.1 < z < 0.2$

$L_X \propto T^{3.18^{+0.92}_{-0.84}}$ for $0.2 < z < 0.3$

$L_X \propto T^{4.65^{+2.33}_{-1.86}}$ for $0.3 < z < 0.56$

steepening at $z > \sim 0.3$ ?
Fig. 4. \( L - T \) relation without (left) and with (right) correction by \( E_{b} \). (Upper panels) Dotted line: slope fixed to the predicted value of 2. Dashed line: slope free. The solid lines represent the local best fit results (from thinnest to thickest line): Markevitch (1998; with core excised in cooling flows clusters), Arnaud & Evrard (1999), Novicki et al. (2002; for objects at \( z < 0.3 \)) and Novicki et al. (2002; for objects at \( 0.6 > z > 0.3 \)). Solid line: Ettori et al. (2002; thinnest line), Allen et al. (2001c). (Bottom panels) Plot of the \( \Delta \chi^{2} \) distribution for the one interesting parameter \( B(B_{z}) \) given in Eq. (7). Each solid line corresponds to a local scaling relation plotted with the same thickness in the upper panel and compared to all the 28 objects with \( z \geq 0.4 \) in our sample. The 2 and 3\( \sigma \) limits are shown as dot-dashed lines.
45 nearby clusters (Mohr et al. 1999) were added together.

cf. Ettori et al. 2004
rc ~100kpc, no significant double for high-z
cDs appear in clusters with small core or double-β clusters.
But difficult to explain the small core scale ~50kpc because the typical core radius of cD galaxy ~10kpc.
The normalization factors are significantly different between two subgroups.
FAQs on the origin of two $r_c$ scales

**ICM origin**
- Abundance gradient? -- may account for the outer core dominant double-\(\beta\) cluster, but not likely.
- Cooling flow? -- The standard model is not likely.

**Dark matter origin**
- cD galaxy potential? -- Not likely because cD core is typically 10 kpc as well as only 50% of small core clusters have cD.
- Merging? -- Possible but that small core clusters and double-\(\beta\) clusters are ~regular clusters...
- DM has two preferable scales? -- Yes as long as we rely on hydrostatic equation and isothermal \(\beta\)-model.

**Other origin**
- MOND?

_In this talk, I focus on the effect of cooling on $L_X-T$_
2. Impact of cooling on the $L_X - T$ relation

i) $L_X - T$ and gas density profile
ii) $L_X - T$ and cooling
iii) $L_X - T \beta$ and X-ray morphology

In this analysis, we use the parameters from single-$\beta$ model.

Ota et al. in prep.
Are cluster profiles self-similar?

$r_{500} - r_c$ relation

Small core clusters $r_c < 100\text{kpc}$

Large core clusters $r_c > 100\text{kpc}$

No correlation. $r_{500} \propto r_c^{0.71 \pm 0.40}$

$r_{500} \propto r_c^{0.15 \pm 0.04}$
Gas density profiles of 69 clusters

Large scatter! ~universal

$r > 0.1 r_{500}$
The small core clusters show higher central density.

$r < 0.1 r_{500}$
The profiles are consistent with “similarity” in outer profiles of nearby clusters (Neuman & Arnaud 1999)
Neumann & Arnaud (1999)

26 clusters
(0.04<z<0.06)

Fig. 2. The scaled emission measure profile (Eq. 7) of the clusters in the spectroscopic sub sample. The radius is normalised to $r_{VT200}$ (Eq. 9). The dotted line shows, for comparison, the emission measure profile of Abell 2163 ($z=0.201$, kT=14.6 keV, Elbaz et al. 1995). Beyond $r/r_{VT200} \sim 0.1$ the profiles look remarkably similar.
$L_X - T$ inside/outside $0.2r_{500}$

Very large scatter
Systematic difference between two groups

$\log(L_X(<0.2r_{500})) \propto T^{4.37^{+1.54}_{-1.50}}$

Surprisingly small scatter
Significantly steeper than $T^2$

cf. Allen & Fabian 1998
What is a control parameter?

