THE MERGING GALAXY CLUSTER A520—A BROKEN-UP COOL CORE, A DARK SUBCLUSTER, AND AN X-RAY CHANNEL

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ABSTRACT

We present results from a deep Chandra X-ray observation of a merging galaxy cluster A520. A high-resolution gas temperature map reveals a long trail of dense, cool clumps—apparently the fragments of a cool core that has been stripped from the infalling subcluster by ram pressure. The clumps should still be connected by the stretched magnetic field lines. The observed temperature variations imply that thermal conductivity is suppressed by a factor >100 across the presumed direction of the magnetic field (as found in other clusters), and is also suppressed along the field lines by a factor of several. Two massive clumps in the periphery of A520, visible in the weak-lensing mass map and the X-ray image, have apparently been completely stripped of gas during the merger, but then re-accreted the surrounding high-entropy gas upon exit from the cluster. The mass clump that hosted the stripped cool core is also reaccreting hotter gas. An X-ray hydrostatic mass estimate for the clump that has the simplest geometry agrees with the lensing mass. Its current gas mass to total mass ratio is very low, 1.5%, which makes it a “dark subcluster.” We also found a curious low X-ray brightness channel (likely a low-density sheet in projection) going across the cluster along the direction of an apparent secondary merger. The channel may be caused by plasma depletion in a region of an amplified magnetic field (with plasma β ~ 10−20). The shock in A520 will be studied in a separate paper.

Key words: galaxies: clusters: individual (A520) – intergalactic medium – X-rays: galaxies: clusters

1. INTRODUCTION

Galaxy clusters form and grow via mergers of less massive systems in a hierarchical process governed by gravity (e.g., Press & Schechter 1974; Springel et al. 2006). In the course of each merger, approximately speaking, the kinetic energy carried by the gas of the colliding clusters dissipates into thermal energy via shocks and turbulence and, in the absence of further disturbances, the hotter gas comes into approximate hydrostatic equilibrium with the deeper gravitational potential of the resulting bigger cluster (e.g., Bahcall & Sarazin 1977) on a ~gigayear timescale. What happens during that gigayear of violent gas motions is very interesting because it can illuminate several aspects of the physics of the intracluster plasma (e.g., Markevitch & Vikhlinin 2007). Ram pressure of the gas flows may strip the subclusters of their gas (e.g., Clowe et al. 2006) and disturb and even destroy their cool cores, either directly (e.g., Fabian & Daines 1991; Markevitch et al. 2000) or by facilitating mixing with the surrounding gas (Zuhone et al. 2010). Temperature gradients in the gas generated by shock heating and mixing of different gas phases should be quickly erased by thermal conduction, if it is not suppressed (e.g., Markevitch et al. 2003b; Eckert et al. 2012). All of this makes observations of merging clusters in the X-ray, where we can map the density and temperature of the hot intracluster plasma, extremely interesting.

The hot (T ~ 7 keV,Govoni et al. 2004) galaxy cluster Abell 520 at z = 0.203 (Westphal et al. 1975) is one of only a handful of merging systems with a shock front clearly visible in the sky plane (Markevitch et al. 2005), which makes the merger geometry quite unambiguous. The cluster has a detailed map of the projected total mass distribution derived from weak gravitational lensing data (Mahdavi et al. 2007; Okabe & Umetsu 2008; Clowe et al. 2012; Jee et al. 2012, 2014). We show an uncropped version of the mass map from Clowe et al. (2012), provided by D. Clowe (2016, private communication), in Figure 1(c). While the above authors disagree on the details (in particular, Mahdavi et al. and Jee et al. reported the presence of a “dark clump” with an anomalously high M/L ratio in the middle of the cluster, marked by a green cross in Figure 1(c), while Clowe et al. contested its statistical significance), the lensing maps agree qualitatively quite well. The overall picture is a “train wreck” of several mass clumps mostly aligned in a chain along the NE–SW direction. This is consistent with the merger direction indicated by the X-ray shock front.

In this paper, we analyze in detail an extra-deep 0.5 Ms Chandra observation of A520. It will allow us to gain insights into many of the above physical processes, such as the cool core stripping and the suppression of thermal conductivity. Analysis of the shock front based on the same X-ray data, supplemented by the archival radio data, will be given in a future paper (Q. H. S. Wang et al. 2016, in preparation).

We assume a flat cosmology with H0 = 70 km s−1 Mpc−1 and Ωm = 0.3, in which 1″ is 3.34 kpc at z = 0.203. Errors are quoted at 90% confidence in text, and at 1σ in the figures, unless otherwise stated.

2. X-RAY DATA ANALYSIS

We analyzed observations of A520 with the Chandra Advanced CCD Imaging Spectrometer (ACIS) between 2007 December and 2008 January for a total of 447 ks (ObsIDs 9424, 9425, 9426, 9430). This gave 423 ks after cleaning for flares as described in the next paragraph. We chose not to combine these with earlier observations (ObsIDs 528, 4215, and 7703 with exposure times 9.47 ks, 66.27 ks, and 5.08 ks, respectively). The two short observations will not meaningfully
improve our results, so we omitted them for simplicity. ObsID 4215 is affected by a long low-level background flare, which Markevitch et al. (2005) modeled as an excess over the quiescent background and propagated the error for spectral modeling. Seeing this would increase our total exposure time by at most 15%, yet potentially introduce more uncertainty to background subtraction (see Section 2.1). We chose not to complicate our subsequent analysis.

We reprocessed Level = 1 event files using acis_process_events of the Chandra X-ray Center (CXC) software, CIAO (4.6).\footnote{http://cxc.harvard.edu/ciao} We applied the standard event filtering procedure of masking bad pixels, grade filtering, removal of cosmic-ray afterglow and streak events and the detector background events identified using the VFAINT mode data. Periods of elevated background were identified using the 2.5–7 keV light curve in a background region free of cluster emission on the ACIS-I chips (by excluding a circle of $r = 7'$ centered on A520 and another circle of $r = 1.5'$ on a small extended source to the SW). Time bins of 1 ks were used, and bins with count rates that were more than 20% different from the mean value were discarded, resulting in 423 ks of total clean exposure. During the clean exposure, no gradual changes in the quiescent background level were apparent during any of the observations; the mean rates varied with time by less than

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example.png}
\caption{(a) Chandra 0.8–4 keV surface brightness binned to 1'' pixels, without smoothing or source removal. The color scale is in units of \text{10}^{-6} \text{ counts s}^{-1} \text{ arcsec}^{-2}. The red cross marks the center of the BCG, offset from the bright tip by about 20'' = 67 kpc. (b) Wavelet smoothing of the image in panel (a), with point sources removed, with brightness contours spaced by a factor of 1.5. (c) Weak-lensing mass contours from D. Clowe (2016, private communication), overlaid on the wavelet X-ray image from panel (b). The contour levels (mass surface density, linear step) are the same as in Clowe et al. (2012). The green cross marks the position of the contested “dark clump” and the red cross marks the BCG. (d) Residual X-ray image after subtracting the >210 kpc scale wavelet components, slightly smoothed. Prominent features discussed in this paper are marked in panels (b) and (d).}
\end{figure}
10%. We also checked that there was no time variability in the ratio of the 2.5–7 keV to 9.5–12 keV counts using time bins of 10 ks. The mean value of this ratio was also in good agreement (within 2%) with that in the blank-sky background data set. The latter two checks ensure the absence of faint residual background flares and the accuracy of modeling the detector background using the blank-sky data set (Hickox & Markevitch 2006) that we describe below.

The ACIS readout artifact was modeled using make_readout_bg\(^5\) and treated as an additional background component in our analysis (as in Markevitch et al. 2000).

