Gas Sloshing and Cold Fronts in Pre-merging Galaxy Cluster A98

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Abstract

We present deep Chandra observations of the pre-merger galaxy cluster Abell 98 (A98). A98 is an early-stage merging system. While the northern (A98N) and central subclusters (A98S) are merging along the north–south direction, A98S is undergoing a separate late-stage merger, with two distinct X-ray cores. We report the detection of a gas sloshing spiral and two cold front edges in A98N. We find two more surface brightness edges along the east direction of the eastern core and west direction of the western core of A98S. By measuring the gas temperatures and densities across those edges, we confirm that the eastern edge appears to be a cold front while the western edge is a shock front with a Mach number $M \approx 1.5$. We detect a spiral structure and a “tail” of X-ray emission associated with the eastern core of A98S. Our measurement indicates that the tail is colder than the surrounding gas at a 4.2$\sigma$ level. This may suggest that the tail and the spiral structures are the results of ram-pressure stripping, as the eastern core orbits in the main cluster’s gravitational potential.

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1. Introduction

Abell 98 (hereafter A98) is an early-stage merger (Forman et al. 1981) with three main subclusters, A98S (central), A98N (northern), and A98SS (southern). Previous studies have reported a shock front associated with the northern subcluster and a filament connecting the northern and central subclusters. (e.g., Alvarez et al. 2022; Sarkar et al. 2022). Alvarez et al. (2022) also reported a filament extending to the north beyond A98N, indicating A98N and A98S lie along a large-scale cosmic filament. In this work, we focus on the northern and central subclusters.

Cluster mergers along large-scale filaments leave imprints on the intracluster medium (ICM) in the form of shocks, cold fronts, and gas sloshing spirals (e.g., Markevitch et al. 2001, 2002; Ascasibar & Markevitch 2006; Markevitch & Vikhlinin 2007). Numerical simulations show that when a subhalo passes the density peak of the central cluster with a nonzero impact parameter, it accelerates the dark matter (DM) and gas peaks toward it. At first they travel together, but as the gas peak moves through the surrounding gas, the ICM velocity field around the main cluster core decelerates the gas peak due to the ram pressure, resulting in a separation between the DM and gas peaks. While the DM peak continues moving toward the receding subhalo, the gas peak is held back. During the core passage, the direction of this motion rapidly changes, leading to an abrupt change in the ram-pressure force exerted on the gas peak, which then overshoots the potential minimum.

Eventually, the gas peak turns around and starts sloshing back and forth around the DM peak. This sloshing motion can be inferred from imaging studies, which reveal the presence of sharp discontinuities in the surface brightness and temperature. In these features, the brighter (denser) side of the surface brightness jump is colder than the fainter (less dense) side; hence this is a “cold front,” as opposed to the shock front (e.g., Markevitch et al. 2000; Vikhlinin et al. 2001).

Gas sloshing motion can induce multiple cold fronts at different radii, growing over time and combining into a spiral pattern, known as a “gas sloshing” spiral (e.g., Ascasibar & Markevitch 2006; Markevitch & Vikhlinin 2007; Roediger et al. 2011; Gattuzz et al. 2022). These spiral structures are commonly observed in several galaxy clusters, such as A1763 (Douglass et al. 2018), A2029 (Paterno-Mahler et al. 2013), A2052 (Blanton et al. 2011), and the Fornax cluster (Su et al. 2017). Measurements of gas properties across the cold fronts reveal that the gas pressure stays almost the same across these cold fronts, as observed in several galaxy clusters, e.g., A2029 (Clarke et al. 2004), Perseus (Ichinohe et al. 2019), A2142 (Rossetti et al. 2013), and in galaxy groups (Gastaldello et al. 2013). This limits the relative gas motion, as ram-pressure forces would increase the gas pressure inside of the cold front. Though there is pressure equilibrium across the cold fronts, observations of other clusters show that the gas outside the edge is nearly at hydrostatic equilibrium, but the gas inside the edge is not (e.g., Fabian et al. 2001; Markevitch & Vikhlinin 2007).

