Probing the Curious Case of a Galaxy Cluster Merger in Abell 115 with High-fidelity Chandra X-Ray Temperature and Radio Maps

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Abstract

We present results from an X-ray and radio study of the merging galaxy cluster Abell 115. We use the full set of five Chandra observations taken of A115 to date (360 ks total integration) to construct high-fidelity temperature and surface brightness maps. We also examine radio data from the Very Large Array at 1.5 GHz and the Giant Metrewave Radio Telescope at 0.6 GHz. We propose that the high X-ray spectral temperature between the subclusters results from the interaction of the bow shocks driven into the intracluster medium by the motion of the subclusters relative to one another. We have identified morphologically similar scenarios in Enzo numerical N-body/hydrodynamic simulations of galaxy clusters in a cosmological context. In addition, the giant radio relic feature in A115, with an arc-like structure and a relatively flat spectral index, is likely consistent with other shock-associated giant radio relics seen in other massive galaxy clusters. We suggest a dynamical scenario that is consistent with the structure of the X-ray gas, the hot region between the clusters, and the radio relic feature.

Key words: cosmology: theory – galaxies: clusters: general – hydrodynamics – intergalactic medium – X-rays: galaxies: clusters

1. Introduction

In a cold-dark-matter-dominated universe, structures form hierarchically, leading to mergers of smaller gravitationally bound objects into bigger ones. When the most massive structures—galaxy clusters—merge, they result in the most energetic events in the universe since the big bang. Observational evidence of shocked gas in merging galaxy clusters is now relatively common (Markevitch et al. 2004; Markevitch & Vikhlinin 2007; Canning et al. 2017; Emery et al. 2017). In particular, X-ray surface brightness and temperature maps show features that strongly suggest they result from shocks driven by the supersonic motion of merging subclusters. A shock in the intracluster medium (ICM) will result in both a density and temperature discontinuity in the gas, which creates an X-ray excess and a spectral temperature jump. Shocks can also manifest observationally in the form of radio “relics,” which are arc-like structures in the outskirts. They are believed to be the result of shocks induced by mergers, the compression of radio lobes, or the remnants of radio galaxies (for recent reviews, see Brüggen et al. 2012; Brunetti & Jones 2014). Except in a few cases (e.g., Finoguenov et al. 2010; Datta et al. 2014), shocks in the ICM associated with radio relics are not detectable by their X-ray emission, due to their location far from the cluster center ($r > 1$ Mpc) where the X-ray surface brightness is too low to reliably detect an enhancement (Hoeft & Brüggen 2007). Prior work (Botteon et al. 2016) suggests that Abell 115 may also be an example where there is an X-ray shock at the location of the relic.

A reasonable expectation is that all merging galaxy clusters will contain shocks (Ryu et al. 2003; Skillman et al. 2008; Vazza et al. 2011), some of which may be observable through X-ray observations, modulo orientation effects that may smear out the contrast across the steep, narrow pressure discontinuity, and the X-ray surface brightness in the local gas.

