Suzaku Observation of Merging Clusters A222 and A223 (Postprint)

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Abstract

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Full Text

Preamble

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Suzaku Observation of Merging Clusters A222 and A223

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Abstract

Previous X-ray and optical studies of the galaxy cluster pair A222/223 suggested the possible presence of a filamentary structure connecting the two clusters, a result that appears to be supported by subsequent weak-lensing analyses. This filament has been reported to host a primordial warm-hot intergalactic medium that existed prior to being heated by cluster interactions. In this study, we examined the reported emission feature using archival Suzaku observations, taking advantage of its low detector background. Because the expected emission is very weak, we first carefully assessed all potential sources of contamination and then modeled the residual emission. Unfortunately, due to large uncertainties, our results can neither confirm nor rule out the presence of the reported emission feature. We discuss the sources of these uncertainties.

Key words: galaxies: clusters: intracluster medium −X-rays: galaxies: clusters −(cosmology:) large-scale structure of universe

1. Introduction

The cosmic missing baryon problem refers to the discrepancy between the observed baryon content in the local universe and measurements from Cosmic Microwave Background observations, primordial elemental abundances, and the Ly forest (Cen & Ostriker 1999). Cosmological simulations (e.g., Cen & Ostriker 1999; Tuominen et al. 2021) show that these "missing" baryons are predominantly located in large-scale filamentary structures. This diffuse gas is often referred to as the warm-hot intergalactic medium (WHIM) because its temperature ranges from 10 to 10 K (Davé et al. 2001). While significant progress has been made in detecting the warm component of WHIM through O VI absorption line observations (Shull et al. 2012), the hot component remains poorly measured.

Detection of the hot WHIM component is highly challenging in the soft X-ray band (Cen & Fang 2006). Nevertheless, extensive efforts have been made to carry out absorption line observations with X-ray gratings onboard Chandra and XMM-Newton, with positive detections reported (see Fang et al. 2024 for a review), albeit limited to only a few lines of sight. Attempts have also been made to detect X-ray emission from hot WHIM in filaments connecting cluster pairs, with some success (Werner et al. 2008; Sato et al. 2010; Alvarez et al. 2018; Reiprich et al. 2021; Mirakhor et al. 2022). The A222/223 system is particularly interesting in this regard. X-ray emission from a filament connecting the two clusters was reported based on XMM-Newton observations, with a detection significance of about 5 (Werner et al. 2008). The presence of this filament was supported by a weak lensing study that also exceeded 5 significance (Dietrich et al. 2012). Neither member cluster appears relaxed, suggesting that merging or sloshing interactions are occurring in the system (Durret et al. 2010).

In this work, we analyzed archival Suzaku observations of A222/223, leveraging its low particle background to examine the filament emission further. The paper is structured as follows: Section 2 describes the Suzaku observations and data analysis. Section 3 presents constraints on WHIM emission properties from the Suzaku data. Section 4 discusses our findings and compares them with previous studies. Unless otherwise stated, all errors are quoted at the 1 confidence level. We adopt a standard ΛCDM cosmology with H = 70 km s^{1} Mpc^{1}, Ω_M = 0.3, and Ω_Λ = 0.7. In this framework, the angular scale is 3.427 arcsec per kpc at the redshift of 0.21 corresponding to the A222/223 system. The quantities r c and r c represent radii where the mean enclosed density is 200 and 500 times the critical density of the universe, respectively.

2.1. Suzaku Observations

A222/223 was observed by Suzaku on 2010 December 25, as summarized in Table 1 along with Chandra and XMM-Newton observations. Figure 1 [Figure 1: see original paper] presents the vignetting-corrected Suzaku image of the A222/223 cluster pair, where A223 is in the northeast and A222 is in the southwest, with X-ray peaks at (01:37:33.5, −12:59:20.9) and (01:37:55.9, −12:49:21.2), respectively. The virial masses M c of the two clusters, derived from weak lensing analysis, are M c(A222) = ( ) and M c(A223) = ( ) (Dietrich et al. 2012). To assess excess emission in the filament region, we carefully selected regions to quantify contributions from known sources, as shown in Table 2 .