A98 is an early-stage merger at a redshift $z \approx 0.1042$ (Beers et al. 1982; Paterno-Mahler et al. 2014). Previous observations confirm that this is a system of Bautz–Morgan type II-III and a richness of class 3 (Abell et al. 1989). The central subcluster A98S is at a redshift $z \approx 0.1063$ and hosts a wide-angle tail.
The primary goals of this paper are to map the thermodynamic structure and reveal any substructures associated with the central regions of A98N and A98S. We organize the paper as follows: in Section 2, we describe the data-reduction procedures; in Section 3, we analyze the actual, residual, the Gaussian gradient magnitude and electron density jumps; in Section 4, we show results from the spectral analysis, including the gas properties across them. We present and summarize our results.

Throughout this paper, we adopt a cosmology of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_m = 0.3$. Unless otherwise stated, all reported error bars correspond to a 90% confidence level.

2. Data Preparation

A98 was observed with Chandra during two epochs, once in September 2009 for 37 ks split into two observations and later in September 2018-February 2019 for 190 ks divided into eight observations. The combined exposure time is ∼227 ks (detailed observation logs are listed in Table 1). We performed the Chandra data reduction with CIAO version 4.12 and CALDB version 4.9.4, distributed by the Chandra X-ray Center (CXC). We have followed a standard data-analyzing thread.

All level 1 event files were reprocessed using the chandra_repro task by employing the latest gain, charge transfer inefficiency correction, and filtering out the bad grades. VFAINT mode was used to improve the background screening. Light curves were extracted and filtered using the lc_clean script to identify and remove periods affected by flares. The filtered exposure times are listed in Table 1. We used the reproject_obs task to reproject all observations to a common tangent position and combine them. The exposure maps in the 0.5–2 keV energy bands were created using the flux_obs script by providing a weighting spectrum, which was generated using the make_instmap_weights task with an absorbed APEC plasma emission model and a plasma temperature of 3 keV. To remove the underexposed edges of the detector, we set the pixel value to zero for those pixels with an exposure of less than 15% of the combined exposure time.

Point sources were identified using wavdetect with a range of wavelet radii between 1 and 16 pixels. We set the detection threshold to $\sim 10^{-6}$, which guaranteed $\lesssim 1$ spurious source detection per CCD. We used blank-sky background observations to model the non-X-ray background emission from foreground structures (e.g., Galactic halo and Local Hot Bubble) along the observed direction and unresolved faint background sources. The blank-sky background files were generated using the blanksky task and then reprojected to match the coordinates of the observations. We finally normalized the resulting blank-sky background to match the 9.5–12 keV count rates in our observations.

3. Imaging Analysis

Figure 1 shows a slightly smoothed image of A98N (northern subcluster) and A98S (central subcluster) in the 0.5–2 keV band, obtained after co-adding all 10 observations and applying the correction for exposure nonuniformity. As reported by earlier studies, the cluster is an early-stage merger, with the merger axis likely aligned along a local north–south (N–S) large-scale filament connecting A98N and A98S (e.g., Paterno-Mahler et al. 2014; Alvarez et al. 2022; Sarkar et al. 2022).

3.1. A98N

We used a residual image of A98N to search for any faint substructures, e.g., associated with gas sloshing or merger

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9 http://cxc.harvard.edu/ciao/threads/index.html
The north and east cold fronts are marked by white arrows. The residual image was created by subtracting the azimuthally averaged surface brightness at each radius (centered on A98N), as shown in Figure 2. The residual image shows an apparent surface brightness excess spiraling clockwise (if traced inward from a large radius), a classic signature of gas sloshing, and is brightest to the north/northeast of the cluster center. The farthest visible arc of the spiral extends out to 140 kpc south from the cluster center. Similar gas sloshing spirals have also been observed in other galaxy clusters, e.g., A2029 (Paterno-Mahler et al. 2013), A1763 (Douglass et al. 2018), A2319 (Ichinohe et al. 2021), and A2142 (Roediger et al. 2012).

The sloshing spiral in A98N indicates A98N experienced a separate merger, unassociated with the ongoing early-stage merger between A98N and A98S, probably in the past few billion years, based on the timescale for the formation of the sloshing spirals seen in simulations (ZuHone et al. 2010). Spiral patterns are understood to have formed when a cool-core system experiences an infall of a subcluster with a nonzero impact parameter. Simulations of the formation of spiral patterns show that during the formation process the relative velocity between the gas density and DM peak stays below 400 km s$^{-1}$ (Ascasibar & Markevitch 2006), and the average offset between gas density–DM peaks is below 30 kpc (Johnson et al. 2010). Additionally, the winding direction of a spiral (when traced inward from large radii) reveals the infalling subcluster’s trajectory, since the direction of angular momentum of spiraling-in gas is the same as that of the infalling subcluster (ZuHone et al. 2011; Douglass et al. 2018). The clockwise winding spiral pattern seen in A98N indicates that the perturbing subcluster may have passed the A98N core from the west to the northeast on the southern side.