To create flux images, exposure maps were created using Alexey Vikhlinin’s tools.\(^6\) The exposure maps account for the position- and energy-dependent variation in effective area and detector efficiency. The exposure maps for different observations were co-added in sky coordinates. Then, the co-added background-subtracted count images were divided by the total exposure map to produce a flux image. The four observations of A520 were set up with small relative offsets in the sky to minimize the effect of chip gaps on the final total image.

We excluded point sources from our analysis by visually inspecting the 0.8–4 keV and 2–7 keV images at different image bining and smoothing scales.

### 2.1. Sky Background

To model the detector and sky background, we used the ACIS blank-sky background data set from the corresponding epoch (“period E”) as described in Markevitch et al. (2003b) and Hickox & Markevitch (2006). The VFAINT mode filter was applied; the events were projected to the sky for each observation using make_acisbg.\(^7\) The count rate derived from the background data was then scaled so that it had the same 9.5–12 keV counts as the observed data. This was further reduced by 1.32% to accommodate the amount of background contained in the readout artifact. For flux images, this was done by multiplying the background counts image by a rescaling factor. For spectral analysis, this was effected by setting the BACKSCAL keyword in the spectra FITS files.

After subtracting the ACIS background normalized by the 9.5–12 keV rate, the 90% uncertainty of the 0.8–9 keV quiescent background normalization is 3% (Hickox & Markevitch 2006). We will vary the background normalization by this amount to estimate its contribution to the overall uncertainties. This is particularly important for the low surface brightness cluster outskirts for which the temperature uncertainties are dominated by the background; hence, our decision to exclude ObsID 4215 in our analysis due to the presence of a flare.

After subtracting the blank-sky and readout artifact backgrounds, the spectrum of the cluster-free background region revealed a small positive residual flux mostly at \(E \sim 2\) keV. Some residual (positive or negative) is expected, as the soft CXB varies across the sky and the blank-sky data set comes from other regions of the sky. We modeled this residual in the 0.5–9 keV band with an empirical spectral model consisting of two APEC components, a power law and a Gaussian. The thermal components were set to temperatures of 0.2 and 0.4 keV and their normalizations were allowed to vary, based on the study of the soft CXB (Markevitch et al. 2003a). The Gaussian component best fit was at \(E = 0.92 \pm 0.02\) keV with zero width (\(\sigma < 0.04\) keV). The power-law component was added to account for the residuals above 2 keV, and it was found that a photon index of 0.6 made a qualitative improvement. Of course, there is no physical significance to this empirical model because it describes a difference between the true CXB (and possibly a very faint residual flare emission) and the CXB components included in the blank-sky data set. An alternative is to use the “stowed” ACIS background data set, which contains only the detector background, and adds physically motivated CXB components. However, the available stowed background data set has a much shorter exposure than the blank-sky data set, which is critically important for our extra-deep A520 observation. We assumed that our empirical residual background was constant across the FOV (before the telescope vignetting), and included this model, adjusted for sky and exposure time, when doing spectral fits for the cluster regions. For the narrow-band flux images, the residual was accounted for by subtracting a constant value such that the flux in the background region was zero. A520 is sufficiently small and there is enough cluster-free area within the FOV to make this additional background modeling step possible.

### 2.2. Spectral Analysis

The instrument responses for spectral analysis were generated as described in Vikhlinin et al. (2005). We used the CHAV tool runextrspec to generate the PHA, ARF, and RMF files for each pointing. The PHA files (observed data, blank-sky background, and readout background) were co-added using addspec from FTOOLS package. The addarf and addrmf from FTOOLS were used to add ARFs and RMFs. They were weighted by 0.5–2 keV counts in the applicable spectral extraction region.

Spectral analysis was performed in XSPEC (version 12.8.2). A single-temperature fit to the cluster in a 3′ circle (0.6 Mpc) centered on soft-band flux centroid at \((\alpha, \delta) = (04:54:09.7, +02:55:25.7)\) (FK5, J2000) gives \(T = 8.3 \pm 0.3\) keV, metal abundance 0.21 ± 0.02 (relative to Anders & Grevesse 1989), and absorption column \(N_H = (6.3 \pm 0.7) \times 10^{20}\) cm\(^{-2}\). Factored into the error are the formal error from fitting, the effect of the modeled soft residual background, and the 3% uncertainty of the blank-sky background.

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5 http://cxc.harvard.edu/contrib/maxim/make_readout_bg
6 http://hea-www.harvard.edu/~alexey/CHAV
7 http://cxc.harvard.edu/contrib/maxim/acisbg/
8 Online tool: http://www.swift.ac.uk/analysis/nhtot/index.php.
3. TEMPERATURE MAPS

Temperature maps shown in Figure 2 were derived following the method described in Markevitch et al. (2000). We extracted six narrow-band flux images between 0.8 and 9 keV, excluding the 1.7–1.9 keV edge and 7.3–7.6 keV (possibly affected by poor subtraction of the instrumental lines). Both flux and error images were smoothed prior to deriving the temperature map. A single-temperature MEKAL model was then fitted to a set of six flux values from each pixel of the image, resulting in a smoothed temperature map. The absorption column and metal abundance were fixed to the cluster best-fit values. Two smoothing methods were used, as described below.

3.1. Smoothing with the Variable-width Gaussian Kernel

For this approach, the narrow-band images were smoothed using a Gaussian kernel for which the width at each image pixel is determined by surface brightness in the 0.8–4 keV band, with the goal of preserving detail in bright regions. As a reference for this smoothing method, but also as a high-quality X-ray image that shows the cluster structure on all scales and omits point sources, we used wavelet reconstruction of the 0.8–4 keV image, as described in Vikhlinin et al. (1994, 1998). We extracted wavelet components (with the atrous kernel and scales increasing in geometric progression) on scales of 53, 105, 210, and 420 kpc (or $15''7$, $31''5$, $63''0$, and $126''$). Point sources are contained in wavelet components on smaller scales than the first scale above, thus not included. These image components were then co-added with the residual image smoothed by the 840 kpc scale wavelet. This procedure retains most of the statistically significant extended structures on various angular scales. The resulting image is shown in Figure 1(b) next to the original unsmoothed image; we will use it as a reference when discussing various features in this cluster.

Based on this reference image, the narrow-band images and their corresponding error images (with point sources excised) were identically smoothed by a variable-width Gaussian. By inspecting the error in the derived temperature map, we determined that using the Gaussian smoothing radius $\propto$ flux$^{-0.7}$, and smoothing radius between 13 and 200 kpc, achieved a balance between revealing the temperature variations and suppressing noise. The resulting temperature map is shown in Figure 2(a).

To check the validity of values shown in the map, we extracted the proper spectra in a few hot spots >10 keV and a cooler spot (regions T1–T4 and T5 in Figure 2(a), respectively) and fitted their projected temperatures in XSPEC. For T1, we obtain $12.1^{+3.4}_{-2.4}$ keV; for T2, $11.3^{+4.1}_{-2.6}$ keV; for T3, we could only obtain a lower bound of 11.9 keV. For T4, the fit is $12.2^{+2.5}_{-1.9}$ keV, and for T5, $6.4^{+1.2}_{-1.4}$ keV—all values close to those in the smoothed map.

3.2. Wavelet-smoothed Temperature Map

The second method uses wavelet image decomposition to identify structures at different angular scales, and leaves only the wavelet components on the scales of interest in the narrow-band images used for temperature fitting, instead of simple Gaussian smoothing. This method allows us, for example, to subtract the structures on large angular scales and recover the temperature contrast of features on the interesting small scales by reducing the projection effects. Of course, such “deprojection” can only be qualitative because we do not know the gas distribution along the l.o.s. and have to assume that structures on different scales are simply projected. Nevertheless, for the interesting high-contrast features in A520, this assumption should be close to reality.

