Thermodynamical Properties of Three X-ray Low Surface Brightness Clusters

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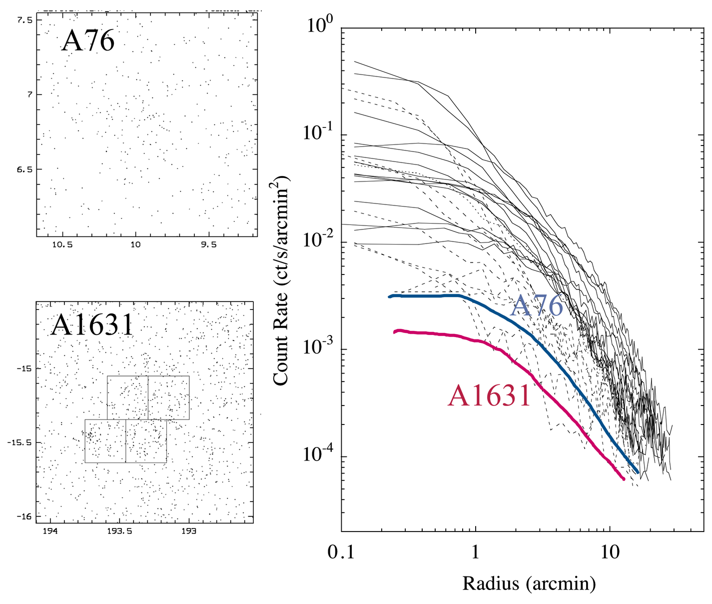
We present results of Suzaku and XMM-Newton observations of three nearby galaxy clusters, A76, A1631, and A2399 (Ota et al. 2013; Babazaki et al. 2018; Mitsuishi et al. 2018). They are classified as low X-ray surface brightness (LSB) clusters and have highly diffuse X-ray emission. So far, only several LSB clusters have been identified, which make up 5-10% of the RASS cluster sample. To study their dynamical state, we derived radial profiles of gas temperature, density, and entropy out to large radii with Suzaku. Common to all three objects, the gas density is extremely low for the observed high temperature. The entropy profile is flat and the central entropy is exceptionally high (~300-400 keV cm^2), which is not readily explained by either gravitational heating or preheating. The X-ray morphology is clumped and irregular, and the spatial distributions of gas and galaxies appear to be different. In addition, we discovered a cold front in A2399. Based on the results, we suggest that a post-merger scenario may explain the observed properties of the LSB clusters. We will briefly discuss prospects for future study of this class of clusters with eROSITA.

1. Introduction

❖ What is the LSB cluster of galaxies?

- A type of cluster that has an extremely low X-ray surface brightness (typically~10^{-14} erg s^{-1}cm^{-2}arcmin^2 in the 0.1–2.4 keV) and irregular morphology with no prominent core
- Several LSB clusters have been identified, which make up 5–10% of the RASS cluster sample [1]. Three LSB clusters in the REXCESS sample [2] tend to show a high central entropy(≥200 keVcm^2) ➜*Their evolution remains a puzzle.*



