Suzaku Observations of the Cluster Outskirts and Intercluster Filament in the Triple Merger Cluster A98

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Abstract

We present Suzaku observations of the Abell 98 (A98) triple galaxy cluster system and the purported intercluster filament. The three subclusters are expected to lie along a large-scale cosmic filament. With partial azimuthal coverage of the northernmost cluster, we find that the inferred entropy profile of this relatively low-mass cluster ($kT \approx 2.8$ keV) adheres to expectations from models of self-similar pure gravitational collapse in the region of the virial radius. There is evidence of extended structure beyond $r_{200}$ to the north of the northernmost cluster, along the merger axis, with properties consistent that are expected for the warm–hot intergalactic medium ($kT = 0.11^{+0.07}_{-0.02}$ keV and $n_e = 7.6 \times 10^{-5} \pm 3.6 \times 10^{-5}$ cm$^{-3}$). No such emission is detected at the same radius in regions away from the merger axis, consistent with the expectation that the merger axis of this triple system lies along a large-scale cosmic filament. In the bridge region between A98N and A98S, there is evidence of filamentary emission at the 2.2$\sigma$ level, as well as a tentative detection of cool gas ($kT \approx 1$ keV). The entropy profile of this intercluster filament suggests that the A98 system is most likely aligned closer to the plane of the sky rather than along the line of sight. The structure to the north of the system, as well as in-between A98N and A98S, is indicative that the clusters are connected to a larger-scale structure spanning at least 4 Mpc.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Intracluster medium (858); Abell clusters (9); High energy astrophysics (739); Large-scale structure of the universe (902)

1. Introduction

Cosmological simulations predict that massive galaxy clusters are generally located at the nodes of the web-like, large-scale structures in the universe (e.g., IllustrisTNG simulation; Nelson et al. 2019). The assembly and evolution of galaxy clusters throughout time are powerful tools for precision cosmology (e.g., Schellenberger & Reiprich 2017), which informs our understanding of the growth and evolution of structure. Simulations predict that the baryons in the cosmic web have been shock heated and compressed to electron temperatures of $T_e \approx 10^5$–$10^7$ K with electron densities of $n_e \approx 10^{-7}$–$10^{-5}$ cm$^{-3}$. This diffuse, primordial baryonic gas is known as the warm–hot intergalactic medium (WHIM), which is thought to comprise approximately 50% of the baryons in the local universe (e.g., Bregman 2007).

One key assumption when using galaxy clusters for precision cosmology is that clusters are in hydrostatic equilibrium. However, it has been observed that many massive galaxy clusters seemingly deviate from hydrostatic equilibrium at large cluster radii (e.g., Walker et al. 2013). This could be due to a number of processes in the intracluster medium (ICM), including the clumping of cool gas (Simonescu et al. 2011; Eckert et al. 2015; Tchernin et al. 2016) at large cluster radii ($\sim r_{200}$) biasing the average surface brightness of cluster outskirts, high, nonthermal pressure support from bulk motions, turbulence, or cosmic rays (Lau et al. 2009; Vazza et al. 2009; Battaglia et al. 2013), and electron–ion nonequilibrium (Fox & Loeb 1997; Wong & Sarazin 2009; Hoshino et al. 2010; Avestruz et al. 2015) (for a review of cluster outskirts, see, e.g., Walker et al. 2019).

The thermodynamic history of clusters is encoded in the entropy profiles of the ICM. Unlike larger-mass clusters, studies of lower-mass galaxy clusters and groups with Suzaku have shown close agreement in the virialization region between the predicted entropy profiles based on self-similar, gravitational-collapse models and the inferred entropy profiles of the systems based on X-ray spectroscopy (Su et al. 2015; Bulbul et al. 2016; Sarkar et al. 2021). This could be due to the fact that galaxy groups are likely more evolved than galaxy clusters (Paul et al. 2017).

Another theory is that due to their smaller mass, galaxy groups are more sensitive to common thermodynamic processes such as stellar and active galactic nucleus (AGN) feedback (e.g., Pratt et al. 2010; Lovisari et al. 2015) injecting entropy into their outskirts. This injected entropy could artificially correct for the entropy deficiency observed in more massive clusters around the virialization region, making the ICM of a lower-mass cluster or group look like it is obeying self-similarity. However, an entropy excess at large group and low-mass cluster radii has not yet been observed. Isolated groups also tend to be in less dynamically active regions than clusters, as they are not at the nodes of the cosmic web. The relative isolation would lead to fewer clumps, weaker accretion shocks, and less turbulence.
Simulations (e.g., Angelinelli et al. 2021) and deep X-ray observations (e.g., Mirahori & Walker 2020) of galaxy clusters have revealed that the thermodynamic structure of the outskirts varies azimuthally, presumably due in large part to the growth of hierarchical structure through cosmic filaments. Understanding the physical processes at work in the ICM in the outskirts of clusters is key to our understanding of the growth of cosmic structure, and to using clusters for precision cosmology.