Next, to reveal any substructures and associated sharp features in the A98N core, we obtained a GGM-filtered image of A98N with a filtering length scale of 8 pixels (Sanders et al. 2016; Sarkar et al. 2022). Each pixel is 0′′492 × 0′′492. Figure 2 (right) shows the GGM image of the A98N core. We observe two regions with relatively large surface brightness gradients in the core, peaking at ∼60 kpc to the north and 70 kpc to the east of the A98N core (indicated by the white arrows in Figure 2), sharply declining at larger radii. To determine the significance of these apparent features, we extracted surface brightness profiles in the east and north directions in 90° sectors. The energy band is restricted to 0.5–2 keV to minimize the effect of variation of X-ray emissivity with temperature while maximizing the signal-to-noise ratio. We match the centers of the curvature of the surface brightness edges to the center of the sectors. Figure 3 shows the extracted surface brightness profiles in the east and north directions.

Both surface brightness profiles exhibit discontinuities and overall shapes that are consistent with what is expected from a projected spherical density discontinuity (Markevitch et al. 2000). We fit each profile with a broken power-law model:

$$n(r) \propto \begin{cases} r^{-\alpha_1}, & \text{if } r < r_{\text{edge}} \\ \frac{1}{\text{jump}} r^{-\alpha_2}, & \text{if } r \geq r_{\text{edge}}, \end{cases}$$

where $n(r)$, $r_{\text{edge}}$, and “jump” represent the three-dimensional (3D) electron density at a radius $r$, the radius of the putative edge, and the density jump factor, respectively. $\alpha_1$ and $\alpha_2$ are the slopes inside and outside the edge, respectively. We project the estimated emission measure profile onto the sky plane and fit the observed surface brightness profile by varying the slopes, edge radius, and the magnitude of the jump (similar to what we did for the shock front in paper I; Sarkar et al. 2022). Figure 3 displays the best-fit models (red) and the 3D density profiles (inset) for both directions. For the east direction, we obtain best-fit power-law indices of $\alpha_1 = 0.70 \pm 0.01$ and $\alpha_2 = 1.0 \pm 0.01$ The associated density jump across the edge is $\rho_1/\rho_2 = 1.38 \pm 0.03$, where suffixes “1” and “2” represent the regions inside and outside of the edge, respectively. Similarly,
for the north direction, we find a best-fit power-law index of $\alpha_1 = 0.80 \pm 0.03$ and $\alpha_2 = 1.10 \pm 0.03$ with a corresponding density jump of $1.47 \pm 0.01$. We obtain the best-fit edge radius of $70 \pm 6$ kpc for the east edge and $60 \pm 4$ kpc for the north edge, as measured with respect to the centroid of the central X-ray surface brightness peak. Both edge radii are consistent with the position of the steep gradients seen in the GGM image (Figure 2). We estimate the uncertainty of each parameter by allowing all the other model parameters to vary freely.

3.2. A98S

Figure 1 reveals that the central subcluster (A98S) hosts two distinct surface brightness peaks. Paterno-Mahler et al. (2014) showed that the western peak coincides with a WAT active galactic nucleus. Using the Sloan Digital Sky Survey r-band magnitude of the galaxy distribution of A98, they concluded that these two surface brightness peaks are likely to be associated with two Brightest Cluster Galaxies (BCGs) from two merging subclusters. We denote the western subcluster as A98Sa and the eastern subcluster as A98Sb. Figure 1 exhibits that the X-ray emission is extended from east to west and appears to cut off abruptly northeast of the A98Sb. To better highlight these features, we create an unsharp-mask image in the following way. We smoothed the background-subtracted and exposure-corrected X-ray image by two-dimensional (2D) Gaussian kernels with $\sigma = 2''$ and $20''$. The images are then subtracted to obtain the unsharp-masked image, as shown in Figure 4 (left). The unsharp-masked image features the different substructures in the ICM of A98S. A98S appears to be separated into three concentrations of X-ray-emitting gas: the two subcluster cores (A98Sa and A98Sb) and a “tail” of emission to the southeast originating from the central region of A98Sb. The unsharp-masked image also reveals a surface brightness edge northeast of A98Sb. In contrast, A98Sa shows a relatively uniform morphology with no prominent surface brightness edges.