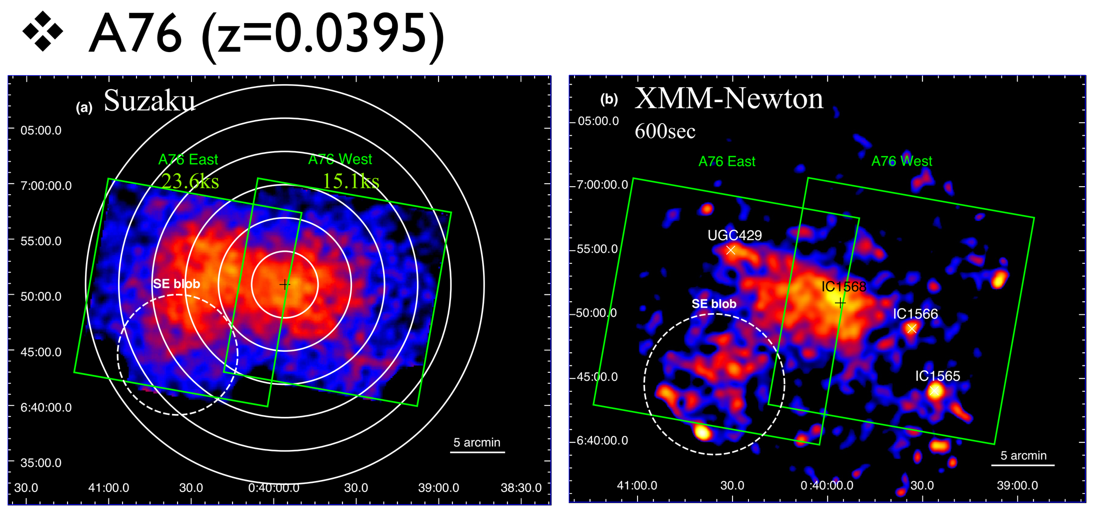
❖ Purpose of this work

- To explore the thermodynamical properties of three LSB clusters based on Suzaku and XMM-Newton observations
- To briefly discuss prospects for the upcoming eROSITA cluster survey

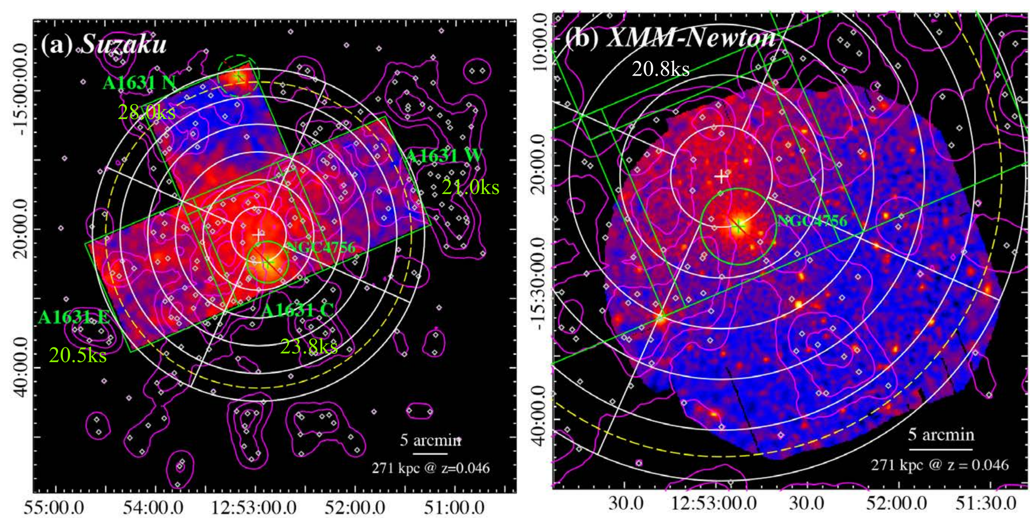
Fig. 1 (left) LSB clusters, A76 and A1631, as seen in the ROSAT All-Sky Survey. (right) X-ray surface brightness of nearby clusters obtained with ROSAT [3]

2. Observation

❖ A76 (z=0.0395)



❖ A1631 (z=0.046)



❖ A2399 (z=0.058)