Abell 98 consists of three subclusters (Abell et al. 1989); Abell 98N (A98N), Abell 98S (A98S), and Abell 98SS (A98SS). The R.A. and decl. (Burns et al. 1994; Jones & Forman 1999), redshift (White et al. 1997; Pinkney et al. 2000), measured electron temperature, and inferred $r_{500}$ (Vikhlinin et al. 2009) are presented in Table 1. $T_{500}$ and $f_{500}$ are inferred by employing an iterative approach where $r_{500}$ is guessed, and then $T_{500}$ is measured until the values are consistent with the $r_{500}$–$T_{500}$ relation presented by Vikhlinin et al. (2009).

The bimodal distribution of A98N and A98S was first seen in the X-ray with the Einstein Observatory (Forman et al. 1981; Henry et al. 1981). A98SS was also later observed with the Einstein Observatory (Jones & Forman 1999). The presence of three subclusters aligned colinearly on megaparsec scales suggests the presence of a local, large-scale structure filament aligned with the subclusters.

Paterno-Mahler et al. (2014) found, with relatively shallow Chandra and XMM-Newton observations, that there is evidence for a shock-heated region to the south of A98N, perhaps due to an early stage cluster merger. Their dynamical analysis supported this conclusion. This study also determined that A98S has an asymmetric ICM distribution, indicating that A98S is still undergoing a major merger.

Sarkar et al. (2022) found definitive evidence of a shocked edge to the south of A98N with deeper Chandra observations, confirming that A98N and A98S are likely in the early stages of a merging event.

The errors reported here are 90% unless otherwise stated. Throughout this work, we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega \lambda = 0.7$. The average redshift of the A98 system is $z = 0.1042$ corresponding to $1'' = 1.913$ kpc. For this analysis we assume the abundance table of Grevesse & Sauval (1998).

### 2. Observations and Data Reduction

In this section we discuss the data and reduction techniques for the X-ray observations of A98 listed in Table 2.

#### 2.1. Suzaku

Suzaku observed the A98 system with a total of six pointings (see Table 2) from 2014 June to December. Three of the four XIS detectors, XIS0, XIS1, and XIS3, were on for each observation. We find that these Suzaku observations are offset by $\sim 33''$ in R.A. from both the Chandra and XMM-Newton observations of the system. When analysing data from the different observations jointly, this astrometry correction is taken into account.

The Suzaku data are reduced using HEASOFT version 6.22.1 and the latest calibration database as of 2014 May. When CIAO tools are being used for analysis, CIAO version 4.9 and CALDB version 4.7.7 were employed. The FTOOL aepipeline is used for the first-order reprocessing of the filtered files. Appropriate filters were applied for an Earth elevation greater than 5°, a sunlit Earth elevation greater than 20°, a cutoff rigidity greater than 6 GeV/c, and passages just before and after the South Atlantic Anomaly with XSELECT. The $5 \times 5$ editing mode files are first converted to the $3 \times 3$ editing mode using $xis5x5to3x3$ and then the events are combined for each detector. The corners of the chips illuminated by the Fe$^{55}$ calibration sources are then removed. The second rows adjacent to the charge-injected rows at 6 keV are removed from XIS1 for further analysis due to the increase in the non-X-ray background (NXB) level on XIS1. Due to the micrometeorite hit to XIS0, the impacted region is excluded from the XIS0 field throughout the analysis. Light curves are extracted from the events files with the CIAO tool dnextest. The CIAO tool dfilter is used on the light curves with the iterative sigma clipping routine $lc\_sigma\_clip$ set to $3\sigma$. No instances of strong flaring in the observations are found.

