Temperature and Abundance measurements in galaxy clusters with high energy resolution spectroscopy

Marie Kondo
Saitama University
Galaxy Clusters

Hot \((10^7 - 10^8 \text{K})\) X-ray emitting gas (ICM) fills the space between galaxies.

Abundances in the ICM enable us to understand the chemical evolution history and evolution process of the clusters.

- What kind of stars synthesized the heavy elements?

Measurement of temperature structure is directly linked to abundance measurement. We need to measure abundances of all the metals from O to Fe, Ni.

Previous study
- Perseus cluster (Hitomi/SXS, XMM/RGS) Simionescu +19 (Not spatially resolved spectra)

- CHEmical Evolution RGS Sample (CHEERS) e.g., de Plaa +17, Mao+19, Fukushima+23

![Graph showing the ratio of SN Ia/SN cc and abundance ratio compared to Solar values for various elements (O, Ne, Mg, Si, S, Ar, Ca, Cr, Mn, Ni).]
Combination of several detectors

\[ \text{Combination of XRISM/Resolve and XMM-Newton/RGS} \]

\[ \rightarrow \text{high resolution spectroscopy over a wide energy band.} \]
✓ XMM-Newton Reflection Grating Spectrometer (RGS)
  energy range: 5-38 Å (0.35-2.5 keV)

Emission lines are broadened by
\[ \Delta \lambda = 0.138 \frac{\Delta \theta}{m} \text{Å} \]
\[ \Delta \theta : \text{spatial extent of the source} \]
\[ m : \text{spectral order} \]

RGS spectrum can be spatially resolved in the direction of cross dispersion angle.

Combination of XRISM/Resolve and XMM-Newton/RGS
→ broad band spectroscopy, spatial distribution of temperature and abundance profile
Target objects

NGC5044
✓ Nearby bright group with cool core
✓ ICM $\sim 1$ keV
✓ X-ray cavities
✓ Asymmetric temperature structure

Abell 262
✓ Nearby bright cluster with cool core
✓ ICM $\sim 2$ keV
✓ X-ray cavities
✓ Relation between AGN activity and X-ray emission

By using RGS spectrum, I tried to reveal the temperature structure and abundance ratio along the cross dispersion direction.
Spectrum of NGC5044 central region (−6″~6″)

phabs*(rgxssrc*bbvvapec_{high\,kT} + \text{gsmooth}*bbvvapec_{low\,kT})

Line broadening of High kT component
Line broadening of low kT component

velocity broadening (km/s) = 172 (fix)

Ogorzalek+17

NGC5044 0.3-2.0 keV
Spectrum of NGC5044 central region (−6′′~6′′)

\[ \text{phabs}(\text{rgxssrc} \times \text{bvwavec}_{\text{high } kT} + \text{gsMOOTH} \times \text{bvwavec}_{\text{low } kT}) \]

Line broadening of High kT component
Line broadening of low kT component

Velocity broadening (km/s) = 172 (fix)

Ogorzalek+17

rgxssrc model
- Convolve RGS spectrum for extended emission
- I use an image (0.7-2.0 keV)

gsmooth model
- Gaussian smoothing
Spectrum of NGC5044 central region (−6″~6″)

In −6″~6″ region, higher kT component has a more diffuse distribution than lower one.

\[ \text{velocity broadening (km/s) = 172 (fix)} \]

\[ \text{Line broadening of High kT component} \]

\[ \text{Line broadening of low kT component} \]

\[ \text{Data (RGS1⋅2/1st order)} \]

\[ \text{Total model High/low temperature component} \]

\[ \text{phabs*(rgsxsrc*bvvapec}_{\text{high kT}} + \text{gsmooth*bvvapec}_{\text{low kT}}) \]
**Temperature**

\[ \text{phabs} \times (\text{rgsxs rc} \times \text{bvv apec}_{\text{high } kT} + \text{gsmooth} \times \text{bvv apec}_{\text{low } kT}) \]

Cross dispersion angle (arcsec)

- 0.6 \sim 0.8 \text{ keV plasma exists in the central region.}
- \frac{\text{Norm}_{\text{low } kT}}{\text{Norm}_{\text{high } kT}} \sim 10-50\%
O/Fe Abundance

NGC5044

\[ \text{phabs} \ast (\text{rgxssrc} \ast \text{bvwpec}_{\text{high } kT} + \text{gsMOOTH} \ast \text{bvwpec}_{\text{low } kT}) \]

Fukushima +23

- > 1 keV objects

- < 1 keV objects

Abundance table: Lodders+09

\[ \sqrt{\frac{O}{Fe}} \sim \text{Solar} \]

\[ \checkmark \] O/Fe ∼ Solar

\[ \checkmark \] No major discrepancy with previous study
O/Fe Abundance  **XSPEC vs SPEX**  NGC5044

**XSPEC** phabs*(rgsxsrc*bvvapec$_{\text{high } kT}$ + gsmooth*bvvapec$_{\text{low } kT}$)  

**SPEX** hot*lpro*(cie + cie)  

Cross dispersion angle (arcsec)  

**Fukushima +23** > 1 keV objects  

**Fukushima +23** < 1 keV objects  

**Mao+19** NGC5044 (SPEXACT)  

Abundance table: Lodders+09  

NGC5044 0.3-2.0 keV
Combination of XMM-Newton/RGS and XRISM/Resolve

We can realize high resolution spectroscopy over a wide energy band.