This method has the greatest utility to recover the small-scale, cool, bright structure at the “foot” and “leg” of A520 (Figure 1). These high-gradient structures are mostly lost in the adaptive Gaussian smoothing. By using the wavelet decomposition instead of smoothing, the shape of these brightness features are better preserved.

We extracted wavelet components from the 0.8 to 4 keV image binned to 1″ pixels, using 6.6, 13, 26, 53, and 105 kpc.
scale wavelets, selecting the thresholds of statistical significance in order to achieve balance between retaining small-scale details and minimizing noise and artifacts. The wavelet decomposition coefficients calculated for the 0.8–4 keV image were used for all narrow-band images and their corresponding error images (that is, the same smoothing was applied in all energy bands, as in Section 3.1). Point sources in the 6.6 kpc wavelet component were removed from those images before coadding different scales. The resulting temperature map is shown in Figure 2(b); it reveals the small-scale structure much better than the one in panel (a) at the expense of being only qualitative.

4. RESULTS

4.1. Shock Front (or Fronts?)

The bow shock to the SW of the cluster center, first reported in Markevitch et al. (2005), is readily apparent in the 0.8–4 keV image (Figure 1) and in the temperature map (Figure 2). The latter shows a region of about 5 keV in front of the shock and 9–10 keV behind the shock. We extracted spectra from four sectors in two annular regions in front of the shock (S3–S10), and three sectors (S0–S2) including the shock (Figure 4). In the preshock region, temperatures are ~5 keV and are remarkably similar over this large area. Overall, it appears that the preshock region is cool and undisturbed, with temperature falling with radius slightly from $T = 5.7 \pm 0.8$ keV (S3–S6 combined, $r \approx 650$ kpc from the cluster center) to $T = 4.5 \pm 0.8$ keV (S7–S10 combined, $r \approx 900$ kpc). Behind the shock, in regions S0–S2, the temperatures span 8–14 keV. The values are consistent with Markevitch et al. (2005) analysis of a shorter data set, who found $T = 4.8^{+1.2}_{-1.0}$ keV in front of the shock and $T = 11.5^{+0.7}_{-0.3}$ keV behind (the latter value is deprojected, and therefore not directly comparable to that here). In region S2, a cool blob of gas appears to be projected onto the shock. This feature is coincident with a small but discernible brightness enhancement in the soft-band image. It could be a splash or a broken off blob of the cool core inside the shocked gas. Regardless of its origin, it may need to be masked in the analysis of the shock, which will be the subject of a separate paper.

There is a kink in the shock surface (marked in Figure 1), behind which (downstream from the shock) is a region of enhanced X-ray brightness (“plume” in Figure 1). The gas in the plume (region S0) is as hot as the post-shock gas elsewhere, though the temperature map (Figure 2) suggests a mixture of different temperatures there. It appears that a local gas inflow from the south is crossing the shock at that location.

There is an apparent steepening of the surface brightness profile along the NE–SW merger direction, northeast of the cluster center (located between splashes B and C in Figure 1(b)) that looks like a counterpart (“reverse”) shock to the main shock front. However, we do not detect a significant difference in projected temperature between regions C3 and C4 (Figure 4) ahead and behind that brightness feature. The presence of other features (splash B, bump C, the tail) makes this a crowded location compared to the clean SW bow shock, and it is unlikely that we can deproject the emission correctly.

4.2. Break up of the Cool Core Remnant

Behind the shock is a twisted structure resembling a leg (labeled in Figures 1(b) and 3). There are dense clumps, as inferred from their high surface brightness, at the foot and at the knee, and more along the ridge extending east from the knee (most pronounced in the unsharp-masked image of Figure 1(d)). The foot (zoomed-in inset of Figure 4) is particularly striking. It consists of two bright, very elongated (50 × 10 kpc and 50 × 20 kpc in projection) clumps separated by a gap with an X-ray brightness contrast of >2. Their
projected temperatures are 1.5–2.5 keV (Figure 4); the narrower finger on the outside is the colder of the two. There is no apparent galaxy coincident with the foot, but the fingers are displaced from the center of the BCG of one of the infalling subclusters by only 16″ = 50 kpc.

The wavelet temperature map in Figure 3 shows that cool clumps trace the structure extending north from the foot to the knee, which then turns east, continuing toward “splash A” and “splash D” (Figure 2; splashes will be discussed in Section 4.3). At the knee, a small X-ray brightness cavity does not show a significant deviation in projected temperature from the bright blobs above it. Not all the surface brightness enhancements correspond to cool spots (as one would expect if the structure were in pressure equilibrium), suggesting that projection effects are significant.

The overall picture strongly suggests that the “foot” and the bent “leg” formed as a result of the disruption of a cool core, once hosted by the subcluster centered on the BCG that is now ahead of the foot (Figure 1). The cool core has been swept off its host by strong ram pressure of the merger, but has not yet been completely mixed with the hot surrounding gas. This is similar to the cool “bullet” in the Bullet cluster displaced from the former subcluster host (Markevitch et al. 2002; Clowe et al. 2006), but, while the cool core in the Bullet cluster remains a coherent shuttlecock structure, in A520 the disruption has gone much further.

To see if this picture is consistent with the properties of the cool clumps, we estimate the gas specific entropy and check if it is similar to that in typical undisturbed cool cores. We calculate the specific entropy using the following definition (widely used in X-ray cluster work):

\[ K = Tn_e^{-2/3} \]  

(1)

where \( T \) is the gas temperature and \( n_e \) is the electron number density. In all of our analyses, we assume \( n_e = 1.17 n_H \). Since the regions in question are small and bright, they dominate the emission along the l.o.s., so no deprojection is needed for a qualitative estimate.

For the outer, thinner finger (F1 in Figure 4), \( T = 1.7 \) keV. If we use the size of the spectral fitting region and assume an elongated shape, i.e., \( 10 \times 10 \times 50 \) kpc square cuboid, the derived density is \( n_H = 2 \times 10^{-2} \text{ cm}^{-3} \), giving \( K \approx 20 \text{ keV cm}^2 \). Since the emission is actually confined to a narrower part of the fitting region, if we assume instead a cylinder of the same length 50 kpc and diameter of 5 kpc (half the width of the extraction region), the density estimate increases by a factor of \( \sqrt{16/\pi} \) to \( 5 \times 10^{-2} \text{ cm}^{-3} \), which gives \( K \approx 12 \text{ keV cm}^2 \). Alternatively, if the blob is cap-like, taking the geometry of a flat cylinder 50 kpc in diameter and 5 kpc thick, the density changes by a factor of \( \sqrt{8/5\pi} \) to \( 1.4 \times 10^{-2} \text{ cm}^{-3} \), which gives \( K \approx 25 \text{ keV cm}^2 \).

For the inner, wider finger (F2 in Figure 4), \( T = 2.4 \) keV in an elliptical spectral extraction region. Its density is \( n_H = 1.3 \times 10^{-2} \text{ cm}^{-3} \), \( K \approx 40 \text{ keV cm}^2 \) assuming constant density for a prolate spheroid with symmetry axis in the sky plane, or \( n_H = 8 \times 10^{-3} \text{ cm}^{-3}, K \approx 60 \text{ keV cm}^2 \) for an oblate spheroid instead.

The entropy estimates vary by a factor of two for the different geometries (elongated versus cap-like) but are not drastically different. Since the specific entropy could only have
increased in the process of merger disruption (e.g., via mild shock heating), such specific entropy values, along with the high gas densities, put these gas clumps confidently in the parameter space of the central core regions of cool-core clusters, where typically $K \sim 15$ keV cm$^2$ as opposed to non-cool-core clusters, where $K \sim 150$ keV cm$^2$ (Cavagnolo et al. 2009). Thus, the cold gas “leg” indeed appears to be a trail of pieces of a merger-disrupted cool core being swept by the gas flows. We will use this conclusion in Section 5.4.