The NXB images are generated using the xisnxbgen routine (Tawara et al. 2008). The NXB images are then scaled so that the hard-band (10–12 keV) count rate matches the source Suzaku observations. After creating source and scaled NXB mosaic images, the mosaic NXB image is then subtracted from the source image. Flat-field images are generated with the routine xissim to create effective exposure maps. The mosaic NXB image is subtracted from the mosaic source image, and the resulting image is divided by the mosaic exposure map to create the final image shown in Figure 1. The point-spread function (PSF) of Suzaku is relatively large ($\sim 2''$). The CIAO tool wavdetect is used on wavelet scales of 14, 28, and 56 pixels, where each pixel is $2''$ in length after binning, to detect point sources. These scales are roughly 1/4, 1/2, and 1 times the size of the 2' PSF, which should detect both bright point sources and fainter point sources where the broad PSF wings may be too faint to be detectable. The image was then inspected by eye in order to make appropriate adjustments to the point-source regions detected for exclusion from further analysis.

#### 2.2. Chandra

The A98 system was observed with Chandra, with a total of three pointings from 2009 September to 2010 September (see Table 2). More recent, deeper Chandra observations of this system will be presented in A. Sarkar et al. (in preparation). CIAO version 4.9 and CALDB version 4.7.7 are used for the Chandra data reduction. After using chandra_repro to generate level 2 events files (see Table 2 for the observations), light curves are extracted with the CIAO tool dnextest, and then run through the dfilter routine to filter the level 2 events files for any possible flares during the observation.

The asphist, mkinstmap, and mkexpmap routines in CIAO are used to generate exposure maps for imaging. The blank-sky
Table 2
Details of the Suzaku, Chandra, and XMM-Newton Observations Used in This Work

| Observatory | Pointing | ObsID    | R.A.      | Decl.      | Date Obs | Exposure (ks) | ACIS-I XIS0/XIS1/XIS3 MOS1/MOS2/PN PI |
|-------------|----------|----------|-----------|------------|----------|---------------|--------------------------------------|
| Suzaku      | A98C     | 809077010 | 00°46′29″39 | +20°33′25″9 | 2014-6-9 | 59.75/58.86/59.63 | S. Randall                           |
| Suzaku      | A98N     | 809078010 | 00°46′18″12 | +20°50′20″0 | 2014-7-2 | ~/-/-/24.9    | S. Randall                           |
| Suzaku      | A98N     | 809078020 | 00°46′18″02 | +20°50′21″1 | 2014-7-3 | 23.3/21.1/22.5 | S. Randall                           |
| Suzaku      | A98N     | 809078030 | 00°46′19″18 | +20°49′43″3 | 2014-12-21 | 48.9/50.3/51.5 | S. Randall                           |
| Suzaku      | A98S     | 809080010 | 00°46′42″48 | +20°16′30″0 | 2014-12-20 | 47.7/48.4/49.0 | S. Randall                           |
| Suzaku      | A98W     | 809079010 | 00°45′15″40 | +20°40′10″2 | 2014-7-3 | 95.6/96.9/99.7 | S. Randall                           |
| Chandra     | A98N     | 11877    | 00°46′24″80 | +20°28′05″0 | 2009-9-17 | 19.5          | S. Murray                            |
| Chandra     | A98S     | 11876    | 00°46′29″30 | +20°37′17″0 | 2009-9-17 | 19.8          | S. Murray                            |
| Chandra     | A98SS    | 12185    | 00°46′36″10 | +20°15′22″5 | 2010-9-8 | 19.8          | S. Murray                            |
| XMM-Newton  | A98C     | 0652460201 | 00°46′13″40 | +20°34′47″5 | 2010-12-26 | 33.0/33.0/24.0 | C. Jones                             |

Note. The exposure times reported are after cleaning for background flares.
files with the closest observation periods to each of the Chandra observations are reprojected to match the observations using the CIAO routine `reproject_events`. The blank-sky background images are hard-band (10–12 keV) scaled to match the high-energy particle background count rate of the source observations. We use the `wavdetect` routine on wavelet scales of 2, 4, 6, 8, 10, 12, and 16 pixels, where the pixels are 0.98 in length to detect background sources for removal. These sources are excluded from further analysis. The routine `dmfilth` is used to fill in the excluded source regions by drawing counts from a Poisson distribution matched to the local surrounding regions for imaging. The mosaic, background-subtracted, exposure-corrected Chandra 0.3–7.0 keV image is presented in Figure 2 (Right).

These Chandra data are used to corroborate the Suzaku measurements, and are in general agreement with the deeper observations presented in A Sarkar et al. (in preparation).

### 2.3. XMM-Newton

The Source Analysis Software (SAS) v18.0.0 is used to reduce the XMM-Newton event lists for A98N. The tools `odfind` and `cifbuild` were used to create the observation data files summary file and to build a current calibration file (CCF) index file, respectively, to prepare the data for further analysis. We then use the tool `xmmextractor` to generate images and calibrate events files for point-like source analysis. A smoothed 0.5–2.0 keV MOS2 events image of this observation is presented in Figure 2 (Left).