Combination of XMM-Newton/RGS (< 2 keV) and XRISM/Resolve

Average abundance ratio (< 60″)

NGC5044
Abell 262

~ Solar

Counts/s/keV

Energy (keV)

XRISM/Resolve spectrum of A262

NH
O
Ne
Mg
Ni

X/Fe (solar)

∼ Solar

200 ksec

Si
Ca
S
Fe
backup
Rgsxs// model was over-extending the O\textsubscript{VIII} line of the low temperature component.
Spectrum of NGC5044

Fit results did not change significantly in SPEX.
Spectrum of NGC5044

\[
\text{phabs}(\text{rgsxsrs} \times \text{bvvapec}_{\text{high} \, kT} + \text{gsmooth} \times \text{bvvapec}_{\text{low} \, kT})
\]

\[
\text{Phabs} \times \text{rgsxsrs} \times (\text{bvvapec}_{\text{high} \, kT} + \text{bvvapec}_{\text{low} \, kT})
\]

Energy (keV)

Counts/s/keV

\[
\chi
\]

Data (RGS1·2/1st order)
Spectrum of NGC5044

XSPEC best fit model

\[ \text{phabs} \ast (\text{rgsxsrc} \ast \text{bvapec}_{\text{high} \, kT} + \text{gsmooth} \ast \text{bvapec}_{\text{low} \, kT}) \]

Data (RGS1⋅2/1st order)

Counts/s/keV

Energy (keV)

0.6 0.7 0.8

\( \chi \)

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

0.6 0.7 0.8

\( \chi \)
NGC5044

0.3-1.0 keV image / 1.0-2.0 keV image

Cross dispersion direction
Abell 262

[Image of Abell 262 with annotations indicating RA, DEC, 0.3-2.0 keV image, Cross dispersion direction, Inner cavity, Outer cavity, Radio emission, and Chandra image of A262 (Clarke+09)].
Differences between XSPEC and SPEX

**XSPEC**

- **Binning:** 1 count/1 bin
- **Statistic:** c-stat

**SPEX**

- **Binning:** Optimal binning
- **Statistic:** c-stat

**Line broadening**

- **XSPEC:** \( \text{phabs*(rgxssrc*bvvapec + gsmooth*bvvapec)} \)
- **SPEX:** \( \text{hot*lpro*(cie + cie)} \)
Table 5. Abundance ratios for NGC 5044 within the extraction region (i.e. \( \leq r/r_{500} \)).

<table>
<thead>
<tr>
<th>X/Fe</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/Fe</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td>O/Fe</td>
<td>0.65 ± 0.05</td>
</tr>
<tr>
<td>Ne/Fe</td>
<td>0.68 ± 0.08</td>
</tr>
<tr>
<td>Mg/Fe</td>
<td>0.77 ± 0.08</td>
</tr>
<tr>
<td>Si/Fe †</td>
<td>0.79 ± 0.10</td>
</tr>
<tr>
<td>S/Fe †</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>Ar/Fe †</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>Ca/Fe †</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>0.72 ± 0.02</td>
</tr>
<tr>
<td>Ni/Fe</td>
<td>1.5 ± 0.3</td>
</tr>
</tbody>
</table>

Notes. Abundance ratios measured with EPIC spectra are labelled with a dagger.
### Table 1. Abundances and abundance ratios within the 3.4 arcmin wide (in the cross-dispersion direction) extraction region.