We next examine the surface brightness edge seen in the northeast of A98Sb by extracting a surface brightness profile across the edge, as shown in Figure 5 (right). The surface brightness profile shows a discontinuity similar to what we have seen in A98N. We fit the profile with a broken power-law model, as detailed in Section 3.1. Figure 5 displays the best-fit model (in red) and 3D density profile (inset). We obtain a best-fit power-law index of $\alpha_1 = 0.650 \pm 0.003$ and $\alpha_2 = 0.7 \pm 0.1$. The associated density jump across the edge is $\rho_1/\rho_2 = 2.8 \pm 0.2$ with a best-fit edge radius of $28 \pm 2$ kpc. To further investigate any faint substructure associated with both subcluster cores (A98Sa and A98Sb), we obtain a $\beta$-model-subtracted image of A98S. We use two 2D elliptical $\beta$ models centered at both subcluster cores to fit the surface brightness image in the 0.5–2 keV energy band. We also include a constant in the model to account for the sky background and any residual particle background. The model is fitted in Sherpa, and the best-fit parameters are obtained by minimizing the Cash statistic (Cash 1979). The best-fit 2D $\beta$-model image is then subtracted from the source image of A98S, leaving the residual image shown in Figure 6.

The excess emission from the “tail” seen in the residual and unsharp-masked image may suggest a trail of materials that has been ram-pressure stripped in the gravitational potential. Figure 6 also reveals a spiral structure at the A98Sb core, indicating the spiral and the tail both originate due to ram-pressure stripping, as the eastern core orbits in the main
cluster’s potential and the tail is potentially influenced by ICM “weather” (e.g., bulk turbulence). A further deeper observation is required to probe the feature in detail.

Compared to A98Sb, A98Sa shows a relatively regular morphology. Since there are clear radio lobes, one might expect cavities in the ICM evacuated by these lobes (Mathews & Brighenti 2008). A weak detection of cavities at the location of the lobes was reported in Paterno-Mahler et al. (2014). We therefore extract an azimuthal surface brightness profile, shown in Figure 5, centering at the A98Sa core with a radius of ∼150″. The sharp increase in the surface brightness to the east with a peak at ∼165° is due to the surface brightness peak associated with A98Sb. Similar results were obtained by Paterno-Mahler et al. (2014). However, we do not find any significant difference between the surface brightness in any other directions. Since A98Sa hosts a WAT radio source, the absence of any substantial decrement in the surface brightness at the north and south directions indicates that either the radio lobes are filled with X-ray-emitting gas or the jet axis is far enough from the plane of the sky to prevent detection. Several previous studies also found jets and lobes in other merging galaxy clusters, such as A2199 (Nulsen et al. 2013), A1682 (Clarke et al. 2019), A1446 (Douglas et al. 2008), A562 (Douglas et al. 2011; Gomez & Calderon 2020), and A1775 (Hu et al. 2021).

The GGM image of A98S shown in Figure 4 features a possible surface brightness edge at about 370 kpc southwest of A98Sa. We extract a surface brightness profile across the edge and fit that profile using a broken power-law model, as seen in Figure 10. We obtain best-fit power-law indices of $\alpha_1 = 0.7 \pm 0.1$ and $\alpha_2 = 0.9 \pm 0.2$. The electron density jumps by a factor of $1.7 \pm 0.5$ across the edge. We find the best-fit edge radius of $375 \pm 10$ kpc coincides with the apparent rapid change in the surface brightness gradient seen in the GGM image (Figure 4). We discuss the spectral properties of the surface brightness edges seen in A98Sa and A98Sb in Section 4.4.

4. Spectral Analysis

4.1. Global Intracluster Medium Properties

To constrain the global properties of both subclusters, we first extracted spectra from two circular regions centering on each subcluster core with a radius of ∼2″ for A98N and 3″ for A98S (roughly similar regions as seen in Paterno-Mahler et al. 2014). Both regions contain $\gtrsim 32,000$ background-subtracted counts in the 0.6–7 keV energy band and contain a vast majority of the cluster emission after eliminating the point sources, which is imperative to probe the global properties of both subclusters. The background spectra were hard-band scaled (10–12 keV) and subtracted from the source spectra before fitting. We restricted the spectral fitting to the 0.6–7 keV energy band and binned the spectra to contain a minimum of 40 counts per bin. We fixed the redshift to $z = 0.1042$. The spectral analysis was performed using Xspec version 12.11.1. All resolved point sources were excluded before the spectral analysis. We used the solar abundance table given in Asplund et al. (2009). For each subcluster, a single-temperature fit to the observed spectra using an absorbed thermal plasma emission model (i.e., phabs$\times$apec) produced a good fit (Smith 2001, Sarkar 2020).