The normalization factors are significantly different between two subgroups.
$L_X-T$ and core radius

$\log(L_{1\text{keV}}) = \log(L_{\text{bol}}/(kT)^{3.01})$

$\log(L_{\text{bol}}) = \log(L_{1\text{keV}}) = \log(L_X) = \log(L) = \log(\text{erg/s})$

$L_X \propto T^{3.01} \pm 0.49$

Systematic difference between two groups

Approximately $L_X \propto T^3 r_c^{-1}$

c.f. Fabian et al. 1994

$L_X \propto T^{3.3} \cdot M\dot{\nu}^{0.4}$
X-ray fundamental plane analysis

Planar fitting in the \((n_{e0}, T, r_c)\) space

- Fundamental plane for the distant sample is consistent with that obtained for nearby clusters (Fujita & Takahara 1999)
- The principal axis

\[
Z \propto n_{e0}^{1.20} T^{-0.69}
\]

\[
\propto t_{\text{cool}}^{-1.2} \implies t_{\text{cool}} \propto T^{1/2}/n_{e0}
\]

\(t_{\text{cool}}\) is likely to be a control parameter!
2. Impact of cooling on the $L_X-T$ relation

i) $L_X-T$ and gas density profile

ii) $L_X-T$ and cooling

iii) $L_X-T \beta$ and X-ray morphology
$t_{\text{cool}} - r_c$ and $T - n_{e0}$

t_{\text{cool}}$ is tightly correlated with $r_c$

For all small core clusters, $t_{\text{cool}} < t_H \rightarrow$ cooling is effective

$n_{e0}$ is higher for smaller $r_c$

$\rightarrow$ central concentration as gas cools

No clear difference in T ranges $\rightarrow$ evidence against the standard CF.

The average T is 30% smaller $\rightarrow$ mild temperature decrease in small core clusters.
$L_X - T$ and cooling time

For $\log(t_{\text{cool}}/t_{\text{age}}) < -0.5$, $L_{1\text{keV}}$ is systematically higher.
Estimation of ambient temperature, $T'$

Assumptions:
- Universal temperature profile; $T(r) \propto r^{0.2}$ (Tamura et al. 2001)
- $\beta$-model; $\beta=0.7$, $r_c=50$ kpc

$\rightarrow T' \sim 1.3 \ T$

$T$ underestimates $T'$ by $30\%$ ~ comparable to the difference in average $T$ between two $r_c$ groups.

Apply $T'=1.3T$ for 26 clusters with $\log(t_{\text{cool}}/t_{\text{age}})<-0.5!$
Tamura et al. (2000)

Fig. 1. Properties of the ICM as a function of projected radius derived from the PN and MOS spectra based on a single temperature model. From top to bottom, absorbing column density, temperature, metal abundance, and the deprojected hydrogen density were shown, respectively. The PN and MOS results were shown by diamonds and crosses, respectively.
$L_X - T'$ and cooling time

$\alpha = 2.34 \pm 0.29$

Small scatter!
No difference between two groups.

$\frac{L_{1\text{keV}}}{(kT)^{2.80 \pm 0.28}}$

$L_{1\text{keV}} \sim \text{constant for a wide range of } t_{\text{cool}}$

cf. Fukazawa et al. 2004
Comparison of $L_{1\text{keV}}$ distribution

$L_x-T$

\[ \frac{\sigma}{\mu} = (7.0 \pm 1.2) \times 10^{-3} \]

$L_x-T'$

The dispersion significantly decreases.

\[ \frac{\sigma}{\mu} = (3.3 \pm 0.9) \times 10^{-3} \]

\[ \frac{\sigma}{\mu} = (3.5 \pm 0.5) \times 10^{-3} \]

\[ \frac{\sigma}{\mu} = (4.2 \pm 0.7) \times 10^{-3} \]
Gas cools but ...