<table>
<thead>
<tr>
<th>Source</th>
<th>A 3526</th>
<th>M 49</th>
<th>M 87</th>
<th>NGC 4636</th>
<th>NGC 4649</th>
<th>NGC 5044</th>
<th>NGC 5813</th>
<th>NGC 5846</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r/r_{500}$</td>
<td>0.026</td>
<td>0.018</td>
<td>0.012</td>
<td>0.022</td>
<td>0.015</td>
<td>0.034</td>
<td>0.031</td>
<td>0.036</td>
</tr>
<tr>
<td>kpc</td>
<td>43.2</td>
<td>18.7</td>
<td>17.7</td>
<td>15.6</td>
<td>15.6</td>
<td>37.7</td>
<td>26.9</td>
<td>25.8</td>
</tr>
<tr>
<td>Model</td>
<td>NH+2T</td>
<td>GDEEM</td>
<td>2T+PL</td>
<td>2T</td>
<td>1T</td>
<td>GDEEM</td>
<td>2T</td>
<td>2T</td>
</tr>
<tr>
<td>C-stat./d.o.f.</td>
<td>2186/1088</td>
<td>852/544</td>
<td>3954/1111</td>
<td>748/480</td>
<td>1530/1096</td>
<td>1670/1094</td>
<td>2480/1649</td>
<td>1825/1093</td>
</tr>
<tr>
<td>$\sigma_{N/Fe}$</td>
<td>~7$\sigma$</td>
<td>~3$\sigma$</td>
<td>~9$\sigma$</td>
<td>~4$\sigma$</td>
<td>~3$\sigma$</td>
<td>~5$\sigma$</td>
<td>~3$\sigma$</td>
<td>~3$\sigma$</td>
</tr>
<tr>
<td>N/O</td>
<td>2.7 ± 0.5</td>
<td>2.7 ± 1.0</td>
<td>2.2 ± 0.3</td>
<td>3.3 ± 1.1</td>
<td>2.9 ± 1.0</td>
<td>2.2 ± 0.5</td>
<td>3.2 ± 0.9</td>
<td>2.7 ± 0.8</td>
</tr>
<tr>
<td>N/Fe</td>
<td>1.5 ± 0.2</td>
<td>1.6 ± 0.6</td>
<td>1.8 ± 0.2</td>
<td>1.9 ± 0.5</td>
<td>2.4 ± 0.8</td>
<td>1.4 ± 0.3</td>
<td>1.9 ± 0.4</td>
<td>2.3 ± 0.7</td>
</tr>
<tr>
<td>O/Fe</td>
<td>0.54 ± 0.04</td>
<td>0.59 ± 0.10</td>
<td>0.82 ± 0.03</td>
<td>0.59 ± 0.08</td>
<td>0.84 ± 0.11</td>
<td>0.65 ± 0.05</td>
<td>0.58 ± 0.07</td>
<td>0.86 ± 0.12</td>
</tr>
<tr>
<td>Ne/Fe</td>
<td>0.57 ± 0.06</td>
<td>0.66 ± 0.17</td>
<td>0.55 ± 0.05</td>
<td>0.64 ± 0.12</td>
<td>1.07 ± 0.19</td>
<td>0.68 ± 0.08</td>
<td>0.53 ± 0.09</td>
<td>0.71 ± 0.14</td>
</tr>
<tr>
<td>Mg/Fe</td>
<td>0.66 ± 0.07</td>
<td>0.79 ± 0.19</td>
<td>0.24 ± 0.04</td>
<td>0.64 ± 0.13</td>
<td>1.40 ± 0.23</td>
<td>0.77 ± 0.08</td>
<td>0.83 ± 0.11</td>
<td>0.66 ± 0.14</td>
</tr>
<tr>
<td>Fe</td>
<td>1.02 ± 0.03</td>
<td>1.50 ± 0.12</td>
<td>0.55 ± 0.01</td>
<td>0.66 ± 0.04</td>
<td>0.55 ± 0.03</td>
<td>0.78 ± 0.03</td>
<td>0.92 ± 0.04</td>
<td>0.77 ± 0.05</td>
</tr>
<tr>
<td>Ni/Fe</td>
<td>1.2 ± 0.1</td>
<td>1.8 ± 0.5</td>
<td>0.65 ± 0.07</td>
<td>2.0 ± 0.4</td>
<td>2.5 ± 0.4</td>
<td>1.5 ± 0.3</td>
<td>–</td>
<td>2.0 ± 0.4</td>
</tr>
</tbody>
</table>

**Notes.** Abundances and abundance ratios are given according to the proto-solar abundance of Lodders et al. (2009). Statistical uncertainties (1$\sigma$) are quoted here. Systematic uncertainties on the abundance ratios are estimated in Sect. 4. $\sigma_{N/Fe}$ is the significance level of nitrogen detection according to the N/Fe ratio (to be greater than zero). The uncertainties shown are 1$\sigma$ statistical error bars. 1T, 2T, and GDEEM refer to single-temperature, two-temperature, and multi-temperature DEM distribution (Sect. 3). For A 3526, “NH” refers to a free Galactic hydrogen column density in the spectral analysis. The Galactic hydrogen column densities for the other seven systems are frozen to literature values. For M 87, we use a power law to model the non-thermal component, which varies between the two observations (Werner et al. 2006a). For NGC 5813, the Ni abundance cannot be constrained, and we fix it to solar during the fitting.
Previous study

Mernier et al. 2022 (NGC 1404)

Figure 6. Best-fitting temperatures (kT), Fe abundances, and X/Fe abundance ratios obtained with XMM–Newton/EPIC, RGS, and ACIS within a rectangular region covering the RGS extraction region of the deepest XMM–Newton observation (see the text and Fig. 3). The MOS, pn, and ACIS measurements are obtained over full-band fits for kT and Fe and narrow-band fits for the abundance ratios (see the text).
NGC5044

○ : XSPEC
× : SPEX
NGC5044

- N
- O
- Mg
- Ne
- Fe
- Ni

[Graphs showing data for N, O, Mg, Ne, Fe, and Ni as a function of XDSP_CORR (arcsec).]