For A98N, we measured a temperature of $3.05 \pm 0.09$ keV and a metal abundance of $0.63 \pm 0.10 Z_{\odot}$ with a $\chi^2$/dof of 786/761. Additionally, spectral fitting to the central subcluster (A98S) yielded a best-fit temperature of $3.04 \pm 0.12$ keV and an abundance of $0.42 \pm 0.10 Z_{\odot}$ with a $\chi^2$/dof of 870/886. In both cases, the hydrogen column density was fixed to the Galactic value, $N_{H} = 3.06 \times 10^{20} \text{ cm}^{-2}$, estimated using the LAB survey (Kalberla et al. 2005). Paterno-Mahler et al. (2014) also reported the temperature and abundance of both subclusters using a 38 ks Chandra observation and a 37 ks XMM-Newton observation. For both subclusters, our results better determine the gas temperatures and abundances, but are consistent with the earlier measurement by Paterno-Mahler et al. (2014).
4.2. Temperature Map

To understand the thermodynamic structures of the ICM in A98N and A98S, we constructed a temperature map following the techniques described in Randall et al. (2008, 2009). We extracted an elliptical region containing both subclusters and binned the image with 10 background-subtracted counts per pixel to aid the computational speed. For each pixel, we extracted spectra from a circular region with a radius set such that the region contains $\sim 2300$ background-subtracted source counts in the 0.6–7 keV energy band. This particular number of source counts was adopted to ensure that the uncertainty in temperature measurements in the fainter regions of the ICM was $\lesssim 25\%$. We generated appropriate response and ancillary response files for each region, and the background spectra were subtracted from the total spectra.

Figure 7 shows the temperature map of A98N/A98S. A98N and A98Sb appear to have cool cores with hot gas enclosing them, which is expected for cool-core clusters. In contrast, A98Sa appears to have a warm core with a uniform gas temperature of $\sim 3.7$ keV within 20 kpc of the core. This suggests that A98Sa was transformed into a non-cool-core cluster during an earlier subcluster merger.

The northern subcluster has an asymmetric “arc” of hot gas with a temperature of $> 3.5$ keV, which is clearly visible in Figure 7. This arc radius ($\sim 400$ kpc) is consistent with the radius of the shock front that we reported in paper I (Sarkar et al. 2022), suggesting the “arc” consists of shock-heated gas. The uncertainties in the temperature map range from $\lesssim 15\%$ for brighter regions and between 20% and 25% for the fainter regions. Since each region in the temperature map contains a fixed source count, the extraction regions are larger in the fainter parts of the ICM, making the temperature map highly smoothed.

4.3. A98N: East and North Cold Fronts

We extracted spectra from the eastern and northern sectors in A98N to measure the temperature and density changes across...
the surface brightness edges seen in Figure 3. Each sector was divided into five individual bins. These bins were positioned to measure the gas properties on either side of the surface brightness edges while maintaining a minimum of 3000 source counts in each extracted spectrum. We set this lower limit to guarantee enough photon counts for good spectral fitting and constraints on the parameters. Spectra were extracted from those bins in each sector.

We fixed the metallicity to an average value of $0.4 \, Z_{\odot}$ since it was poorly constrained if left free (Russell et al. 2010). The best-fit parameters were obtained by minimizing the Cash statistics. Figure 8 shows the radial profiles of the best-fit projected temperatures and pressures obtained across the eastern and northern edges. The temperature of the gas increases from the A98N core to the larger radii in both directions. Our measurements confirm the electron density jumps detected in the surface brightness profile analysis, but the temperature and pressure profiles appear continuous across the edges. Since A98N is a cool-core cluster, the temperature jumps correspond to both cold fronts may be hidden in the overall cluster profiles.