### 3. Analysis

XSPEC version 12.11.0 was used to perform the spectral analysis. An absorbed (phabs) APEC model (Smith et al. 2001) was used for the source spectra.
Table 3
The Free Parameters for the Fits to the Dashed Green Background Regions Shown in Figure 1 (Left)

| BG Region | CXB Norm (photons keV^{-1} cm^{-2} s^{-1} arcmin^{-2}) | GH $kT$ (keV) | GH $N_{\text{cm}}$ (arcmin^{-2}) | LHB Norm (cm^{-2} arcmin^{-2}) |
|-----------|----------------------------------------------------------|--------------|----------------------------------|--------------------------------|
| West      | $6.9e^{-7,4e-8}$                                         | $0.19^{+0.01}_{-0.00}$ | $1.3e-6, 2e-7$                  | $2.1e-7, 2e-7$                |
| North     | $6.8e^{-7,4e-8}$                                         | $0.19^{+0.02}_{-0.00}$ | $1.4e-6, 2e-7$                  | $1.8e-7, 1e-7$                |

### 3.1. Suzaku Spectroscopy

To extract spectra from the Suzaku observations, the XSELECT environment and subsequently the extract spec routine are utilized. Then the corresponding redistribution matrix file (RMF) is generated with xisrmfgen. The RMF and source spectrum are then used to generate the ancillary response files (ARFs) with xissimarfgen.

Two different ARFs are generated for each spectrum to be folded into two different model components in the spectral fits: the source model and the background model. The beta2d function in Sherpa is utilized to fit the 2D-$\beta$ models simultaneously to all three clusters in the mosaic Chandra image shown in Figure 2 (Right). In order to create more accurate ARFs for the source spectra, xissimarfgen utilizes an image of the 2D-$\beta$ model. A uniform circle with a radius of 20' is used to generate the ARFs folded into the background model, under the assumption that it is uniform.

The background model includes components from the local hot bubble (LHB), the Galactic halo (GH) and the cosmic X-ray background (CXB). These background components are modeled simultaneously with the source components in each fit. The LHB temperature component is fixed in the background-only fit, as the normalization for this component is low (see Table 3), and the component temperature could not be constrained when left free to vary. The NXB spectra are generated with xisxbgen (for more details see Tawa et al. 2008) and are subtracted from the source spectra in XSPEC. We group all of our spectra such that each bin contains a minimum of 40 counts. In order to constrain the GH and LHB, and CXB emission further, we extract a spectrum of an annulus from the ROSAT All Sky Survey (RASS). The RASS annulus is centered on R.A. = $0^\circ 46'18''8872$ and decl. = $20^\circ 28'13'557$, approximately on the X-ray centroid of A98SS, with an inner radius of 0.5643 and an outer radius of 0.6738. The background-only-fit model parameters can be seen in Table 3. The LHB temperature is fixed to $kT = 0.1$ keV, the GH temperature is fixed to $kT = 0.2$ keV, and the power-law component for the CXB is fixed to $\Gamma = 1.4$ when performing simultaneous modeling with the source components. The normalizations for the GH, LHB, and CXB are left as free parameters in all spectral fits presented in this work in order to account for systematic errors.

Most point sources are removed by inspecting the Suzaku observations listed in Table 2. The bright point sources that are not excluded from the regions for analysis are shown in Figure 2 (Left), and are modeled using the XMM-Newton data presented in this work (see Section 3.2). We take the parameters from the XMM-Newton spectral models to simulate the same Suzaku point source with the FTOOLS xisim. We use this simulation to estimate the Suzaku normalization for the point-source models and then fold the point-source models into the region fits, allowing the point-source parameters to vary within their 90% errors derived from the XMM-Newton fit of the source.

### 3.1.1. Suzaku Scattered Light

Due to Suzaku’s relatively large PSF, one must consider the effects of scattered light from adjacent regions when performing a spectral analysis. In order to determine the effect of scattered light across adjacent regions, we use $xissim$ to simulate each region with $2 \times 10^6$ photons as is done in, e.g., Walker et al. (2012) and Bulbul et al. (2016). We calculate the percentage of photons that originate from the region of interest and are detected in that region, and what percentage of photons are scattered into the adjacent region in order to include a properly weighted component in the spectral fit to the adjacent region (Table 4). We use these values to test whether the scattered light affects our results, particularly in the faintest regions analysed in this work. We find that the scattered light does not change the final results for the analysis of A98N, as the statistical errors dominate the effect of scattered light. We find that the scattered light from outside of the field of view (FOV) is negligible. Therefore, we omitted the values from Table 4 where the adjacent sector was outside of the FOV of the observation containing the source sector.