4.3. Splashes, Bumps, and Islands

The eastward extension of the leg curves to the SE after about 300 kpc, and ends with a steep brightness drop (“splash A” in Figure 1(b)) not far beyond. The gas at the dense side of the brightness drop appears to be cooler than the surroundings, including the gas along this structure but closer to the center. While the projected temperature in region G3 (which contains the tip of the splash) is only marginally lower than in regions G2, G1 in Figure 4, and the temperature in region G4 in front of the splash is poorly constrained, the temperature contrast becomes quite pronounced in the wavelet temperature map in Figure 2(b). This splash looks like a hydrodynamic feature caused by a “ram pressure slingshot” (Hallman & Markevitch 2004), in which a rapid decline of ram pressure in a merger causes a parcel of gas to move into the less-dense gas and expand adiabatically, forming a cool spot. In this case, it could be one of the low-entropy clumps remaining of the cool core and forming the cool leg.

North of the cluster center, there is another hydrodynamic structure of likely similar origin (“splash B” in Figure 1(b); also region T5 in Figure 2). The surface brightness structure is picked out by wavelet decomposition, which can be seen in the original image to appear like a pointed stream of gas. The temperature maps indicate that this region is cool. The gas there is not necessarily related to the cool core.

There is a subtle brightness island extending further SE from splash A, marked “island D” in Figures 1 and 2, whose origin is unclear. Its projected temperature is not well constrained but does not rule out a cool structure.

Another splash-like structure (“bump C” in Figure 1(b)) is located symmetrically opposite splash B about the merger axis. Unlike splashes A and B and island D, it coincides with one of the weak-lensing mass clumps. Its projected temperature is in line with the cluster average and may even be higher (as suggested by the wavelet map). This bump may have an entirely different origin, a subcluster adiabatically accreting gas, similar to the feature that we will discuss in Section 5.3.

5. DISCUSSION

5.1. Scene of a “Train Wreck”

The detail-rich Chandra X-ray image and gas temperature maps of A520, especially the map in which we subtracted the large-scale cluster emission using wavelet transformation, tell a complex story about the events in this merging cluster. From the X-ray and weak-lensing data, we see a major merger proceeding mostly along the NE-SW axis. The NE chain of subclusters have apparently moved away from the collision site, completely stripped of their gas and currently hosting only low-level bumps of X-ray emission (we will discuss this in detail in Section 5.3). The SW subcluster is also moving away from the cluster center, driving a prominent shock front.

Figure 5. Radial profiles, extracted in the annular sector in Figure 3(a), of X-ray surface brightness (upper panel) and gas temperature (lower panel). The gray band is 30 kpc wide centered on the location of the channel, marked by white ticks in the profile extraction sector. Error bars for X-ray brightness and temperature are 1σ. Radial distance is from the center of curvature of the sector.

Apparantly, this subcluster had a cool core, which is now being stripped by ram pressure, leaving a trail of cool clumps —“foot,” “knee,” and “leg.” The meandering shape of this trail, its ending with splashes A and D, together with several other signs of complex hydrodynamics, such as the kink in the shock surface, the “plume” next to it, and “splash B” (Figure 1), suggest a secondary collision along the north–south direction. A curious X-ray “channel,” possibly resulting from this secondary merger, will be discussed in Section 5.2. The full history and details of this “train wreck” of a cluster may be understood better with a dedicated hydrodynamic simulation. However, our present broad-brush understanding of the A520 merger already lets us make three measurements that are interesting from the cluster physics viewpoint.

5.2. X-Ray Channel

A close look at the X-ray image (in particular, Figure 3(a), which show the image with different bin sizes, and Figure 1(d), which shows an “unsharp-masked” image), reveals a subtle, long X-ray brightness “channel.” It aligns with the direction of the secondary merger that we mentioned above, running from the “plume” in the south through the central region of the cluster toward “splash B” in the north (Figure 1). We selected a sector in which this channel is most apparent and which excludes any interfering features such as the leg, as shown in Figure 3(a). An X-ray brightness profile across the channel extracted in this sector is shown in Figure 5. It confirms a highly significant ~10%–12% drop in X-ray surface brightness. The channel is about 30 kpc (9″) wide and at least 200 kpc long, which is its length within our sector; though, the channel clearly extends beyond it and can be traced as an X-ray dip in the leg and plume in the south, and similarly further to the north.
The channel has to be a relatively thin sheet of lower-density gas seen along the edge. If we assume a rough spherical symmetry of the main cluster body, and assume that the channel is completely devoid of gas in 3D, the sheet’s extent along the l.o.s. would have to be $\sim 75$ kpc to give the observed projected X-ray brightness drop. Since it cannot be completely empty, the extent should be significantly greater.

It is interesting to speculate on the origin of the X-ray channel. First, we note that X-ray “cavities” filled with radio emission are routinely observed in cluster cool cores (e.g., McNamara et al. 2000; Fabian et al. 2002, and later works); they are created by outbursts of the central AGN, where the ejected relativistic matter expands and pushes the thermal gas away.

However, the channel/filament in A520 is not in a cool core, and its 500–700 kpc size is far greater than any of the cavities seen in cluster cores. In principle, if in a certain region, the magnetic field pressure reaches levels comparable to the thermal pressure of the ICM, it may push the plasma away from this region, in a manner similar to “plasma depletion layers” observed near planets (e.g., Øieroset et al. 2004) and features seen in the galaxy cluster context in MHD simulations by ZuHone et al. (2011; see their Figure 23). Such a phenomenon may have recently been observed by Werner et al. (2016) in the core of the Virgo cluster (though they observed X-ray enhancements rather than depletion regions).

In such a scenario, the sum of thermal and magnetic pressure inside the channel would equal the thermal pressure outside (assuming the magnetic pressure outside to be negligible, as expected for the bulk of the ICM). Neglecting projection effects—that is, assuming the channel to be a broad sheet spanning the whole cluster along the l.o.s.—the observed drop in X-ray brightness would correspond to a drop in gas density by 5%–6% and a drop in thermal pressure by 5%–15% depending on the temperature behavior. Such a drop of thermal pressure would imply a plasma $\beta_p$ parameter ($\beta_p \equiv p_{\text{thermal}}/p_B$) reaching 10–20, compared to the usual $\beta_p \sim $ few $\times 100$. In a high-$B$ filament seen in simulations by ZuHone et al., both density and temperature of the gas decline by similar factors, so the temperature is likely to decline in this scenario.

Alternatively, the channel may be a purely hydrodynamic feature—for example, a region of shock-heated gas currently in thermal pressure equilibrium, which has been squeezed into a sheet by gas flows. In this case, the temperature in the channel should be higher, by at least 5%, than that on the outside.

To test these two possibilities, we extracted a projected temperature profile in the same sector across the channel (Figure 5). It does not show any significant temperature changes from the regions outside the channel, but a 10% deviation in either direction cannot be excluded. Thus, both possibilities are viable on the basis of the X-ray data. If the channel’s span along the l.o.s. is less than assumed above, the 3D density and temperature contrast may be higher (and the magnetic field in the first scenario is higher too), but the projected surrounding denser gas would still make it difficult to detect any temperature difference.