We defined sector regions for cluster emission centered on the X-ray surface brightness peaks, with a222-1 and a223-1 representing the core regions and a222-2 and a223-2 the outskirts (shown in cyan). Sector radii were chosen to be sufficiently large to account for scattered cluster emission, with outer boundaries extending to 1.1r c, where r c are 1.28 ± 0.11 Mpc and 1.55 ± 0.15 Mpc for A222 and A223, respectively. The filament region (fila-box) was defined as a 6.1 × 5.3 arcmin^2 rectangular box positioned on the merging axis connecting the two clusters (marked in yellow), fully encompassed by the outer boundaries of the cluster outskirt regions. This configuration allows assessment of cluster outskirts emission contribution to the filament region. To avoid double counting, we carefully separated the filament, a222-2, and a223-2 regions in their definitions. A sky background region was defined as the area outside the magenta circles marking the 1.1r c boundaries of both clusters. Point sources with 2–8 keV flux exceeding 1.8 × 10^{1} erg s^{1} cm^{2} are marked with green circles and excluded from subsequent analyses.

For Suzaku data reduction, we generally followed the official pipeline for the X-ray Imaging Spectrometers (XIS). We used standard screened event files from the observation and combined events from both the 5 × 5 and 3 × 3 clocking modes. The cutoff rigidity (COR) threshold was set to 8 GV instead of 6 GV. After screening, we examined the light curves and excluded time intervals with count rates exceeding 3 , yielding 82 ks effective exposure time for the XIS0/1/3 detectors. Since the vignetting effect was not accounted for by the xisexpmapgen task, we generated a vignetting map using XISSIM by simulating the vignetting effect with a flat-field input image. We then multiplied the exposure map by the normalized vignetting map to generate the effective exposure time map and divided the counts map by it to produce the count rate map.

2.2. Effects of Scattered Light

Because our primary objective is to detect excess emission in the faint filament region, we must carefully assess all sources of contamination. For Suzaku observations, scattered light is a major concern (Ishisaki et al. 2007). We utilized Chandra data, taking advantage of its superior angular resolution, and the XISSIM simulator to compute scattered light distributions.

We processed the Chandra data using CIAO v4.15 and CALDB 4.11.27. Event and auxiliary files were generated using the chandra-repro task, and all observations were merged. Stowed event files were used as particle background. The resulting image is shown in Figure 2 [Figure 2: see original paper]. To derive cluster surface brightness profiles, we defined cyan regions that avoid the filament region and the A223 subcluster (see Appendix). Point sources detected with wavdetect are shown as green ellipses and excluded from subsequent analyses. The surface brightness profiles in the 0.5–7 keV band are presented in Figure 3 [Figure 3: see original paper] for A222 and A223.

The surface brightness profiles were fitted with a double beta model using pyproffit (Eckert et al. 2020):

$$S(x) = S\,[1 + (x/r\_c,)^2]^{3 \quad \cdot} + S\,[1 + (x/r\_c,)^2]^{3 \quad \cdot} + B$$

where x is the radial distance and B represents the sky background. The best fits are shown in Figure 3 [Figure 3: see original paper], with ^{2} values of 54 (39 dof) and 45 (39 dof) for A222 and A223, respectively. Model parameters are summarized in Table 3 .

The best-fit surface brightness profiles were used to generate input images for the XISSIM simulator, with results shown in Figure 4 [Figure 4: see original paper]. For the simulation, we adopted an absorbed APEC spectral model with a temperature of 3 keV, typical for galaxy clusters of M_tot 3×10^1 M (Finoguenov et al. 2001; Dietrich et al. 2012). We ran the simulation to collect 10 photons for XIS0, XIS1, and XIS3. The simulated images are shown in Figure 5 [Figure 5: see original paper], displaying the distribution of scattered X-rays from each region of interest. Based on these images, we computed the fraction of flux from each "source" region scattered to all other "receiving" regions, with results summarized in Table 4 . Clearly, scattered light effects are significant for all regions and must be properly accounted for in subsequent analyses.

3. Results

A spectrum was extracted from each region of interest and the sky background region. Each spectrum contains contributions from the non-X-ray background (NXB), cosmic X-ray background (CXB), the Local Bubble (LHB), and possibly the Galactic halo (GH), all of which must be carefully modeled to reveal signals of scientific interest.

Non-X-ray background. The NXB spectrum was generated with the xisnxbgen task. Since counts in the 10–14 keV band are dominated by NXB, we used them to scale the NXB spectrum, with uncertainties estimated at approximately 3.6% (Tawa et al. 2008).