### 3.1.2. Systematic Errors in the CXB

Suzaku is able to detect point sources down to a flux of $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$. Moretti et al. (2003) defines the unresolved CXB flux in erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ as

$$F_{\text{CXB}} = (2.18 \pm 0.13) \times 10^{-11} - \int_{S_{\text{lim}}}^{S_{\text{max}}} \frac{dN}{dS} \times S \, dS.$$  

The normalization in this equation is derived from Swift data (Moretti et al. 2003). The analytical form of the source flux distribution in the 2–10 keV band is characterized as (Moretti et al. 2003)

$$N(>S) = N_{0} \left( \frac{2}{S_{0} + S_{\text{lim}}^{1.5} S^{3}} \right) \text{erg cm}^{-2} \text{s}^{-1},$$  

where $\alpha = 1.57_{-0.08}^{+0.10}$ and $\beta = 0.44_{-0.12}^{+0.12}$ are the power-law indices for the bright and faint components of the distribution, respectively, $N_{0} = 5300 \pm 2850$ s$^{-1}$, $S_{0} = 4.5_{-1.7}^{+3.7} \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, $S_{\text{lim}}$ is the flux of the faintest point source detected in the observation, and $S_{\text{max}} = 8 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The nominal value, $S_{\text{lim}}$, for Suzaku point sources is $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ (e.g., Walker et al. 2013). Therefore the unresolved CXB in the background region used in the Suzaku observations has a flux of $1.87 \pm 0.23 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$.

Finally, the expected 1$\sigma$ spatial variance in the unresolved CXB flux may be given by

$$\sigma^2 = \frac{1}{\Omega} \int_{S_{\text{lim}}}^{S_{\text{max}}} \frac{dN}{dS} \times S^2 \, dS,$$  

where $\Omega$ is the solid angle (Bautz et al. 2009). We use this method to constrain the normalization of the CXB component.
of the background, and allow this parameter to vary within the derived 1σ errors.

### 3.2. XMM-Newton Spectral Analysis

SAS is used to generate all of the necessary files of the point-like regions shown in Figure 2 (Left) for analysis in XSPEC. In order to generate the source and background spectra, we use the \texttt{evselect} routine. The background spectrum was extracted from a local region close to the point sources shown in Figure 2 (Left). We then use the \texttt{rmfgen} routine to generate the RMFs and the \texttt{arfgen} routine to generate the ARF for the spectrum. The XMM-Newton spectra are grouped such that each bin contains a minimum of 25 counts due to the relatively low counts observed for the point sources. The northernmost region highlighted in Figure 2 (Left) preferred an APEC model, and coincides spatially with a Galactic star cataloged in the GAIA archive. The remaining two sources preferred an absorbed power-law model, and are most likely AGNs.

### 4. Results and Discussion

In this section we present the temperature, electron density, and entropy profiles for the regions shown in Figure 1.

The electron density of a region of interest is derived from the normalization of the APEC model in XSPEC. The electron density may be derived from the XSPEC normalization with the following equation

\begin{equation}
    n_e = \frac{1.2 N \times 4.07 \times 10^{-10} (1 + z)^2}{D_A^2 \left( \frac{V}{\text{Mpc}^3} \right)^{1/2}},
\end{equation}

where $D_A$ is the angular diameter distance to the system, $V$ is the volume for an assumed geometry of the region, $N$ is the XSPEC normalization, and $z$ is the redshift of the object. The assumed ratio for $\frac{D_A}{n_e}$ is 1.2 (Boehringer & Hensler 1989).

#### 4.1. Clusters’ Thermodynamic Properties

Here we present thermodynamic profiles of the subclusters in the A98 system. In order to deproject our temperature measurements and APEC normalizations, we use the “onion peeling” method (Ettori et al. 2010) and assume a spherical geometry for the galaxy cluster components in the system.

The Suzaku temperature profile of A98N in partial azimuth (see the sector regions in, e.g., Figure 1 (Left)) is shown in Figure 3 as well as the “universal” temperature profile (Ghirardini et al. 2019) expected based upon the average electron temperature of the system. The sector regions were chosen such that there are at least 2000 counts per region. While not all of the error constraints are tight, the temperature profile of A98N is not only consistent in partial azimuth, but also seems to adhere to expectations of the temperature profile based on the average cluster temperature (the cluster’s $T_{500}$ measurements made with Suzaku are presented in Table 1).