Both of the above configurations may have emerged as a result of a minor merger along the north–south direction. For example, a small subcluster infalling from the south (to explain the kink in the shock surface) and crossing the main cluster could have stretched the magnetic fields in its wake, and/or generated a shock-heated region. Subsequently, this region could have been squeezed into a sheet—for example, by large-scale gas motions of the main NE–SW merger. One can also think of a radio-filled X-ray cavity swept off one of the merging cluster cores, stretched by an N–S merger and compressed into a sheet. It is unclear where that subcluster is now in the lensing mass map (it may be clump N in Okabe & Umetsu 2008, which is not, however, a particularly significant feature in Clowe et al. 2012), or how a low-density, unstable gas sheet could have survived as a coherent structure in the middle of an ongoing merger. Such details might be clarified by a dedicated hydrodynamic simulation. In all of the above scenarios, we expect the magnetic field in the channel to be enhanced and oriented preferentially along the channel (because of stretching and compression). This may produce a bright filament in the cluster’s giant radio halo (Govoni et al. 2001; Vacca et al. 2014), because the synchrotron radio emissivity is proportional to $B^2$, and that filament would be polarized. Giant radio halos are unpolarized (Feretti et al. 2012), so this would be a notable feature. The currently available radio data lack angular resolution to test this prediction (Q. H. S. Wang et al. 2016, in preparation).

5.3. Dark Subclusters in the Northeast

A520 exhibits a low X-ray brightness, relatively narrow tail, which is a subtle feature but is clearly visible out to about 1.3 Mpc northeast from the cluster center (Figure 1; seen more clearly in a heavily binned image in Figure 6). It has two broad X-ray peaks, each of which coincides with a mass clump seen in the weak-lensing map (Figure 6). The tail and the clumps are aligned in the NE–SW direction of the main merger. The outermost clump, centered 1.2 Mpc from the cluster center and approximately 0.5 Mpc in diameter, is particularly interesting, because it is relatively free of projection of the rest of the messy cluster, which lets us make several quantitative measurements.

Only two Chandra pointings (ObsIDs 9425, 9526) captured the tail, for an effective exposure of about 200 ks. Spectra
extracted from regions C1 and C2, which approximately include the outer and inner of the two tail clumps, respectively, show that they are both hot, with the outer tail clump (C1) being slightly hotter than the inner (Figure 4).

The tail mass peaks are visible in two independent data sets, Subaru (see Figure 11 in Okabe & Umemtsu 2008) and Magellan (Clowe et al. 2012). In the latter paper, only the inner-tail peak is shown (peak 1 in their Figure 2); the outer, less significant peak is not shown because it was outside the HST FOV, but it is seen in the uncropped version of the map provided by D. Clowe, which we show in Figures 1 and 6. The Subaru map covers a bigger field than Magellan or Chandra and reveals another clump (their clump NE1) still further to the northeast, but the Subaru map does not resolve these two Magellan tail clumps, showing them as one (NE2). For the quite substantial mass of the tail clumps suggested by lensing, not much gas can be seen in the Chandra image, and not much galaxy light is seen in the Subaru i'-band image either—in particular, in the outer tail clump (Figure 11c) in Okabe & Umemtsu). This is very interesting in view of the debated “dark core” in the center of A520; these clumps may be even “darker” and we will try to quantify this below.

We will now concentrate on the outer tail clump, because it is least affected by X-ray projection. (The inner-tail clump is more significant in the lensing map, but it is hopeless to deproject it in X-rays.) We will compare the specific entropy of the gas in the clump with that for the main cluster gas at the same distance from the cluster center, estimate the clump total mass under the hydrostatic equilibrium assumption, and derive a gas-to-mass ratio for the clump.

5.3.1. Specific Entropy of the Clump

To derive the gas density, we fit the heavily binned X-ray image (Figure 6) with a simple model consisting of two spherically symmetric 3D $\beta$-model density profiles—one for the clump and another for the main cluster outskirts near the radius of the clump. The $\beta$-model profile is given by

$$n_H(r) = n_{H,0} \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

where $r_c$, $n_{H,0}$ and $\beta$ are free parameters. Integrating $n_H^2$ along the I.o.s. gives an observed X-ray surface brightness profile (more precisely, the projected emission measure, which is very close to the surface brightness for the relevant range of gas temperatures and the Chandra energy band) in the form

$$\Sigma_X(\theta) \propto \left[1 + \left(\frac{d_\theta}{r_c}\right)^2\right]^{-3\beta+1/2},$$

where $d_\theta$ is the angular diameter distance and $\theta$ the angular distance from center.

For the cluster outskirts, we extracted a 0.8–4 keV radial surface brightness profile in an annulus around the same distance from the cluster center as the clump, with prominent asymmetric features (tail including the clump, foot, shock, splashes) masked out as shown in Figure 6. It is not obvious where the “center” of a messy merger is; for this exercise, the center is selected as a centroid of the X-ray emission at the relevant radii in the outskirts. We fit the profile in this annulus using a model given by (3), fixing the core radius $r_c$ at a typical value of 180 kpc (since we fit very far from the core). To determine the normalization $n_{H,0}$, we extracted a spectrum in the same region, fit it in XSPEC using an APEC model, and compared the model emission measure integrated over the region $\int n_H n_e dV$ with the absolute APEC model normalization given by XSPEC. The best-fit projected temperature is $T = 4.1^{+1.4}_{-0.9}$ keV, and the beta-model parameters are $\beta = 0.62^{+0.04}_{-0.08}$ and $n_{H,0} = (4.4^{+1.6}_{-1.2}) \times 10^{-3}$ cm$^{-3}$. At the clump’s radius, the outskirts density is $n_H = (1.3 \pm 0.1) \times 10^{-4}$ cm$^{-3}$ (density in the outskirts is better constrained than the beta-model normalization, which is an extrapolation of the profile in the outskirts).

The clump density model was then fitted in 2D (that is, pixel-by-pixel, as opposed to extracting a radial profile), because the cluster outskirts contribution makes the surface brightness distribution non-radial. We added a $\beta$-model density component for the clump to the density model for the outskirts, fixing the latter at its best fit derived above (which masked out the clump region with a good margin). We chose to add the clump density component, rather than replacing one with the other in the 3D region of the clump, to avoid any smoothness issues for the hydrostatic mass estimates; this choice does not matter as long as the model fits the X-ray image well. The sum of the two density components was calculated in 3D and a projected emission measure was calculated for each pixel of the X-ray image in a masked near-circular region of $r = 250$ kpc (Figure 6). The best-fit shape parameters for the clump are $\beta = 0.80 \pm 0.07$ and $r_c = 203^{+20}_{-16}$ kpc (uncertainties determined with the other parameter fixed at best-fit value) and the model fits the image well ($\chi^2 = 135/199 = 0.68$).

To derive the absolute gas density in the clump, we need the gas temperature. If we assume the clump to be isothermal with the outskirts, its density normalization can be derived directly from the X-ray surface brightness and the outskirts model derived above. This gives a density of $n_H = (1.0 \pm 0.1) \times 10^{-3}$ cm$^{-3}$ at the clump, of which the clump component dominates the outskirts component by a factor of seven—a significant gas overdensity.

However, the clump appears to have a higher projected temperature than the outskirts, $T = 8.1^{+3.6}_{-1.9}$ keV (for region C1 in Figure 4, which covers the clump), and its 3D temperature should be higher still. Therefore, we also consider the case in which an isothermal, but hotter, clump is embedded in the outskirts. We make a simple assumption that all gas within a $r = 250$ kpc sphere of the clump is at a higher temperature. We generate a model image with a cutout for this sphere and calculate the projected contribution of the 4 keV outskirts to the clump spectrum (it is about 9% in projected emission measure at the center of the clump). Adding this as a “background” model for the spectrum of the clump, we obtain a “deprojected” clump temperature $T = 9.7^{+2.5}_{-3.3}$ keV, which is slightly higher but consistent with the projected temperature (as expected, given the relatively high brightness contrast) and the density at the center of the clump increased by 10% to $n_H \approx 1.1 \times 10^{-3}$ cm$^{-3}$ compared to the isothermal assumption—a negligible change for our qualitative estimates, and considering the systematic uncertainties due to the unknown geometry.