Cosmic X-ray background. We used the log N–log S function of AGN derived from the Chandra Deep Field South (CDF-S) survey to estimate the unresolved CXB contribution (Lehmer et al. 2012). Focusing on the 2.0–8.0 keV band, we computed CXB surface brightness using the cxbtools tool (De Plaa 2017). For spectral analysis, we adopted an absorbed power law to model CXB with the photon index fixed at 1.41. We computed uncertainties for the regions of interest as shown in Table 5 , considering three cases: CXB at the mean level (1.26×10^{11} erg s ^{1} cm ^{2} deg ^{2}, referred to as "med"), 1 higher ("hi"), and 1 lower ("lo").

Local Bubble and Galactic Halo. To constrain LHB and possible GH contributions, we included ROSAT All-Sky Survey (RASS) data (Snowden et al. 1997) in our fitting. We extracted an RASS spectrum from an annulus centered at the midpoint along the merger axis of the two clusters, with inner and outer radii of 1° and 2°, respectively. We modeled the spectrum with an APEC component (for LHB), an absorbed APEC component (for GH), and a power law (for CXB), with chemical abundances fixed to 1 Z . While preliminary temperatures for LHB and GH were set to 0.08 keV and 0.2 keV, the best-fit temperatures were found to be 0.092 ± 0.012 keV and 0.196 ± 0.007 keV, respectively, consistent with previous results (Kuntz & Snowden 2000; Yeung et al. 2024 for LHB; Henley & Shelton 2013; Yoshino et al. 2009 for GH).

Scattered light. All regions of interest are affected by scattered light. For spectral analysis, we used an APEC model for this component in each region, with model parameters tied together across all regions. Normalizations were properly scaled according to the ratios shown in Table 4 . For instance, the ratio of scattered flux in a222-2 to flux in a222-1 was determined by the sky areas of a222-1 and a222-2, respectively.

All components except LHB are subject to interstellar absorption in the Milky Way. We adopted the TBabs model for absorption with N_H,tot fixed at 1.62×10^{2} cm ^{2}, a weighted average based on the Swift survey (Willingale et al. 2013). The spectra extracted from the a223-2 and bkg regions show an absorption line feature at approximately 0.65 keV. This feature appears in the XIS1 spectrum but not in XIS0/3 spectra, likely an artifact caused by Optical Blocking Filter (OBF) contamination in XIS1. In subsequent spectral analyses, we simply excluded the 0.55–0.80 keV range from XIS1 spectra.

With spectra optimally binned (Kaastra & Bleeker 2016), we performed joint spectral fits across all regions and instruments to disentangle source and background/foreground components. The best-fit model parameters for background/foreground components are shown in Table 6 , with uncertainties derived from MCMC analysis. Figure 6 [Figure 6: see original paper] displays the spectra and corresponding best-fit models for the regions of interest.

In the cluster outskirt regions (a222-2 and a223-2), CXB contributes most to the X-ray emission, followed by intrinsic cluster emission and scattered light from the cores. The best-fit gas properties are shown in Table 7 . The first set of uncertainties are statistical errors from MCMC analysis, while the second set represents systematic errors associated with uncertainties in CXB contributions (derived by comparing fits in "lo," "mid," and "hi" cases). The temperature is lower in the outskirts than in the core for A223, while it is comparable for A222, showing non-cool-core characteristics consistent with previous XMM-Newton findings (Durret et al. 2010). The metallicity in the cores is around 0.3 Z , typical for galaxy clusters (Walker et al. 2019), but poorly constrained in the outskirts (and thus fixed to 0.3 Z in the fitting process). For the filament region, the observed spectrum is well modeled by the sum of background/foreground components, indicating that the data do not require a WHIM contribution.

To derive upper limits on properties of undetected WHIM emission, we refitted the spectra with an additional APEC component while fixing metallicities, GH and LHB temperatures, and instrumental constants. MCMC analysis yielded confidence intervals for remaining parameters, with results shown in Figure 7 [Figure 7: see original paper]. The WHIM component temperature is poorly constrained, with a best-fit normalization of 7.59×10 , though this is less than 2 from zero. Fixing the normalization at 3.5×10^{3} (as in Werner et al. 2008) yields a temperature upper limit of 2.34 keV (90% confidence). Conversely, fixing the temperature at 0.91 keV (as in Werner et al. 2008) gives a normalization upper limit of 1.29×10^{3}, corresponding to a density of 1.32×10 cm ^{3} (/ _c 60), following Werner et al. (2008) in converting normalization to density.