$L_{1\text{keV}} \sim$ constant for a wide range of $t_{\text{cool}}$

- The standard CF model predicts cooling that accelerates as time

- Our result showed luminosity $\sim$ a rate of thermal energy loss is kept nearly constant even after the onset of cooling

→ This suggests some steady-state of gas is realized in small core clusters.
Possibility of quasi-hydrostatic state

🌟 Quasi-hydrostatic model (Masai & Kitayama 2004)
- describes gas under radiative cooling supposing a moderate and smooth gas inflow so as to compensate the thermal pressure loss and keep local hydrostatic balance.
- Predicted temperature profile
  - central temperature \(~\frac{1}{3}\) the ambient temperature
- Mass inflow is expected not vary very much

→ Our results can be consistently understood within a framework of the quasi-hydrostatic model.
2. Impact of cooling on the $L_X-T$ relation

i) $L_X-T$ and gas density profile

ii) $L_X-T$ and cooling

iii) $L_X-T \beta$ and X-ray morphology
Virial temperature under $\beta$-model

Under the virial theorem and the $\beta$-model,

$$T_{\text{vir}} = T_{\text{gas}} \beta \frac{x^2}{(1+x^2)} \sim T_{\text{gas}} \beta \ (x \equiv r_{\text{vir}}/r_c \gg 1)$$

We examine $L_X - T\beta$ and $L_X - T'\beta$ and discuss the relevance to X-ray morphology.

$\beta$; slope parameter determined from the ROSAT radial profile fitting
$L_X \propto T^{3.01^{+0.49}_{-0.44}}$

$\sigma/\mu = (7.0\pm1.2)e^{-3}$

$\sigma/\mu = (4.2\pm0.7)e^{-3}$

$L_X \propto (T\beta)^{2.67^{+0.44}_{-0.44}}$

$\sigma/\mu = (4.6\pm0.7)e^{-3}$

$\sigma/\mu = (10.8\pm7.8)e^{-3}$

$\sigma/\mu = (4.6\pm0.7)e^{-3}$

$\sigma/\mu = (10.8\pm7.8)e^{-3}$
5 clusters with very large core >400kpc show signatures of merging or cold front in the surface brightness

Merging clusters segregate from the regular clusters on the $L_X-T\beta$ plane.
Morphological change along $r_c$-axis
$L_X \propto (T'\beta)^{2.54^{+0.29}_{-0.26}}$

$\sigma/\mu = (2.7\pm0.5)e^{-3}$ for Reg.

$\sigma/\mu = (6.7\pm1.6)e^{-3}$ for Irr.

Morphological change along $t_{\text{cool}}$!
Discussion
Three phases of ICM evolution

(i) \( t_{\text{cool}} < t_{\text{age}} \) Irregular, Large \( r_c \)

(ii) \( t_{\text{age}}/3 < t_{\text{cool}} < t_{\text{age}} \)
    Regular, Large \( r_c \)

(iii) \( t_{\text{cool}} < t_{\text{age}}/3 \) Regular, Small \( r_c \), Double-\( \beta \) appears!
After cluster collapses, $t_{\text{cool}}$ falls below $t_{\text{age}}$, core is radiatively cooled with keeping quasi-hydrostatic balancing, and the central density becomes higher to evolve from an outer-core-dominant cluster to inner-core-dominant cluster.
Summary
Summary and future observations

Based on the ROSAT & ASCA distant sample, we showed:
1. $L_X$–$T$ and gas density profile
2. $L_X$–$T$, $L_X$–$T'$ and $t_{\text{cool}}$
3. $L_X$–$T\beta$, $L_X$–$T'\beta$ and X-ray morphology
   → Cooling has a significant impact on the Lx-T. The results can be consistently understood within a framework of quasi-hydrostatic model.

Things to be further studied
1. Temperature profiles are not directly constrained
2. Detailed calc. on density profile under quasi-static model
3. Heating

Future observations
1. High-resolution SZ+X
2. Astro-E2