Temperature Structure in the Perseus Cluster Core Observed with Hitomi

S. Nakashima (RIKEN), K. Matsushita, K. Sato, M. Furukawa (TUS), A. Simionescu, T. Tamura (ISAS), Y. Kato (U. Tokyo), N. Werner (Masaryk U.), M. Bautz (MIT), and the Hitomi collaboration
Temperature structure of Perseus cluster

- Central gas density $\sim 10^{-2} \text{ cm}^{-3}$ $\Rightarrow$ Cooling time $\sim 10 \text{ Gyr} < \text{Cluster age}$
- How to sustain the hot gas in the cluster core?
  - Feedback from the AGN in the cD galaxy? (e.g., McNamara+07)
  - Energy transfer from moving member galaxies? (e.g., Makishima+01, Gu+13)
  - Cosmic-ray streaming with Alfven waves? (e.g., Fujita+13)
- Actual temperature structure might be more complicated (multi-phase, NEI, etc.).
• Multi-phase gas (0.5–8 keV) is detected at the central region in addition to possible power-law component.

• Temperature is determined by a continuum and Fe-K/L lines in the CCD spectrum => Subject to uncertainties of the effective area calibration and atomic code.

• High resolution spectroscopy will reveal more precise temperature structure
XMM-Newton/RGS result

- Resolve emission lines in the 0.5-2.0 keV band.
- Reproduced by 0.6 keV + 2.3 keV plasma model.
- Not sensitive to >3 keV gas.
Hitomi X-ray observatory

- Launched Feb. 2016 (but accident of attitude control on Mar. 2016)
- Unprecedented $E/\Delta E \sim 1200$ @6 keV (cf. $E/\Delta E \sim 40$ for CCD)
Hitomi observations of the Perseus cluster

- Four observations covering the central ~7 arcmin region: 340 ks in total.
- Mainly focus on the Entire Core (obs2+obs3+obs4) region in this talk.

**Table 1: List of observations.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Observation ID</th>
<th>$\alpha_{2000.0}$</th>
<th>$\delta_{2000.0}$</th>
<th>Observation Date</th>
<th>Effective Exposure</th>
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<tbody>
<tr>
<td>Hitomi/SXS</td>
<td>obs1 100040010</td>
<td>49.878</td>
<td>41.484</td>
<td>2016-02-24 – 2016-02-25</td>
<td>49 ks</td>
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<tr>
<td></td>
<td>obs2 100040020</td>
<td>49.935</td>
<td>41.519</td>
<td>2016-02-25 – 2016-02-27</td>
<td>97 ks</td>
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<tr>
<td></td>
<td>obs3 100040030, 100040040, 100040050</td>
<td>49.936</td>
<td>41.520</td>
<td>2016-03-04 – 2016-03-06</td>
<td>146 ks</td>
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<tr>
<td></td>
<td>obs4 100040060</td>
<td>49.955</td>
<td>41.512</td>
<td>2016-03-06 – 2016-03-07</td>
<td>46 ks</td>
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<tr>
<td>Chandra/ACIS-I</td>
<td>11714</td>
<td>49.928</td>
<td>41.569</td>
<td>2009-12-07 – 2009-12-08</td>
<td>92 ks</td>
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<tr>
<td></td>
<td>0305780101</td>
<td>49.950</td>
<td>41.513</td>
<td>2006-01-29 – 2006-01-31</td>
<td>125 ks</td>
</tr>
</tbody>
</table>

**Fig. 1:** (left) SXS FoVs of the Hitomi observations overlaid on the Chandra X-ray color image in the 1.8–9.0 keV band. The green, cyan, and blue polygons indicate obs1, obs2 and obs3, and obs4, respectively. The 35 square boxes in each FoV correspond to the SXS pixels. The Entire core region covering the whole obs2/obs3 and obs4 is also shown in magenta. (right) Analysis regions used in Section 3.3 overlaid on the same Chandra image. The H$\alpha$ emission obtained with the WIYN 3.5 m telescope (Conselice et al. 2001) is also shown in the black contours. The cyan, blue, and green polygons corresponds to the Nebula, Rim, and Outer regions, respectively. For Nebula and Rim regions, we used slightly different sky regions between obs2/obs3 and obs4; the regions with solid line are for obs2/obs3 and those with dashed line are for obs4 (see text for details).
Hitomi/SXS spectrum