1.1. Abell 115

Abell 115 is a well-known massive (total virial mass $M_v \approx 3 \times 10^{15} M_\odot$) galaxy cluster at redshift $z = 0.192$, with a double-peaked structure in the X-ray surface brightness (Forman et al. 1981; Shibata et al. 1999; Gutierrez & Krawczynski 2005). Optical studies (Barrena et al. 2007) indicate two distinct, redshift-separable components in the local galaxy population, roughly coincident with the two X-ray peaks. Both subclusters have disturbed morphology in the X-ray and host cool cores, where some of the cool gas appears to be in the process of being stripped from the cluster core. X-ray and optical observational data, therefore, are consistent with the interpretation that the two subclusters are in the process of a merger. In addition, the northern subcluster hosts a 3C radio source at its center, 3C 28 (Forman et al. 2010). As has been noted by prior studies, to the northeast of 3C 28, there exists extended, diffuse radio emission in an arc-like structure that seems consistent with the appearance of other so-called cluster radio “relics” (Govoni et al. 2001; Botteon et al. 2016). While some of the radio emission appears to come directly from discrete radio galaxies, there is a significant radio structure stretching between these individual sources. One possible interpretation of the extended radio structure is that this emission results from particle acceleration at a shock, or shocks, driven into the ICM by the motion of the subclusters relative to one another. Arc-like relics exist in other massive galaxy clusters (e.g., Rottgering et al. 1997; Bonafede et al. 2009; Giovannini et al. 2010; van Weeren et al. 2010), and in many cases, a convincing argument has been made that the emission results from the synchrotron radiation of a Fermi-accelerated particle population in the ambient intracluster magnetic field. Indeed, a prior work on A115 has made a similar argument (Botteon et al. 2016), citing evidence in the X-ray data for a shock feature coincident with the location of the extended radio structure to the northeast of 3C 28.
Until now, a detailed description of the dynamics of A115 that is consistent with all of the multiwavelength observations of A115 has not been offered. In this work, we deduce the dynamics of A115 using evidence from the X-ray, radio, and optical observations, in addition to comparison with numerical simulations. In Section 2, we discuss the data reduction we used for the Chandra X-ray observations of A115. In Section 3, we describe the data reduction of the VLA and GMRT radio observations. In Section 4, we give a description of the X-ray temperature structure and the likely dynamics of the cluster. In Section 5, we combine our evidence from both X-ray and radio data to interpret the location and morphology of the radio relic. In Section 6, we summarize the results and suggest future work.

2. Chandra X-Ray Data Reduction

We used multiple Chandra observations in our analysis. The Chandra observations (IDs 3233, 13458, 13459, 15578, 15581) were obtained from the Chandra Data Archive. The observations for 3233 were taken in 2002, while the last four were taken in 2012 November. Exposure times were \(\sim 50\) ks, \(\sim 115\) ks, \(\sim 100\) ks, \(\sim 65\) ks, and \(\sim 30\) ks, respectively, for a combined total of roughly 360 ks across the five observations. All were observed in VFAINT mode.

2.1. The X-Ray “Pypeline” for Data Reduction and Temperature Maps

The X-ray data reduction is described in detail in Schenck et al. (2014) and Datta et al. (2014). The data reduction described in these studies has been aggregated into a data pipeline, which is designed to take Chandra observations and generate high-resolution adaptive circular binned (ACB) temperature maps. Once Chandra observation IDs are given as input, the pipeline automatically downloads the data using CIAO\(^5\) and merges the multiple observations into a single image. Currently, the end user needs to provide an SAO DS9\(^6\) region file containing the point sources for exclusion. Once the source file is given to the pipeline, it removes the sources from the images. The pipeline then generates light curves for each observation and removes flares. The user has the ability to inspect and customize this process to ensure accuracy. Response files are then generated for each observation using specextract. To create the ACB temperature map, \(\mathcal{O}(10^5)\) spectral fits are generated. This part of the process can be done in parallel on a supercomputer to drastically reduce the time required to complete the map.

The ACB temperature maps were produced using a method adapted from Randall et al. (2008, 2010). In these two papers, spectra were extracted from circular regions that were just large enough to reach some threshold of counts. The fitted temperature of each region was assigned to the pixel at the center of the circle. The circles are allowed to overlap, so some pixels will share counts with other pixels, and the fitted temperatures will not be independent from one another.

The pipeline itself is written in Python and available for the community at large as an open-source project on GitHub.\(^6\) Future desired functionalities include native Python multithreading support, an automatic source finder, and graphical user interface improvements. The pipeline is currently in beta.

2.2. X-Ray Surface Brightness and Temperature Image Generation

The Chandra data were calibrated using CIAO 4.7 and CALDB 4.7, the most up-to-date versions at the time of analysis. Bad pixels and cosmic rays were removed using acis_remove_hotpix, and charge transfer inefficiency corrections were made using acis_process_events. Intervals of background flaring were excluded using light curves in the full band and the 9–12 keV band. The light curves were binned at 259 s per bin, the binning used for the blank-sky backgrounds. Count rates greater than 3\(\sigma\) from the mean were removed using deflare. We visually inspected the light curves to ensure flares were effectively removed. We used the blank-sky backgrounds in CALDB 4.7. The backgrounds were reprojected and processed to match the observations. Figure 1 shows the combined, background-subtracted, smoothed (1\(\sigma\) FWHM), 0.5–8.0 keV X-ray image constructed from all five Chandra observations used in this study. Point sources have been excised. Units are counts cm\(^{-2}\) s\(^{-1}\).

