High metallicity of the X-ray gas up to the virial radius of a binary cluster of galaxies: evidence of galactic superwinds at high-redshift

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Outline

- Metal Abundance of intracluster medium (ICM) in the outskirts of clusters
  - Suzaku observation of binary clusters A399/A401
  - Metal transfer from galaxies to the ICM
- Ionization equilibrium of the ICM
- Summary
Metal Transfer

- Metals in the ICM come from galaxies
- What transfers metals from the galaxies to the surrounding ICM?
  - Ram-pressure stripping
  - Galactic winds
- Which is the main mechanism?
Ram-pressure stripping

- Galaxies in a cluster are moving in the ICM (~1000 km s⁻¹)
- Metal-enriched gas in the galaxies are stripped by the ram-pressure from the ICM
- Effective in the central region of a cluster
  - Large velocities of galaxies
  - Large density of the ICM
    → Large ram-pressure

Quilis et al. (2000)

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Galactic winds

- Winds from galaxies
  - Supernova explosions followed by starburst blow winds of metal-enriched gas from a galaxy
- Effective in the outskirt of a cluster or in an immature cluster
  - External pressure from the ICM, which prevents the development of the winds, is small
Outskirts of clusters

- Metal abundance of the ICM in the outskirts of clusters tells us which mechanism is important for metal transfer from galaxies to the ICM
  - Ram-pressure stripping
    - Almost no metals in the outskirts
  - Galactic winds
    - There should be some amount of metals in the outskirts
However …

- Suzaku has a low background
  - It is the best instrument to observe the dim outskirt
  - Temperature of the ICM around the virial radius has been measured for several clusters

- Even with Suzaku, measurement of the metal abundance at the outskirt of clusters is extremely difficult
  - Many photons are required
A399/A401

- Binary clusters with a projection distance of ~3 Mpc
  - Redshift
    - 0.0718 (A399)
    - 0.0737 (A401)
  - Temperatures in their central regions
    - 7.23 keV (A399)
    - 8.47 keV (A401)
  - Massive clusters
  - In the early stage of a cluster merger

ROSAT X-ray image. Dashed lines are the virial radii. Blue square is the Suzaku field.

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We observed the link region between the two clusters.

The region is brighter than that is expected from simple superposition of the two clusters.

- The clusters are interacting.
- The ICM in the link region seems to be compressed.
- In spite of the distance from the cluster centers ($\gtrsim 1$ Mpc), the region is bright.

Surface brightness profiles along a 1-arcmin wide stripe that intersects the two cluster centers (Sakelliou & Ponman 2004).
We observed a region where the virial radii of the two clusters ($r = r_{\text{vir}}$) cross each other.

- Exposure time: 150 ks

ROSAT X-ray image. Dashed lines are the virial radii. Blue square is the Suzaku field.
Results

- Temperature and metal abundance
- Abundance in this region (close to the virial radii) is not much different from that at the cluster centers
  - $Z \sim 0.2 \, Z_\odot$
Cluster Merger

- Are A399/A401 have already passed each other?
  - The ICM has been mixed up and the metal abundance has become uniform up to the virial radii? 
  - No!
Cluster Merger

- Simulations
  - At a collision, dark matter and galaxies can pass the other cluster because they are collision-less
  - The ICM cannot
    - The ICM is stripped from dark matter and galaxies
    - This not the case for A399/A401

Simulation of a cluster merger (gas distribution)

Takizawa (1999)

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What do we know from the high metal abundance?