The deprojected electron density profile of A98N in the northern and western sectors is shown in Figure 4. The profiles are consistent with each other within the errors.

The deprojected entropy profiles for A98N in the northern and western sectors, for the regions shown in, e.g., Figure 1 (Left), are shown in Figure 5. Here, the entropy is defined as $K = kT_e n_e^{-2/3}$, where $k$ is Boltzmann’s constant, $T_e$ is the measured electron temperature, and $n_e$ is the derived electron density assuming a region with an appropriate volume as described in Equation (4). The statistical uncertainty in the normalization for the self-similar entropy profile in Figure 5, and the normalization of the temperature profile presented in Figure 3 are included as the shaded blue region. Unknown biases such as
instrumental calibrations (i.e., Schellenberger et al. 2015) could affect any conclusions derived from these figures.

We find that, in both sectors, the entropy values for A98N are consistent with the self-similar prediction of pure gravitational collapse, based upon spherical hydrodynamic (SPH) simulations of galaxy clusters, near the virial radius, in which the entropy follows $K \propto r^{1.1}$ (Voit et al. 2005). There is some hint of entropy flattening, however the errors on the entropy are too large to say definitively. This is in agreement with similar studies of lower-mass systems (e.g., Su et al. 2015; Bulbul et al. 2016; Sarkar et al. 2021) even though A98N is most likely undergoing a merging event (Paterno-Mahler et al. 2014; A Sarkar et al. in preparation). At small cluster radii ($r < r_{500}$), the entropy of A98N is above that expected for self-similarity. This excess is consistent with what is seen in other systems, particularly lower-mass systems (Sun et al. 2009), and is likely due to the effect of nongravitational processes in the central region (e.g., AGN feedback; e.g., O’Sullivan et al. 2011).

![Figure 5](image)

**Figure 5.** The blue line is the entropy profile expected from pure gravitational collapse (Voit et al. 2005) for A98N. The black points are for the sector regions to the north of A98N and the pink points are for the sector regions to the west of A98N shown in Figure 1.

4.2. Large-scale Filament

The box region to the north of A98N shown in Figure 1 (Left) is used to investigate larger-scale structure beyond $r_{200}$ of A98N. The excluded region within the box does not appear to be a point source, and also does not appear to be associated with the A98 system. Inspecting images from the DSS and Sloan Digital Sky Survey (SDSS) reveals no obvious clustering of galaxies. There are not enough photons available to model the spectrum of this source reliably. This source could be a background galaxy cluster or a faint group, although it would require further observations to determine its nature. A 1D-$\beta$ model is fit to the circular region encompassing the possible background cluster, with best-fit parameters of $\beta \approx 1.3$ and $r_c \approx 2\prime$. This model is extrapolated to compare the expected surface brightness to the measured surface brightness in the rest of the box region shown in Figure 1 (left panel). The measured surface brightness is larger than the expected surface brightness by approximately a factor of 4. The box region was fitted with an absorbed APEC model. The best-fit values for this box region, excluding the possible background cluster, yield a projected temperature of $kT = 0.11^{+0.01}_{-0.02}\text{ keV}$, a projected electron density of $n_e = 7.6 \times 10^{-5} \pm 3.6 \times 10^{-5}\text{ cm}^{-3}$, and a projected entropy of $K = 61^{+20}_{-22}\text{ keV cm}^2\text{ s}^{-1}$ assuming a cylindrical volume with a length of $l = 0.62\text{ Mpc}$ and a radius of $r = 0.61\text{ Mpc}$, and filling factor of 1 for the density measurement. The choices of the length and radius are based on the height and half-width of the box region, respectively, and we assume cylindrical geometry. This temperature measurement is similar to the nominal LHB temperature of 0.1 keV, however, we expect that for this normalization to be 2.5 orders of magnitude larger than the LHB normalization. The normalizations differ by $\sim 3\sigma$. The normalizations for the LHB in the two background regions, separated by $\sim 20\prime$, shown in Table 3 agree well with each other and with similar works (e.g., Bulbul et al. 2016). It is possible that there are large surface brightness fluctuations on small scales in the LHB, but in order to be within 1$\sigma$ of the amplitude of the normalization of the box region, these small-scale fluctuations in the surface brightness would have to span approximately 2 orders of magnitude. The box region is fit with a background-only model for comparison. The model with the extra APEC component ($\chi^2/\text{dof} = 289/273$) is marginally preferred ($\rho = 0.06$) over the background-only model ($\chi^2/\text{dof} = 293/274$). While this measured temperature is not within the energy range used for the spectral modeling (0.5–7.0 keV), approximately 30% of the model emission falls within the energy range used in this work. These thermodynamic values are consistent with the dense end of the WHIM, where the ICM in the outskirts of the cluster interacts with the large-scale structure filament (e.g., Dolag et al. 2006; Werner et al. 2008), especially if the system is not oriented in the plane of the sky.