Not sensitive to <2 keV gas, but unprecedented sensitivity for >3 keV gas
Hitomi/SXS v.s. CCD

Detect weak emission lines!
Resolve the S, Ar, and Ca lines!
Hitomi/SXS v.s. CCD

- Ni XXVII Heα (w)
- Fe XXV Heβ
- Fe XXV Heγ
- Fe XXV Heδ
- Fe XXV Heε
- Fe XXVI Lyβ

Lines from higher quantum numbers (up to n=5)
Detection of Fe Kα line from NGC1275

- Detect Fe Kα line. EW ~ 10 eV.
- Redshift ~ 0.01702 ± 0.00060 => consistent with optical measurements
- Velocity width ~ 500-1600 km/s (FWHM) => smaller than Hα velocity (2750 km/s)
- Not from accretion disk nor broad line region, but from molecular torus or a rotating molecular disk.

Fitting with 1T model

- Almost reproduced by the 1T model. (Surprising!)
- Non-equilibrium ionization (NEI) model does not improve the fit.
- More detailed temperature diagnostics with emission lines.
**Temperature diagnostics with line ratios**

Flux ratio of Lyβ to Lyα (or Heβ to Heα) => reflects "excitation temperature"

Flux ratio of H-like line/He-like line => reflects ionization degree

Assuming the ionization equilibrium, we can derive "ionization temperature"
Temperature derived from line ratios

Excitation Temperatures

Ionization Temperature

\( kT \) (keV)

APEC

SPEX

Si Ly\( \alpha /\)Ly\( \alpha \)
S Ly\( \gamma /\)Ly\( \alpha \)
Ar Ly\( \beta /\)Ly\( \alpha \)
Ca He\( \beta /\)He\( \beta \)
Fe He\( \beta /\)He\( \beta \)
Fe He\( \gamma /\)He\( \gamma \)
Fe He\( \delta /\)He\( \delta \)
Fe He\( \epsilon /\)He\( \epsilon \)

Si

S

Ar

Ca

Fe

\(~3\) keV

Observed spectrum is composite of 3-6 keV gases

at most 6 keV

Truly multi-phase? or Projection effect of single-phase?
Combined radial profiles associated with the bubbles of relativistic plasma that push up the X-ray gas. Due to this density drop in figure 7, there is a density drop in the innermost region (the first point from the center) likely region (see also table 3). Right: Optical depth profile of the Fe from Urban et al. (2014).

Chandra data are used in the inner density; middle: deprojected gas electron temperature; bottom: deprojected abundance of heavy elements relative to Solar abundance from Lodders & Palme.

Fig. 7.

Observed line ratios are consistent with the projection model.
**Fitting with 6-T model**

Fit the 6-T model (1, 2, 3, 4, and 8 keV) to the spectrum.

- **Peak temperature depends on the analysis energy band**
  - SXS: 1.8-20 keV
  - ACIS: 0.6-8 keV
  - RGS: 0.5-2 keV

**Upper limit for 8 keV gas**
- **No detection of power-law**

**Need microcalorimeter obs. covering broader band for a complete picture**
Summary

• We observed the Perseus cluster with Hitomi/SXS (~340 ks).

• Utilizing 2-20 keV band pass and resolved emission lines from Si through Ni, SXS achieved unprecedented sensitivity for >3 keV gas.

• The spectrum is almost reproduced by ~4 keV plasma model, but the detailed temperature diagnostic with line ratios reveals that the spectrum is a composite of 3-6 keV gases, which is consistent with the projection effect.

• Neither >8 keV gas or non-thermal component is detected.

• For the precise measurement including <2 keV gases, future observations with microcalorimeter are necessary.