Using the deprojected temperature and density for the clump, we can estimate the specific entropy of the gas at its center, defined as in Equation (1), $K = 930^{+510}_{-320}$ keV cm$^2$ (error accounts only for the uncertainty in temperature). For comparison, the gas in the outskirts has $K = 1540^{+320}_{-340}$ keV cm$^2$ at this radius. The two values are consistent, and both are
consistent with the entropy range of $(1-2) \times 10^3 \text{keV cm}^2$ observed at $r \sim 1-1.3$ Mpc for a large sample of clusters (Cavagnolo et al. 2009). The temperature and density of the gas in the clump are consistent with the adiabatic compression of the 4 keV gas from the outskirts perturbed by the gravitational attraction of the clump. In contrast, for cool cores, Cavagnolo et al. observe $K < 50$ keV cm$^2$, far below the observed value for the clump, so this gas cannot be a remnant of a former cool core (like the “foot,” Section 4.2). We will speculate on the sequence of events that could have created this clump after estimating its mass below.

### 5.3.2. Total Mass of the “Dark Clump” and its Possible Origin

Given the relative isolation of the tail clump, we can try to estimate its total mass, assuming that its hot gas is close to hydrostatic equilibrium with the clump’s gravitational potential. The equilibrium should be achieved on a timescale of sound crossing the size of the subcluster. Considering that the subcluster is unlikely to move supersonically at such a distance from the core (we also do not see any shocks around it), this assumption should be adequate for a qualitative estimate.

The total enclosed mass within the radius $r$ for a spherical mass clump is given by (e.g., Sarazin 1988)

$$M(<r) = -\frac{kT(r)r}{G\mu m_p} \left[ \frac{d \ln n_H}{d \ln r} + \frac{d \ln T}{d \ln r} \right],$$

where $\mu$ is the mean atomic mass per gas particle ($\mu \approx 0.6$ for ICM), $T(r)$ is the local gas temperature at the radius $r$, and $n_H$ is the gas density, which is the sum of the clump and outskirt density models in our case. For an accurate estimate, a temperature profile is required, for which our data are not adequate—all we know is that the temperature near the clump center is around 10 keV and it goes down to 4 keV in the main cluster’s outskirts. Therefore, we will make two isothermal estimates for these two temperature values to get a rough range of masses. (The higher temperature estimate would neglect the $(d \ln T/d \ln r)$ contribution, which should be nonzero in this case, partially canceling out the effect of the expected lower local $T$ at the radius of the estimate.) For the gas density gradient, we will use the best-fit model (sum of offset 3D beta-models) obtained above, calculating the gradient in the direction tangential to the main cluster in order to isolate the effect of the clump. We will calculate the mass for a radius well within our model fit above. Within a $r = 200$ kpc sphere, we obtain the total mass of $2.5 \times 10^{13} M_\odot$ and $6 \times 10^{13} M_\odot$ for the lower and higher temperature values, respectively (of course, statistical errors do not matter with such a modeling uncertainty). This is consistent with masses within the same radius derived for real mid-temperature clusters (e.g., Vikhlinin et al. 2006).

To assess the sensitivity of the clump hydrostatic mass estimate to our assumption of spherical symmetry for the main cluster’s outskirt, we varied the surface brightness of the outskirt by a factor of $\pm 2$ in the region of the clump and refitted the density model for the clump. The resulting variations in the quantity $d \log n_H/d \log r$ (where $n_H$ is the sum of the clump and outskirt components, and $r$ is the distance from the center of the clump), which determines the clump mass estimate, varies by at most 40% in the radial range of interest. Thus, our estimate should be relatively robust to geometric assumptions.

It is interesting to compare our mass estimate with a weak-lensing mass for this clump. D. Clowe (2016, private communication) provided us with an estimate of a projected mass within a cylinder of $r = 150$ kpc. Depending on whether the HST data (partially covering the clump) are included in the reconstruction along with the Magellan data, the projected mass is $(1.7-2.3) \times 10^{13} M_\odot$; the statistical significance of this clump detection is only 2–3$\sigma$. To convert our 3D measurement into a projected mass, we assume that the clump’s total mass profile is truncated at $r = 300$ kpc. For the low and high temperatures, we obtain the projected masses within the $r = 150$ kpc aperture of $2.4 \times 10^{13} M_\odot$ and $5.6 \times 10^{13} M_\odot$, respectively. The lower range of our X-ray estimates is in agreement with the lensing value.

With this qualitative validation for our mass estimate, we now estimate the gas mass fraction $f_{\text{gas}}$ for the clump. Within the $r = 200$ kpc sphere, we get $f_{\text{gas}} = 0.03$ and 0.014 for the cool and hot clump assumptions, respectively. This is low—even the former, conservatively high value is at least a factor of two below the $f_{\text{gas}}$ values observed within the same radius in relaxed clusters (e.g., Vikhlinin et al. 2006). So the tail clump appears to be “dark” in terms of the apparent deficit of both the galaxy light and the ICM density. The caveat here is that the uncertainty in the total mass is quite high, and one cannot be entirely confident in the X-ray hydrostatic equilibrium assumption here; a more sensitive weak-lensing observation may reduce the total mass and $f_{\text{gas}}$ uncertainty.

Based on the high specific entropy that we derived in Section 5.3.1 (consistent with that in the A520 outskirts), a cluster-like total mass and an anomalously low gas fraction, we speculate that this clump entered the collision site from the SW as a fairly massive subcluster. It then lost all of its gas to ram pressure stripping (and probably all matter in its outskirts to tidal stripping) during the passage through the main cluster, but re-accreted some high-entropy gas from the A520 outskirts once it emerged on the other side. The gas compressed adiabatically into its potential well once the subcluster slowed down sufficiently. Of course, the resulting $f_{\text{gas}}$ need not be anywhere near the universal value. On subsequent infall, such a subcluster would be the analog of the dark-matter dominated “gasless” subclusters used in idealized hydrodynamic simulations (e.g., Ascasibar & Markevitch 2006; ZuHone et al. 2010), which disturb the gravitational potential but produce few hydrodynamic effects.

Judging from the X-ray/lensing overlay, the more prominent inner-tail lensing mass peak (clump 1 in Clowe et al. 2012) appears to have a similar or even lower gas-to-mass ratio (the peak X-ray brightness is similar and the lensing mass is higher). We did not attempt any quantitative X-ray estimates for this clump because the 3D geometry is very uncertain.

We also note that the mass clump that hosted the stripped cool core, denoted “front clump” in Figure 6, appears to be reaccreting or concentrating the surrounding hotter gas. It is seen as an enhancement in density of the preshock gas at the position of the clump. Although this subcluster appears to be more massive than the tail clump, its gas density enhancement is smaller, probably because the gas is flowing over this dip in the gravitational potential toward the shock front with a higher velocity. As this subcluster moves to the periphery and slows
down with respect to the gas, it may re-accrete a gas halo similar to that of the tail clump.

Interestingly, Sasaki et al. (2015) observed three massive weak-lensing subhalos in the periphery of the Coma cluster with Suzaku. One of their subhalos exhibits a diffuse X-ray emission excess with the projected gas temperature similar to that of the surrounding ICM. They derive an extremely low gas fraction of \(0.001\) for it. These subhalos may be of similar nature to our dark clump—complete stripping of the original gas and subsequent reaccretion of the surrounding ICM.

5.4. Constraints on Thermal Conduction

Thermal conductivity is one of the important but poorly known properties of the ICM. It is determined by the topology of the tangled magnetic field frozen into the ICM and by plasma microphysics. The heat transport should be completely suppressed across the field lines (because the electron gyroradii are many orders of magnitude smaller than other relevant linear scales in the ICM, Sarazin 1988), while heat may flow along the lines between those regions of the ICM for which such a path along the lines exists. However, even along the field lines, the heat transport may be strongly suppressed in a high-\(\beta_p\) plasma (such as the ICM) because of micro-scale plasma instabilities (e.g., Schekochihin et al. 2008).