We compare a similar region to the west, and fit the region with the best-fit parameters for the model of the northern region. The fit for the northern box region yields a $\chi^2$ of 289 with 272 degrees of freedom (dof). We find that the western comparison region is consistent with background only with a fit that gives a $\chi^2$ of 555 with 321 dof when the data are fit with the best-fit model of the northern region. Such detections of this material are very rare (e.g., Werner et al. 2008; Bulbul et al. 2016). This detection is consistent with the detection of larger-scale structure in the Abell 1750 system, another low-mass triple cluster system (Bulbul et al. 2016) similar to A98. With the advent of eRosita and future X-ray missions (e.g., Athena, Lynx), such detections should become more common.

4.2.1. A98N–A98S Bridge

To investigate whether the apparent surface brightness enhancement in-between A98N and A98S is due to two cluster halos overlapping, we compare the combined surface brightness profiles of A98N and A98S to the emission across the bridge, as done by Paterno-Mahler et al. (2014) and A. Sarkar et al. (in preparation).

We combine the background-subtracted surface brightness profiles of the box annuli to the north of A98N and to the south of A98S shown in Figure 6. These box annuli are oriented to avoid the large-scale and intercluster filaments in the system. We then compare these values to the surface brightnesses in the apparent bridge regions connecting A98N and A98S shown in Figure 6.

The combined ICM surface brightness profile as compared to the bridge, and the resulting filament excess are presented in Figure 7 where the zero point on the $x$-axis is the midpoint of the region connecting A98N and A98S. The emission across the A98N–A98S bridge appears to be slightly enhanced, with a marginal (2.2$\sigma$) detection of excess filament emission. This excess emission is also seen at a higher significance with
4.2.2. Bridge’s Thermodynamic Properties

We measure the temperature, electron density, entropy, and metallicity across the A98 system with the box regions shown in, e.g., Figure 1 (Right). The temperature profile from north to south is shown in Figure 8, and is relatively flat across A98N and A98S before dipping in-between A98S and A98SS. When compared to Chandra, the temperature profiles are consistent. We find that in the intercluster region between A98N and A98S that a two-temperature model is preferred (Table 5). We freeze the metallicity at its best-fit value found from the one-temperature fit, and freeze the metallicity of the second temperature component to $Z = 0.2 Z_{\odot}$.

The inferred electron density (Equation (4)) for the regions across the bridge is presented in Figure 9. A cylindrical geometry, where the radius of the cylinder is the half-width of the region, is assumed for the regions in this profile. Assuming a box geometry for the regions across the bridge yields the same result within the errors; therefore neither geometry is preferred. There is a steady decline in the electron density profile with local peaks corresponding to the cluster centers.

The metallicity profile across the bridge is shown in Figure 10. This profile suggests that the metallicity of the ICM is radius-dependent, with a higher metallicity toward the center of the clusters, and decreases with radius.

4.2.3. Filament Orientation

The cyan box regions shown in, e.g., Figure 1 (Right) between A98N and A98S can be used to explore the entropy, presumed geometry, and inclination of the system. The entropy profile for the box regions between A98N and A98S is shown in Figure 11. We only include the regions from the center of A98N to the center of A98S in this entropy profile to investigate the filament orientation (cyan regions in, e.g., Figure 1 (Right)).
The two extremes for filament orientation: along the line of sight (LOS) and in the plane of the sky (POS) are investigated (see Figure 11). At the midpoint of the filament, the measured entropy is already approximately the expected ICM value at this radius if the filament is in the POS. This means that either the filament is in the POS, or the entropy of the gas has somehow been increased (e.g., due to a merger shock; A. Sarkar et al. in preparation). The filament is more likely inclined close to the POS, as a LOS filament orientation yields entropy values well above what is expected from the self-similar entropy profiles of the clusters (Voit et al. 2005). Furthermore, an LOS orientation of the system yields entropy values $\sim 2$ times higher than what is expected in the outskirts of both subclusters. These measurements rule out a significant contribution from WHIM emission in this region. The reported entropy values similarly assume a cylindrical geometry for the bridge regions, and assuming a box geometry yields a similar result within errors.