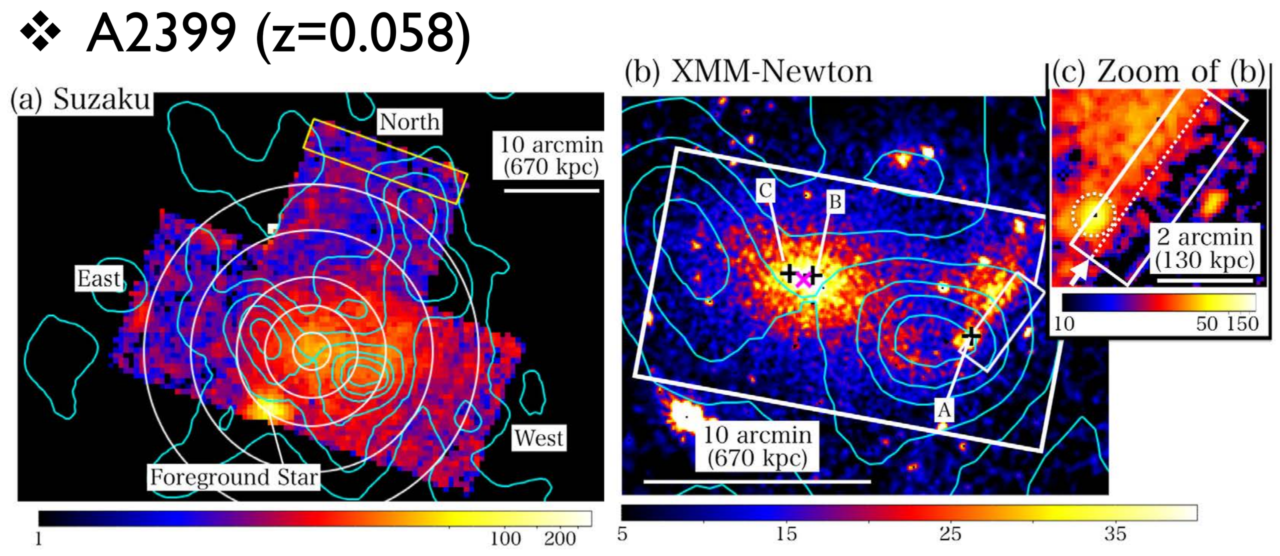


Fig. 2 (a) Suzaku and (b) XMM-Newton images of three LSB clusters, A76 (left), A1631(middle), and A2399 (right). The green box shows Suzaku/XIS field of view in each pointing observation. The spectral integration regions for the deprojection analysis (§ 3) are shown by the white circles.

+: X-ray peak, +: foreground elliptical galaxy
Magenta contours: distribution of member galaxies [4].

X: X-ray peak, +: The 1st, 2nd, 3rd brightest galaxy are denoted by A, B, C, respectively. Cyan contours: distribution of member galaxies [4].
We discovered a clear discontinuity in the surface brightness and temperature distributions in the western gas clump (panel c).

3. Analysis and results

❖ Spectral deprojection analysis

- Simultaneous fit of Suzaku/XIS annular spectra assuming the APEC model [5] and a spherical symmetry
- The gas entropy, $S = kT\,n_e^{-2/3}$, is evaluated from the temperature and density