We test if the gas inside the edges is cooler by comparing the temperature profiles of the northern and eastern sectors with the temperature profile of the western sector, as shown in Figure 8. The temperatures across the edges of the north and south directions are consistent with that of the west direction within their uncertainty. We further investigate by comparing the temperature of the sloshing-spiral structure with the surrounding gas, as marked on the residual image in Figure 2. The temperature of the spiral gas (region 2 in Figure 2) is $3.14^{+0.16}_{-0.15}$ keV, while the temperatures of the surrounding gas (region 1) is $3.85^{+0.33}_{-0.6}$, respectively. Our measurement indicates that the gas in the spiral structure is 2.3σ cooler than the surrounding gas, which is more consistent with a cold-front interpretation. Similar cold fronts are also found in other clusters such as the Bullet cluster (Markevitch et al. 2002), A2142 (Markevitch et al. 2000), A3667 (Vikhlinin et al. 2001), A2146 (Russell et al. 2010), A2256 (Ge et al. 2020), A2554 (Erdim & Hudaverdi 2019), Perseus (Walker et al. 2017, and Walker 2022), and in many others (Botteon et al. 2018).

4.4. A98S: Cold Front, Tail, and Western Surface Brightness Edge

A98S consists of two individual subclusters, A98Sa and A98Sb. The temperature map in Figure 7 shows that the central region of A98Sb is cooler than A98Sa. Previous Chandra observations by Paterno-Mahler et al. (2014) showed that A98Sb is cooler than A98Sa at a 3σ level. With our deeper Chandra observations, we examined the spectra of each subcluster to measure the global ICM temperatures of individual subclusters. We extracted spectra from a circular region with 50′ radius and centering at both subclusters cores. These regions were chosen based on the peaks of the X-ray emission, assuming each of them includes the prominent extended emission from the corresponding subcluster. Point sources and background spectra were analyzed as described in Section 4. We measured a temperature of $3.70^{+0.33}_{-0.28}$ keV for the western subcluster (A98Sa) and $2.47^{+0.21}_{-0.20}$ for the eastern subcluster (A98Sb). Our measured temperatures are consistent with that of Paterno-Mahler et al. (2014) within their uncertainties (90% confidence limit). We also found that A98Sb is cooler than A98Sa at a 5σ level. This implies that A98Sb has a remnant cool core, whereas the core of A98Sa has been disrupted so that this is a non-cool-core cluster. The surrounding ICM of A98Sa may have been heated by either the ongoing merger or a previous merger.

We next examined the “tail”-like substructure of the eastern subcluster that appeared in the unsharp-masked image (Figure 4). We extracted spectra from three individual regions, as shown in Figure 4. For region 2, this yielded a temperature $kT = 1.8^{+0.3}_{-0.2} \, $keV and an abundance $Z = 0.35^{+0.40}_{-0.27} \, Z_{\odot}$. Due to low photon counts in regions 1 and 3, we linked the parameters for those two regions while fitting, assuming they have similar temperature and abundance. For regions 1 and 3 together, we measured a temperature $kT = 3.1^{+0.6}_{-0.5} \, $keV and an abundance $Z = 0.80^{+0.91}_{-0.57} \, Z_{\odot}$. We found the tail is significantly cooler than the surrounding gas at about the 4.2σ level, which suggests that it is likely to be a cool-core remnant that is being ram-pressure stripped.

Figure 5 shows that A98Sb has a surface brightness edge in the northeast direction at about 28 kpc from its core. To measure the temperature across the surface brightness edge, we divided the eastern sector into four individual regions and extracted spectra from them. Those regions were drawn to contain a minimum of 1000 background-subtracted photon counts in each extracted spectrum. We set this lower limit to ensure reasonable constraints on the parameters. We fitted each spectrum with the abundance fixed to $Z = 0.4 \, Z_{\odot}$. Figure 9 shows the best-fit projected temperature profile of the eastern...
Figure 8. Temperature (a), deprojected electron density (b), and projected electron pressure (c) profiles centered on the A98N core. The metallicity was fixed to $0.4 Z_{\odot}$. The projected pressure profile was estimated using the deprojected densities and projected temperatures. The vertical dashed line represents the position of the surface brightness edges. Top panels: profiles for northern sector. Bottom panels: profiles for eastern sector. In both panels (a) red represents the temperature profile for the western sector.