5. Conclusions and Summary

In this paper we present results from an analysis of Suzaku, Chandra, and XMM-Newton observations of the diffuse emission in the A98 system. We find the following:

1. The entropy profiles in the northern and western sectors, along and away from the merger axis and the putative large-scale structure filament, for A98N generally agree with each other, and with the self-similar expectation in the virialization region. This is consistent with previous suggestions (e.g., Su et al. 2015; Bulbul et al. 2016) that lower-mass clusters and groups adhere more closely to self-similar expectations in their outskirts, in contrast with what is seen in most massive systems.

2. The region to the north of A98N, beyond $r_{200}$, was found to have a temperature, density, and entropy consistent with those expected for the dense end of the WHIM. We find a temperature of $kT = 0.11^{+0.02}_{-0.01}$ keV, a projected electron density of $n_e = 7.6 \times 10^{-3} \pm 3.6 \times 10^{-3} \text{ cm}^{-3}$, and a projected entropy of $K = 61^{+22}_{-18} \text{ keV cm}^2$ for this region. However, the errors on these values are large. The presence of similar emission at the same radius to the west, away from the putative large-scale structure filament, is ruled out. This serves as further evidence that the system is consistent with the expectation that the merger axis lies along a large-scale structure filament. A similar result was found in the colinear triple system Abell 1750 (Bulbul et al. 2016). These measurements provide tantalizing evidence for the presence of a larger-scale structure, with the diffuse WHIM connecting to the cluster outskirts along cosmic filaments.

3. When comparing the surface brightness of the A98N–A98S bridge regions to the combined surface brightness profiles of the two overlapping halos, a nominal $2.2 \sigma$ excess in bridge emission is detected. This detection is suggestive of the presence of an intercluster filament in-between the two clusters. Additionally, there is evidence of two-phase plasma in this region; the lower temperature component ($kT \sim 1$ keV) is consistent with the dense end of the WHIM.
4. Comparing the entropy profile of the A98N–A98S bridge to that of the self-similar expectations for A98N and A98S reveals that the system is likely inclined closer to the POS. This suggests that the clusters are interacting with each other as they are well within each other’s virial radius in projection.

In this study, a picture similar to the large-scale structure seen in cosmological simulations starts to emerge. Suzaku was a powerful tool for studying diffuse ICM emission at large cluster radii, but it is no longer functional and available for future observations. The next generation of X-ray telescopes such as eRosita, XRISM, Athena, and Lynx will provide a wealth of information on the diffuse ICM in the virialization region of galaxy clusters and the surrounding large-scale structure (e.g., Reiprich et al. 2021). The ability to study increasingly low surface brightness cluster outskirts will help to answer key questions about the physical processes occurring in these interface regions. This will lead to a new era of synergy between observations and simulations in the pursuit to understand the cosmology and the physics that govern the observable universe.

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Appendix A
χ² Versus Cash Statistics

In this work, we employ χ² statistics in our models. It has been shown (e.g., Leccardi & Molendi 2007) that Cash statistics yield a more accurate result than χ² statistics, particularly for low-count spectra with a few counts per spectral bin. We therefore investigate whether employing Cash statistics yields a significantly different result in two of our faintest regions.

We employ Cash statistics to the northern box filament region shown in Figure 1 (Left), and the box region along the putative intercluster filament between A98S and A98SS shown in Figure 1 (Right; 5th box from the bottom). The northern box and southern box regions are not only faint, but also lie in observations with two different exposure times, ~90 ks and ~50 ks, respectively (see Table 2). Varying the NXB by 5% does not significantly affect the best-fit parameters. Considering the fits for these faint regions with different exposure times yield a similar best-fit temperature regardless of the statistics used (see Table A1); thus, the employment of χ² statistics in this work seems to be sufficient.

Table A1
A Comparison of Two Faint Regions Explored in This Work Using χ² and Cash Statistics to Fit the Spectra

| Region           | χ² KT (keV)   | Cash KT (keV) |
|------------------|---------------|---------------|
| Northern Fil Box | 0.11±0.02     | 0.12±0.01     |
|                  | 1.05±0.05     | 1.06±0.04     |
| Box 5            | 1.66±0.03     | 1.61±0.04     |

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