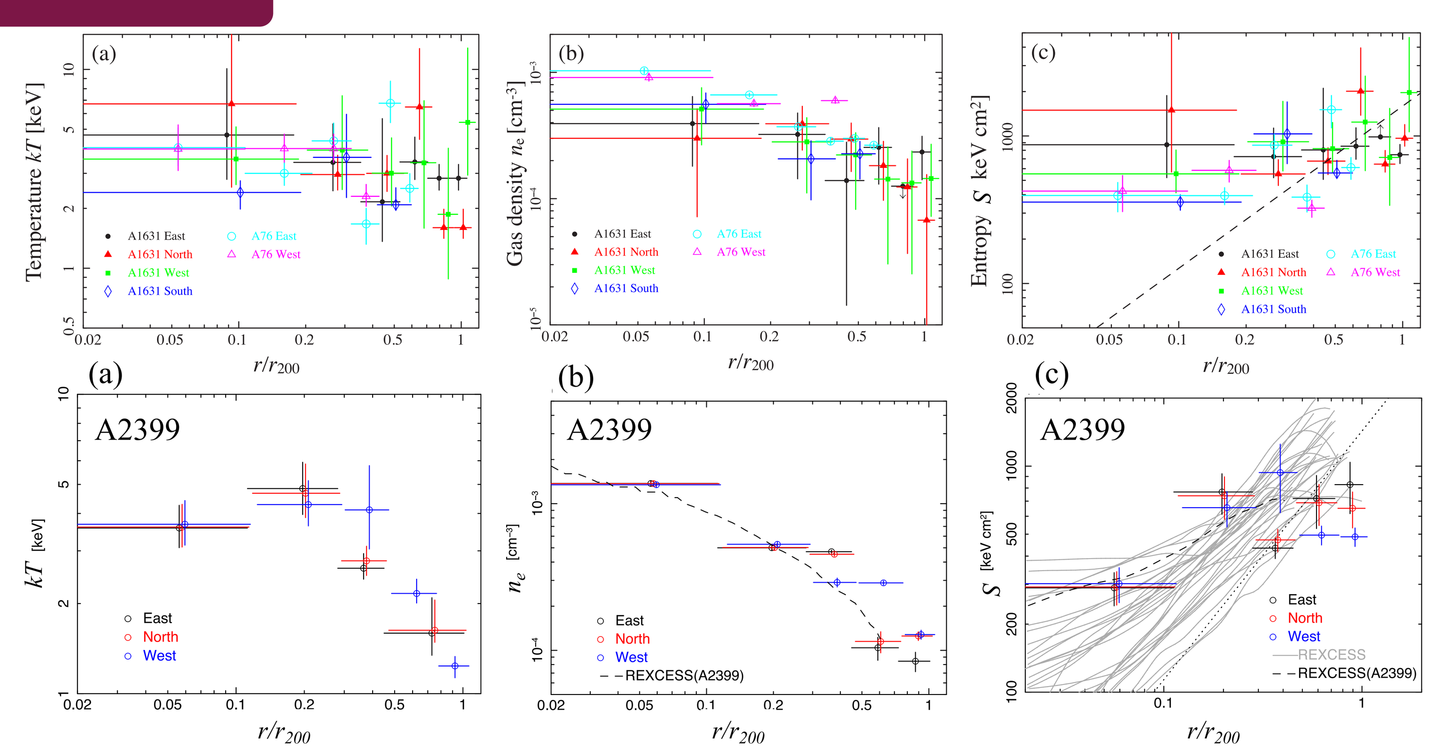


Fig. 3 (a) Temperature, (b) electron density and (c) entropy profiles derived from Suzaku deprojection analysis [6,7,8]. The errors indicate the 90% confidence intervals.

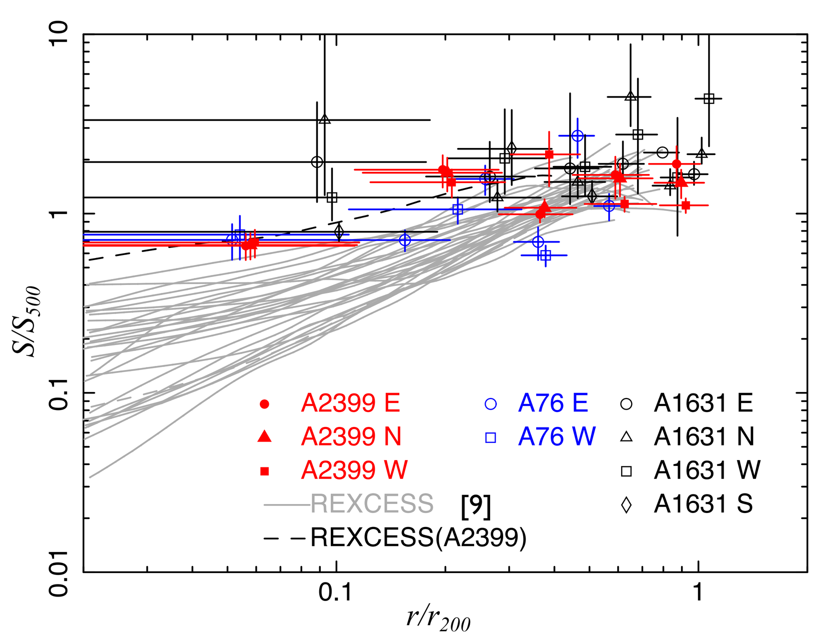


Fig. 4 Scaled entropy profiles of A2399 (red), A76 (blue), and A1631 (black) as derived from the Suzaku analysis [8].

4. Discussion

❖ Summary of observed properties in three LSB clusters

1. Flatter radial profile of gas temperature, and entropy (Fig. 3)
2. Very high entropy ~300–400 keVcm^2 at $r < 0.1r_{200}$ (Figs. 3, 4)
3. A factor of 2–3 deviations from the scaling relations of nearby clusters, *S–T* (Fig. 5), *L–T*, *σ–L*
4. Clumpy galaxy distributions (Fig. 2)
5. Large offset between gas and galaxy distributions (Fig. 2)
6. Temperature and brightness discontinuity ➜ Cold front in A2399 (Fig. 2; see [8] for details)

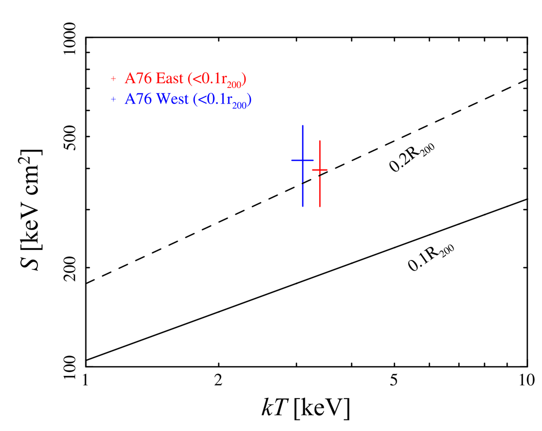


Fig. 5 Entropy-temperature relation. The Suzaku results for A76 (crosses) and the S-T relation of 10 relaxed clusters at $0.1/0.2r_{200}$ (solid/dashed line)[9].