Observationally, few definitive measurements have been done. Across cold fronts, where the temperature jumps abruptly, thermal conductivity has been shown to be suppressed by at least a couple of orders of magnitude compared to the Spitzer value (Ettori & Fabian 2000, and later works). The likely explanation is the magnetic field “draping” along the cold front surface as a result of the gas flowing around it, which effectively isolates the two sides of the front from each other (Vikhlinin et al. 2001; Markevitch & Vikhlinin 2007; ZuHone et al. 2011). Some constraints outside the special regions of cold fronts have been reported, based on the existence of spatial temperature variations in the ICM. For example, Markevitch et al. (2003b) derived an order of magnitude suppression of conductivity between regions of different temperature in the body of a hot merging cluster A754, and Eckert et al. (2012) derived a large suppression factor based on the survival of a tail of cool gas stripped from a group infalling into the hot cluster A2142. In both cases, the physical significance of the constraints is ambiguous because the topology of the magnetic fields is unclear—for example, it is possible (and, in the case of the infalling group, likely) that the observed regions of the different temperature come from separate subclusters whose magnetic field structures remained topologically disconnected even after the merger, so there are simply no pathways for heat exchange (as suggested in Markevitch et al. 2003b). Indirect upper limits on the effective isotropic conduction based on the analysis of ICM density fluctuations have also been derived (e.g., Gaspari & Churazov 2013).

In our picture of A520, the cool clumps in the “leg” (from the “foot” to the “knee,” then east along the bright ridge) come from the same cool core (Section 4.2), so their magnetic field structure should be (a) interconnected and (b) stretched along the trail by the same gas motions that separated the cool core pieces. This offers a unique opportunity to constrain the conductivity along the field lines. We know the Mach number of the shock front and the velocity of the post-shock flow (Markevitch et al. 2005), which lets us estimate how long ago they were stripped based on their distance along the trail. We can then determine if the conductivity between them should be suppressed by comparing the Spitzer conduction timescale with their age,

\[
\kappa/\kappa_S = (t_{\text{age}}/t_{\text{cond}})^{-1}.
\]  

In our simple picture, the “foot” is the last piece of the former cool core that is still gravitationally bound to the subcluster that drives the shock (or, at least, it has been bound until recently). The post-shock gas flow peels away pieces of the cool core, carrying them off at the downstream velocity of \(1000\ km\ s^{-1}\) (Markevitch et al. 2005). Guided by the temperature map (Figure 3(b)), we picked two pairs of circular regions in near contact (in projection) that have large and significant temperature differences. The blobs are assumed to attain their present temperature and spatial separation upon stripping from the core, and then to move with the flow together; the distance of the pair from the “foot” along the “leg” gives the age of the pair.

We estimated the thermal conduction timescale as in, e.g., Markevitch et al. (2003b):

\[
\frac{t_{\text{cond}}}{T} \approx 1.2 \times 10^7 \left( \frac{n_e}{2 \times 10^{-3} \text{ cm}^{-3}} \right) \left( \frac{l_T}{100 \text{ kpc}} \right)^2 \left( \frac{T}{10 \text{ keV}} \right)^{-5/2} \text{ year},
\]

where \(n_e\) is the electron number density, \(l_T \equiv T/|\nabla T|\) is the thermal gradient scale length, and \(T\) is the electron temperature. This equation applies when the heat flux is unsaturated—where \(l_T \gg \lambda_e\), the electron mean-free path (Spitzer 1956):

\[
\lambda_e \approx 31 \text{ kpc} \left( \frac{kT}{10 \text{ keV}} \right)^2 \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{-1}.
\]

The regions we selected are far from saturation. The density in (6) is taken to be the average density in the corresponding stretch of the leg, \(n_H = 0.01 \text{ cm}^{-3}\). This is uncertain to a factor of two, based on density estimates for each region using two different geometric assumptions—all emission originating from a sphere in projection (leading to higher densities and therefore longer \(t_{\text{cond}}\)), or from cylinder along the l.o.s. that is 400 kpc long (the opposite effect). Therefore, our values of \(\kappa_S/\kappa\) also have a factor of two uncertainty arising from this.

We also consider how the uncertainty in \(l_T\) affect our results. Since \(t_{\text{cond}} \sim l_T^2\), it is important to estimate the gradient correctly. For one set of estimates, we use the projected temperatures in the regions of interest, measured using XSPEC. However, projection is likely to wash out the temperature gradient, resulting in longer \(l_T\). While our wavelet temperature map (Section 3.2) is qualitative, it removes most of the projection effects and leaves only the relevant linear scales. Figure 3(b) shows a temperature map created with only the smallest wavelet components that correspond to the angular scale of the structures in the leg. Using the temperature values from this map, the values of \(T/\Delta T\) are up to two times smaller. We note that since we calculate the gradients using projected distances between the regions, this is a lower limit for \(l_T\). On the other hand, the leg may be bent along the l.o.s., so our ages for the region pairs may be underestimated. Furthermore, of course, the absence of a temperature gradient does not always result from thermal conduction, so we can only place a lower
limit for an order-of-magnitude estimate of a suppression factor.

The results are shown in Table 1. For regions 1 and 2 (see Figure 3(b)), we cannot say whether the conduction is suppressed—the suppression factor is consistent with 1 for both the projected or deprojected temperatures. For regions 3 and 4, $\kappa_S/\kappa \sim 3.3–11$, so there seems to be some suppression.

We did not use splash A at the end of the cool trail for this estimate, even though there appears to be a significant temperature gradient there. The splash should have been cooling via adiabatic expansion as it formed, so its age is very uncertain.

The above attempted constraints for the suppression along the field lines can be contrasted with thermal conductivity across the edge of the cool trail of gas. In our scheme for A520, the cool trail should be isolated from the surrounding gas by a magnetic field stretched along its boundary (a likely analog of the infalling group in Eckert et al. 2012). For example, consider the feature marked “edge” in Figure 3(b). Along this trail of cool gas the temperature gradient is small, but in the perpendicular direction it jumps from about 4.5 keV in the leg to 12 keV for the post-shock gas on a scale smaller than 10 kpc. The surface brightness jump there is unresolved by Chandra (Figure 7). The trail is 120 kpc long, implying an age of $1.2 \times 10^8$ year from the cool core at the downstream velocity. The density inside the trail is estimated from the emission measure in the same region (assuming cylindrical shape) to be $6 \times 10^{-3}$ cm$^{-3}$. For these values, $\lambda_c = 3.5$ kpc, so this is still in the unsaturated condensation regime. We find $t_{\text{cond}} = 7 \times 10^3$ year, implying $(\kappa_S/\kappa_S)_{X} \gtrsim 170$. Thus, this trail could not have formed in the presence of any significant thermal conduction across the edge.

### Table 1

| Reg | $t_{\text{age}}, \text{y}$ | $T_{\text{proj}}^\text{proj}$ | $T_{\text{proj}}^\text{dep}$ | $\kappa_S/\kappa_{\text{proj}}$ | $T_{\text{dep}}^\text{proj}$ | $T_{\text{dep}}^\text{dep}$ | $\kappa_S/\kappa_{\text{dep}}$ |
|-----|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 1, 2 | $1.9 \times 10^8$ | 5.2 | 7.4 | 1.1 | 4.5 | 7 | 1.4 |
| 3, 4 | $2.6 \times 10^8$ | 7.4 | 11.9 | 3.3 | 6 | 14 | 11 |

**Note.** The columns are estimated age of the feature in years, projected temperatures in keV, suppression factor ($\kappa_S/\kappa = t_{\text{age}}/t_{\text{cond}}$) using projected temperatures, deprojected temperatures from the wavelet temperature map, and suppression factor using deprojected temperatures.