- Ram-pressure stripping (RPS) is not the main mechanism of metal transfer from galaxies to the ICM
  - RPS is not effective in the outskirts of a cluster
  - In the outskirt region, the ICM density is $\sim 3.4 \times 10^{-4}$ cm$^{-3}$
  - RPS requires $v_{\text{rel}} > 2000$ km s$^{-1}$, which is unlikely to be achieved in the region far from the cluster centers
    - RPS cannot explain the metal abundance we found

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Condition of Ram-Pressure Stripping

\[ \rho_{\text{ICM}} v_{\text{rel}}^2 \]

\[ > \]

\[ = \]

\[ = 2.1 \times 10^{-11} \text{dyn cm}^{-2} \left( \frac{v_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2 \]

\[ \times \left( \frac{R}{10 \text{ kpc}} \right)^{-1} \left( \frac{\Sigma_{\text{HI}}}{8 \times 10^{20} \text{ m}_\text{H} \text{ cm}^{-2}} \right), \]

\[ \rho_{\text{ICM}} : \text{ICM} \]

\[ v_{\text{rel}} : \text{galaxy velocity} \]

\[ v_{\text{rot}} : \text{galaxy rotation velocity} \]

\[ R : \text{radius of a galaxy} \]

\[ \Sigma_{\text{HI}} : \text{column density of galaxy gas} \]

(Gunn & Gott 1972; Fujita & Nagashima 1999)

- Ram-pressure stripping is effective when
  - the galaxy is moving fast in the ICM
  - and/or the density of the ICM is large

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Galactic winds?

- They are not effective mechanism at least recently \((z \sim 0)\) inside the clusters
  - Energy of a galactic wind: \(E_w \sim 10^{60}\) erg
  - The distance to which a wind can reach against the pressure from the surrounding ICM: \(d_w\)
    - \(E_w \sim (4 \pi/3) P d_w^3\)
    - \(P\) : ICM pressure, \(P = n k T\)
Galactic winds?

- For typical values of $n$ and $T$ inside a typical cluster

$$d_w \sim 86 \left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right)^{-1/3} \left( \frac{T}{8 \text{ keV}} \right)^{-1/3} \left( \frac{E_w}{10^{60} \text{ erg}} \right)^{1/3} \text{kpc}$$

- Much smaller than the cluster size ($\sim 2 \text{ Mpc}$)
- Galaxies concentrated at the cluster centers ($\approx 0.5 r_{\text{vir}}$) at present cannot blow metals off to close to the virial radii
Theoretical Predictions

- Numerical simulations often predict centrally concentrated abundance distributions in comparison with observations.

Lines: theory
Dots: observations (average of 12 clusters)
(Tornatore et al. 2004)
Galactic Superwinds?

- The abundance profile becomes flatter, if winds blow before the clusters grow \((z \sim 1-2)\) and are strong enough.
  - Supernova explosions alone may not be enough?
  - Contribution of AGN activities?
    - So-called “superwinds” (e.g. Moll et al. 2007)
Caution

- We observed a special region around the clusters
  - Link region
- The observed abundance may reflect that of the cosmological filament that had connected the two clusters
  - The abundance may relate to preprocessing of galaxies in the filament (Fujita 2004)
Ionization equilibrium

- We assumed ionization equilibrium
- Gas density is very small in the outskirt of a cluster
  - $n \sim 10^{-4}$ cm$^{-3}$
- The timescale required to reach collisional ionization equilibrium for an ionizing plasma is long
  - $\sim$ Gyr
  - Comparable to the timescale of a cluster merger
  - Non-ionization equilibrium?
Ionization equilibrium

- Numerical simulation
  - Two-temperature
    - Electron and ion temperatures can be different
  - The ICM is in non-equilibrium state only at passing shocks
    - It does not affect our Suzaku observations
      - Future shock observations would be interesting

The ratio of the Fe XXV fraction relative to that in the ionization equilibrium state (Akahori & Yoshikawa 2008)
Summary

- We observed the link region between A399 and A401 with Suzaku
  - The metal abundance of the ICM is not much different from that in their central regions ($Z \sim 0.2 \ Z_\odot$)
    - Ram-pressure stripping is not the main mechanism of metal transfer from galaxies to the ICM
    - Strong galactic winds (superwinds) might have blown at high-redshifts

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