❖ What is the origin of the central high entropy?

- Gravitational heating [10] ~100–150 keVcm^2
- Preheating [11] ~140 keVcm^2
- AGN heating [12] ~1 keVcm^2 ➜ Unlikely

❖ Possible scenario – a post merger –

- The observed characteristics incl. complex morphologies support that the LSB clusters are in some stage of merging.
- The hydrodynamical simulations suggest that the excess entropy can be attributed to ICM mixing during a cluster merger [13]

5. Prospects for the eROSITA survey

- eROSITA simulations of LSB clusters by *SIXTE* version 2.5.10 [14]
  - Cluster: XMM image, the APEC model with 3 keV & 0.2 solar, 0.2–4.5keV flux of 1.1×10^{-11}/5.1×10^{-12} erg s^{-1}cm^{-2}arcmin^2 for A76/A2399
  - Background: GXB, CXB + particle background [15]

  ➜ The count rates are estimated as 7.3/3.9 counts sec^{-1} for A76/A2399.
- eROSITA will detect a large number of clusters including faint ones [16]. Thus, it is important to understand the nature of LSB clusters, which may not follow the mass-scaling relations of bright clusters.

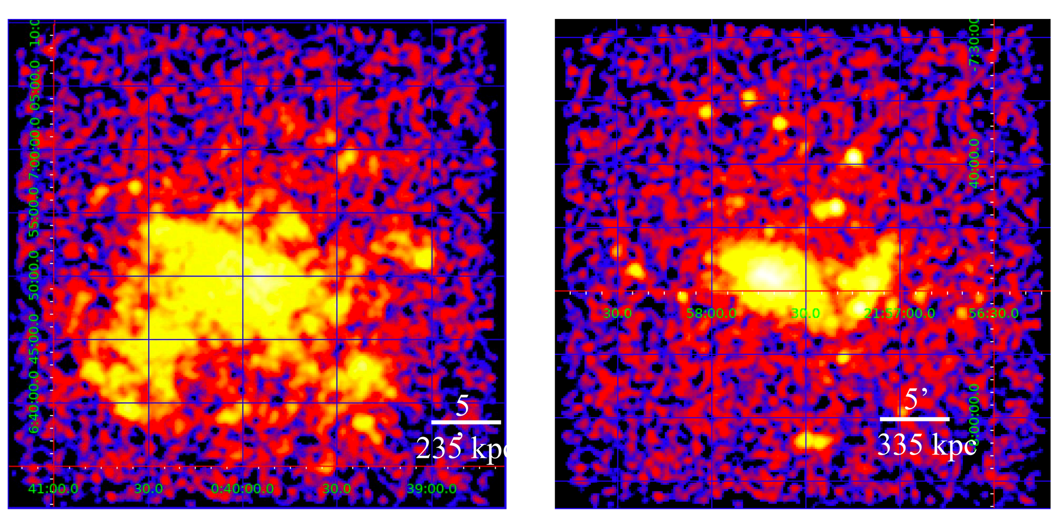


Fig. 6 Simulated eROSITA images of the LSB clusters, A76 (left) and A2399 (right). The exposure of 2 ks is assumed

References

[1] Böhringer et al. 2001, A&A, 369, 826; [2] Böhringer et al. 2007, A&A, 469, 363; [3] Neumann & Arnaud 1999, A&A, 348, 711; [4] Moretti et al. 2017, A&A, 599, A81; [5] Smith et al. 2001, ApJ, 556, L91; [6] Ota et al. 2012 A&A, 556, A21; [7] Babazaki et al. 2018, PASJ, 70, 46; [8] Mitsuishi et al. 2018, PASJ, 70, 112; [9] Pratt et al., A&A, 2010, 511, A85; [10] Voit et al. 2005, MNRAS, 364, 909; [11] Ponman et al. 2003, MNRAS, 343, 331; [12] Wang et al. 2010, RAA, 10, 1013; [13] ZuHone 2011, ApJ, 728, 54; [14] https://www.sternwarte.uni-erlangen.de/research/sixte/index.php; [15] Born et al. 2014, A&A, 567, A65; [16] Merloni et al. 2012 arXiv:1209.3114

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