6. SUMMARY

The deep Chandra exposure of Abell 520 revealed rich structure in this cluster train wreck, including a prominent bow shock. Some of these structures provide interesting constraints on cluster physics. We derived detailed gas temperature maps using two methods, one that utilizes variable-width smoothing and evaluates the projected temperature, and another that uses wavelet decomposition to “deproject” the large-scale structure in a qualitative way and enhance the contrast of the interesting small-scale structure.

On small scales, A520 exhibits an apparent disrupted cool core at a unique evolutionary stage—the gas of the core is swept away from the central galaxy of its former host subcluster by ram pressure of the gas flow downstream of the shock front, completely displacing the gas peak from the galaxy (by 50–70 kpc). The disrupted core is not mixed with the hot gas but still forms a physically connected trail of dense clumps (a cool “leg”). Its twisted structure apparently reflects the chaotic gas velocities in this region. The core remnant in A520 is at a later stage of disruption compared to the bullet in the Bullet cluster, where it is still seen as a regular shuttlecock structure. The specific entropy of the gas in the clumps is much lower than elsewhere in the cluster and is typical of other cool cores.

In the above scenario, the magnetic field within the leg should be stretched along the leg and still connect the clumps (since they come from the same core), while insulating the leg from the surrounding hot gas. We use the observed temperature variations between the cool leg and the surrounding gas, and within the leg, to constrain thermal conductivity across the field lines (a factor $>100$ suppression from the Spitzer value) and, for the first time, suggest that the conductivity along the lines may also be suppressed by a factor of at least several. This is, of course, dependent on our assumption about the magnetic field structure.

About 1.3 Mpc northeast of the cluster center, the X-ray image reveals a subtle tail of low X-ray brightness. Two clumps in the tail coincide with mass peaks seen in the weak-lensing mass map. For one of the clumps that is least affected by projection, we derived a specific entropy of the X-ray gas, which turns out to be similar to the high value for the cluster gas at that radius, while the gas density in the clump is several times higher. Thus, the X-ray enhancement at that clump appears to be due to adiabatic compression of the surrounding gas. The second clump looks similar, though quantitative estimates are difficult because of projection. It appears that these clumps have passed through the cluster merger site and lost all of their gas (or, alternatively, arrived to the cluster already gasless) and then re-accreted the surrounding outskirts gas as soon as they slowed down sufficiently. An X-ray hydrostatic estimate the total mass of the clump is consistent with the lensing mass. The ratio of the X-ray measured mass to total mass is 1.5%–3%, much lower than the typical average cluster value, making these clumps truly “dark subclusters.” Of course, considering our scenario for their origin with stripping and reaccretion, it would have to be a coincidence if the resulting gas fraction ended up the same as the universal cluster value.

Finally, we found a curious long ($>200$ kpc), narrow (30 kpc or 9") X-ray “channel," going across the bright cluster region along the direction of an apparent secondary merger. The projected X-ray brightness in the channel is 10%–12% lower.
than in the adjacent regions. The channel has to be a sheet spanning at least 75 kpc along the l.o.s. It is possible that this is a “plasma depletion layer” with the magnetic field stretched and enhanced by the merger; the plasma $\beta$ parameter should reach 10–20 in the sheet. In this scenario, we predict that the channel will be seen as a bright filament in the radio image of sufficient angular resolution, and the filament will be polarized.

The prominent bow shock in this cluster will be studied in our subsequent work (Q. H. S. Wang et al. 2016, in preparation).

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REFERENCES

Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Ascasibar, Y., & Markevitch, M. 2006, ApJ, 650, 102
Bahcall, J. N., & Sarazin, C. L. 1977, ApJL, 213, L99
Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2009, ApJS, 182, 12
Clow, D., Bradač, M., Gonzalez, A. H., et al. 2006, ApJL, 648, L109
Clow, D., Markevitch, M., Bradač, M., et al. 2012, ApJ, 758, 128
Eckert, D., Vazza, F., Ettori, S., et al. 2012, A&A, 541, A57
Ettori, S., & Fabian, A. C. 2000, MNRAS, 317, L57
Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., & Perley, R. A. 2002, MNRAS, 331, 369
Fabian, A. C., & Daines, S. J. 1991, MNRAS, 252, 17
Feretti, L., Giovannini, G., Govoni, F., & Murgia, M. 2012, A&ARv, 20, 54
Gaspari, M., & Churazov, E. 2013, A&A, 559, A78
Govoni, F., Feretti, L., Giovannini, G., et al. 2001, A&A, 376, 803
Govoni, F., Markevitch, M., Vikhlinin, A., et al. 2004, ApJ, 605, 695
Hallman, E. J., & Markevitch, M. 2004, ApJL, 610, L81
Hickox, R. C., & Markevitch, M. 2006, ApJ, 645, 95
Jee, M. J., Hoekstra, H., Mahdavi, A., & Babul, A. 2014, ApJ, 783, 78
Jee, M. J., Mahdavi, A., Hoekstra, H., et al. 2012, ApJ, 747, 96
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Mahdavi, A., Hoekstra, H., Babul, A., Balam, D. D., & Capak, P. L. 2007, ApJ, 668, 806
Markevitch, M., Bautz, M. W., Biller, B., et al. 2003a, ApJ, 583, 70
Markevitch, M., Gonzalez, A. H., David, L., et al. 2002, ApJL, 567, L27
Markevitch, M., Govoni, F., Brunetti, G., & Jerius, D. 2005, ApJ, 627, 733
Markevitch, M., Mazzotta, P., Vikhlinin, A., et al. 2003b, ApJL, 586, L19
Markevitch, M., Ponman, T. J., Nulsen, P. E. J., et al. 2000, ApJ, 541, 542
Markevitch, M., & Vikhlinin, A. 2007, PhR, 443, 1
McNamara, B. R., Wise, M., Nulsen, P. E. J., et al. 2000, ApJL, 534, L135
Ołczyk, M., Mitchell, D. L., Phan, T. D., et al. 2004, SSRv, 111, 185
Okabe, N., & Umetsu, K. 2008, PASJ, 60, 345
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Sarazin, C. L. 1988, X-ray Emission From Clusters of Galaxies (Cambridge: Cambridge Univ. Press)
Sasaki, T., Matsushita, K., Sato, K., & Okabe, N. 2015, ApJ, 806, 123
Schechter, P. 1974, ApJ, 187, 425
Springel, V., Frenk, C. S., & White, S. D. M. 2006, Natur, 440, 1137
Vacca, V., Feretti, L., Giovannini, G., et al. 2014, A&A, 561, A52
Vikhlinin, A., Forman, W., & Jones, C. 2001, ApJ, 545, 162
Vikhlinin, A., Kravtsov, A., Forman, W., et al. 2006, ApJ, 640, 691
Vikhlinin, A., Markevitch, M., & Murray, S. S. 2001, ApJL, 549, L47
Vikhlinin, A., Markevitch, M., Murray, S. S., et al. 2005, ApJ, 626, 555
Werner, N., Zhuravleva, I., et al. 2016, MNRAS, 455, 846
Westphal, J. A., Kristian, J., & Sandage, A. 1975, ApJL, 197, L95
Williger, G. G., Starling, R. L. C., Beardmore, A. P., Tanvir, N. R., & O’Brien, P. T. 2013, MNRAS, 431, 394
Worrall, J. A., Markevitch, M., & Johnson, R. E. 2010, ApJ, 717, 908
ZuHone, J. A., Markevitch, M., & Lee, D. 2011, ApJ, 743, 16