Suzaku Observations of the Outskirts of A399/A401

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Outline

- Metal Abundance of intracluster medium (ICM) in the outskirts of binary clusters, A399/A401.
  - Metal transfer from galaxies to the ICM
- Warm-hot intergalactic medium (WHIM)
  - Missing baryon around clusters
- Summary
Metal Transfer

- Metals in the ICM come from galaxies
- What transfers metals from 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)
Galactic winds

- Winds from galaxies
  - Supernova explosions followed by starburst cause 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
A399/A401

- Binary clusters with a projection distance of ~3 Mpc
  - Redshift
    - 0.0718 (A399)
    - 0.0737 (A401)
  - Temperature in their central regions
    - 7.23 keV (A399)
    - 8.47 keV (A401)
    - (Sakelliou & Ponman 2004)
  - 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.
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.
- Compressed filament gas?
  - Some of the gas was in a cosmological filament that had connected the two clusters.
- In spite of the distance from the cluster centers (τ1Mpc), the region is bright.
  - Suitable to study the nature of the ICM in the outermost region of clusters.

Surface brightness profiles along a 1-arcmin wide stripe that intersects the two cluster centers (Sakelliou & Ponman 2004)
Suzaku Observation

- Suzaku XIS
  - High sensitivity
  - Low background
- We observed a region where the virial radii of the two clusters ($r = r_{\text{vir}}$) cross each other
- With Chandra and XMM-Newton, $r < 0.5r_{\text{vir}}$ is the limit for the observation of metal abundance of the ICM

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

- No prominent objects
  - No group of galaxies that could eject metals
  - For regions A and B, we analyzed the spectra
Spectrum

- Spectrum for region A
  - Summed spectrum of the three FI chips
    - Exposure time is 150 ks
  - Fe K is clearly seen

Cross: observations
Red line: fitting results
Green line: ICM
Blue line: other components (Galactic, CXB)
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 clusters that have passed each other?
  - The ICM is mixed up and the metal abundance becomes uniform?
  - No!

- **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)

Poole et al. (2006)
Object that Eject Metals?

- Suzaku image
  - No objects that can eject large amount of metals
- Abundance is almost the same between region A and B
  - Abundance is uniform at least on a scale of ~1 Mpc
    - High Abundance is not a local phenomenon
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
    - Condition of RPS

$$\rho_{\text{ICM}} v_{\text{rel}}^2$$

$$> 2\pi G \Sigma \Sigma_{\text{HI}}$$

$$= v_{\text{rot}}^2 R^{-1} \Sigma_{\text{HI}}$$

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

$$\times \left( \frac{R}{10 \text{ kpc}} \right)^{-1} \left( \frac{\Sigma_{\text{HI}}}{8 \times 10^{20} m_{\text{H}} \text{ cm}^{-2}} \right)$$

- In the outskirt region, the ICM density is $\sim 3.4 \times 10^{-4} \text{cm}^{-3}$
  - RPS requires $v_{\text{rel}} > 2000 \text{ km s}^{-1}$ and it is unlikely to happen in the region far from the cluster centers

\(\rho_{\text{ICM}}\): ICM
\(v_{\text{rel}}\): galaxy velocity
\(v_{\text{rot}}\): galaxy rotation velocity
\(R\): radius of a galaxy
\(\Sigma_{\text{HI}}\): column density of galaxy gas

(Fujita & Nagashima 1999)
Galactic winds?

- At least they did not happen recently (z~0) inside the clusters
  - Energy of a galactic wind: \( E_w \sim 10^{60} \text{ erg} \)
  - The distance to which a wind can reach against the pressure from the surrounding ICM: \( d_w \)
    - \( E_w \sim (4 \pi/3) P d_w^3 \)
    - \( P : \text{ICM pressure, } P = n k T \)
  - 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 (~2 Mpc)
  - It is difficult for galaxies concentrated at the cluster centers (< 0.5 \( r_{\text{vir}} \)) at present to blow metals off to close to the virial radii
Theoretical Predictions

- Abundance distributions simulated with standard parameters for star formation
- Steep abundance gradient

Tornatore et al. (2004)
Galactic Superwinds?

- Metals cannot reach the outskirts of a cluster through galactic winds after the cluster has grown up because the surrounding pressure is large.
  - Winds must blow before the clusters grow ($z \sim 2$) and must be strong enough.
  - Supernova explosions alone may not be enough?
  - Contribution of AGN activities?
    - So-called “superwinds”
Simulations for WHIM

- Yoshikawa et al. (2001)

Fig. 2. — Simulated distribution of matter in the universe: Upper-left: dark matter, Upper-right: galaxies (cold baryon clumps below $T^*=K$), Lower-left: hot intra-galactic medium ($T>10^4K$), and Lower-right: warm-hot intergalactic medium ($10^2K < T < 10^3K$). The size of the plotted boxes corresponds to $30h^{-1}$Mpc $\times 20h^{-1}$Mpc with the depth of $10h^{-1}$Mpc.
Observations of WHIM

- The region we observed was probably a cosmological filament that had connected the two clusters.
  - WHIM may remain around the region.
  - WHIM could be observed in the line of sight.
Spectrum

- Spectrum obtained by XIS BI
  - At the redshift of the clusters, O VII line should be observed at $E = 0.53$ keV
  - No line is seen

Cross : observations
Red line : fitting results
Green line : ICM
Blue line : other components (Galactic, CXB)
Upper limit of WHIM

- Assuming $T = 2 \times 10^6$ K

$$n_H = 9.2 \times 10^{-5} \text{cm}^{-3} \left( \frac{I}{1 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}} \right)^{1/2} \left( \frac{Z}{0.1 Z_\odot} \right)^{-1/2} \left( \frac{L}{1 \text{Mpc}} \right)^{-1/2}$$

- $I$: line intensity, $Z$: abundance, $L$: depth in the line of sight
- Observation
  - $I < 8.0 \times 10^{-8} \text{ photons cm}^{-2} \text{ arcmin}^{-2}$
  - $n_H < 4.1 \times 10^{-5} \text{ cm}^{-3}$ (for $Z = 0.2 Z_\odot$, $L = 2 \text{ Mpc}$)
Results

- For O VII line from WHIM
- We obtained a strict upper limit

This Work

\[ I \left( 10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} \text{arcmin}^{-2} \right) \]

- Finoguenov et al. 2003
- Kaaste et al. 2003

Coma-11, Sersic, MKW3s, A2052, Galactic, Lumb, Offset-A, A2218

Takei et al. (2007)

Suzaku
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-redshift
      - The abundance may reflect that of gas in a cosmological filament
  - We could not detect WHIM in the link region
    - However, we obtained a strict upper limit