Figure 9. Eastern sector projected temperature, deprojected electron density, and projected electron pressure profiles centered on the A98Sb core. The metallicity was fixed to $0.4 Z_{\odot}$. The projected pressure profile was estimated using the deprojected densities and projected temperatures. Vertical dashed line represents the position of the surface brightness edge.
sector. The projected temperature of the gas increases rapidly at about 28 kpc, by a factor of 3.6. This temperature jump coincides with the surface brightness edge at 28 kpc, as shown in Figure 9, and corresponds to a drop in the deprojected electron density by a factor of about 2.8. Figure 9 also shows the projected electron pressure profile of the eastern sector. We found that the electron pressure is roughly constant across the surface brightness edge. We, therefore, confirm this edge as a cold front contact discontinuity.

We next examined the surface brightness edge shown in Figure 10 (left) southwest of A98Sa by extracting spectra from that sector, dividing it into five individual regions. We fitted the spectrum from each region with the abundance fixed to 0.4 $Z_{\odot}$. The best-fit projected temperature profiles are shown in Figure 10 (right) with different levels of uncertainty. Considering both levels of uncertainties, we found that the temperature profile rises to $kT = 5.1$ keV at about $\sim 375$ kpc, then drops suddenly to $kT = 3.3$ keV with a jump factor of $\sim 1.5$. Taken all together, this is consistent with a shock. From the 3D density jump factor we obtained the Mach number of $\approx 1.47 \pm 0.20$. Since this jump corresponds to a drop in the projected electron density by a factor of $\approx 1.47 \pm 0.20$ keV, $2.1\sigma$ cooler than the surrounding gas, bolstering the idea that the spiral structure indeed a gas sloshing spiral.

1. The residual image of A98N shown in Figure 2 reveals a gas sloshing spiral winding clockwise when traced inward from a large radius. The sloshing spiral in A98N indicates that it too experienced a separate merger, probably in the past few billion years based on the timescale for the formation of the sloshing spirals seen in simulations. The temperature of the spiral structure is $3.14^{+0.16}_{-0.15}$ keV, $2.3\sigma$ cooler than the surrounding gas, bolstering the idea that the spiral structure indeed a gas sloshing spiral.

2. We have detected two cold fronts in the north and east directions at about 60 kpc and 70 kpc, respectively, from the A98N core. For the northern cold front, we obtain a drop in the deprojected electron density by a factor of $\rho_1/\rho_2 \approx 1.47 \pm 0.01$. This jump corresponds to an increase in the projected temperature by a factor of 1.4. Similarly, for the eastern cold front, we find a decrease in the electron density by a factor of $\rho_1/\rho_2 \approx 1.38 \pm 0.03$ and an increment in the temperature by a factor of 1.3. These two cold fronts are likely to be associated with the gas sloshing at the central region of A98N.

3. With our deeper Chandra data, we find the average temperature of A98Sa, $kT = 3.70^{+0.33}_{-0.28}$ keV, and of A98Sb, $kT = 2.47^{+0.21}_{-0.20}$ keV, consistent with that of Paterno-Mahler et al. (2014). We report that the eastern subcluster is cooler than the western subcluster with about a 5$\sigma$ significance.

4. The unsharp-masked image shown in Figure 4 exhibits a tail of X-ray emission in the south/southwest direction of the A98Sb core. Our measurement shows that the tail is considerably cooler ($1.8^{+0.3}_{-0.2}$ keV) than the surrounding gas ($3.1^{+0.6}_{-0.4}$ keV) at a 4.2$\sigma$ level and the A98Sb core ($2.47^{+0.21}_{-0.20}$ keV) at a 2.9$\sigma$ level. This implies that the tail is
likely to be ram-pressure-stripped material from a cool-core remnant.

5. Figure 6 shows that the excess X-ray emission near the central region of A98Sb appears to be a spiral pattern winding counterclockwise if traced inward from a larger radius. The spiral structure and the tail are more likely to be associated with ram-pressure stripping, as the cluster orbits in the main cluster’s gravitational potential. We have detected a cold front in the east direction of A98Sb. We measure a drop in the deprojected electron density by a factor $\rho_2/\rho_1 \approx 2.8 \pm 0.02$ and a rise in the projected gas temperature by a factor of 3.6 across the front.

6. We have reported detecting a surface brightness edge at 375 kpc southwest from the A98Sb core, visible in Figure 10. The deprojected electron density drops by a factor $\rho_1/\rho_2 \approx 1.7 \pm 0.5$ and the projected temperature drops by a factor of $\approx 1.5$, suggesting the edge is a shock front with a Mach number $M \approx 1.5$.

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