4. Discussion

Motivated by the detection of X-ray emission from a filament connecting A222 and A223 (Werner et al. 2008), we conducted a detailed study of the system using Suzaku archival data. Our initial intention was to leverage Suzaku' s low NXB for detecting extended low surface brightness emission. However, we encountered significant scattered light issues that introduce uncertainties comparable to those from CXB. Our results show that emission in the putative WHIM region (Werner et al. 2008) can be accounted for (within uncertainties) by the combination of scattered cluster emission, CXB, Galactic foreground, and NXB. While a WHIM component can be accommodated by the data, its properties are not well constrained. With one parameter (normalization or temperature) fixed at the Werner et al. (2008) value, the 90% confidence upper limit on the other parameter is consistent with published results.

A possible way to reduce CXB flux uncertainties in Suzaku observations is to lower the source detection limit using data from telescopes with better angular resolution (e.g., Bulbul et al. 2016; Zhang et al. 2020). To this end, we attempted to improve constraints on WHIM emission using XMM-Newton data, with details provided in the Appendix. This reduced the CXB flux and its uncertainty by approximately 30%. Similar spectral analyses again poorly constrained the WHIM component properties. Fixing the WHIM temperature at kT = 0.91 keV yields an upper limit on normalization of 3.3×10 , corresponding to 3.4×10 cm ^{3}; fixing normalization at 3.5×10 ^{3} gives an upper limit on kT of 0.16 keV. Both limits are significantly lower than before.

In summary, based on Suzaku observations alone, we can neither confirm nor rule out WHIM emission, but the derived upper limits on WHIM properties are broadly consistent with published results (Werner et al. 2008). Mirakhor et al. (2022) also found evidence for X-ray emission from a filament connecting A2029 and A2033 using Suzaku data, determining a WHIM temperature of 0.7 keV, which is higher than our upper limit (derived with XMM-Newton assistance). Even higher temperatures (3.5 keV) have been reported for WHIM emission in A399/401 and A3395/3391 (Sakelliou & Ponman 2004; Alvarez et al. 2018; Reiprich et al. 2021) based on eROSITA, attributed to shock heating in those systems. The APEC normalization of the WHIM component (derived with both kT and normalization free) implies a 90% upper limit of 10^{1} on WHIM overdensity, aligning with previous results: / _c 60 for A2801/2804/2811 (Sato et al. 2010) and 160 ± 70 (90% confidence) for A2029/2033 (Mirakhor et al. 2022).

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Appendix: Deriving Unresolved CXB Flux with XMM-Newton Observations

Previous Suzaku studies have applied a uniform detection limit across the entire field of view (e.g., Walker et al. 2012; Bulbul et al. 2016). However, this approach does not utilize all resolved CXB information. To address this, we calculated unresolved point source flux on a pixel-by-pixel basis using the XMM-Newton sensitivity map, following the method of H. R. Huang et al. (2025, in preparation) to generate a sensitivity map in the 2.0–4.5 keV band. We integrated the CXB in every pixel using the CDF-S logN-logS relation from zero to each pixel' s detection limit. The CDF-S logN-logS relation aligns with the A222/223 field of view (see Figure A1).

To calculate XMM-Newton-resolved CXB, we considered scattering effects from point sources. We selected sources from the XMM-Newton catalog and ran XIS-SIM simulations for each source with the same input photon number. We then used a calibrated on-axis source to account for vignetting effects, scaled the output image with source fluxes from the XMM-Newton catalog, and summed all output images for subsequent analyses. In Figure A2, resolved point sources are marked in white on the XMM-Newton image. The northeastern subcluster associated with A223 is visible in XMM-Newton but undetected in Suzaku due to limited field of view. This subcluster' s centroid is at a projected angular separation of 4.8 arcmin from the A223 cluster center, corresponding to a physical separation of approximately 987 kpc at position (01:38:01.8, −12:45:07.0) (Dietrich et al. 2002). Separating this subcluster from the main cluster is difficult, so its mass was not measured in previous works (Dietrich et al. 2002, 2005). The mass density map from weak lensing analysis is available in Dietrich et al. (2012).

Using updated CXB tables for resolved (Table A1) and unresolved CXB (Table A2), we refitted the spectra. The XMM-Newton-resolved CXB was additionally modeled by a power law with photon index constrained at 1.89 ± 0.34 by fitting XMM-Newton sky background spectra. We considered photon index uncertainties while ensuring normalization remained consistent. Table A3 shows the spectral fitting results, with properties consistent with Section 3 results within 1 .

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Note: Figure translations are in progress. See original paper for figures.