Figure 1. Combined, background-subtracted, smoothed (1\(\sigma\) FWHM), 0.5–8.0 keV X-ray image constructed from all five Chandra observations used in this study. Point sources have been excised. Units are counts cm\(^{-2}\) s\(^{-1}\).
The spectra were then fit using an APEC thermal plasma model in XSPEC.\(^7\) We included photoelectric absorption, but the Galactic hydrogen column density was not fitted. Instead, it was frozen at a value of $5.2 \times 10^{20}$ cm\(^{-2}\) (Stark et al. 1992). The resulting temperature map, with X-ray surface brightness contours, is shown in Figure 2.

### 3. Radio Data

So far, the radio map for A115 has been published by Botteon et al. (2016) for VLA C+D-array data (also produced here as red contours in Figure 5). Here, we have used archival multifrequency radio observations of Abell 115 (see Table 1) in order to investigate the nature of the diffuse radio emission in the cluster.

#### 3.1. GMRT 610 MHz

GMRT 610 MHz archival data on A115 were analyzed in CASA (see Table 1). The data were downloaded in FITS format. We converted the FITS file into CASA measurement set (MS) format through the CASA task importgmrt. First, nonfunctional antennas were flagged based on the observing log. Then, we used AOFlagger\(^8\) (Offringa et al. 2012) for radio frequency interference (RFI) flagging. AOFlagger is a framework that implements several methods for dealing with RFI. About 30% of the data were flagged in AOFlagger. Then, in the output MS, further manual flagging was done. Twelve out of thirty antennas and 73 out of 256 channels were flagged, including the frequency band edges. After flagging some outliers and clipping some bad data, the rest were calibrated with the standard calibrator 3C 48 (used as both flux and phase calibrator). Then, we separated the calibrated target data with the task split.

We tried to recover diffuse emission from the GMRT 610 MHz data at the region between 3C 28 and the head–tail source as seen in Figure 5. However, at the fullest resolution of the GMRT 610 MHz data, we were hardly able to recover any diffuse emission. Hence, we have selected only the 0 to $\sim$15 \(\ell_k\)–\(v\) range of GMRT data at 610 MHz for imaging, which recovered some amount of diffuse emission in the bridge region as now seen in Figure 3. The imaging was performed by the CASA task clean, choosing a cell size of 9\(''\). Briggs weighting was again used with robust parameter $-1$. Wide-field imaging was done in CASA using the W-projection algorithm with 512 W-projection planes. The image was restored with a 45\(''\) x 45\(''\) beam. The rms noise near the center of the field is $\approx 1.4$ mJy/beam.

#### 3.2. VLA L-band D Configuration

The A115 VLA L-band D-configuration archival data were analyzed in CASA.\(^9\) The data were converted into MS format

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\(^7\) [https://heasarc.gsfc.nasa.gov/xanadu/xspec/](https://heasarc.gsfc.nasa.gov/xanadu/xspec/)

\(^8\) [http://aoflagger.sourceforge.net](http://aoflagger.sourceforge.net)

\(^9\) [https://casa.nrao.edu/](https://casa.nrao.edu/)
via task importvla. Then, in the output MS file, we have applied manual flagging. Seven out of twenty-seven antennas were flagged. Then, the calibration was completed using the standard flux calibrator 3C 48 and the phase calibrator 0119+321. The calibrated target field data was separated from the multisource data set by the task split, choosing only RR and LL correlations. Imaging was performed by the CASA task clean with the imaging mode "channel" as these archival data contain a single channel per IF. The VLA D-configuration synthesized beam size in the L band is 45", so we chose the cell size to be 9". Briggs weighting was used with robust parameter $-1$. Wide-field imaging was done in CASA using the W-projection algorithm with 128 W-projection planes. The image was restored with restoring beam $3''2 \times 2''8$ with a beam position angle of 78°. The rms noise is $\approx 45 \mu$Jy/beam near the center of the image. The results from the VLA B-array L band are shown in Figure 5. It is evident from this figure that the resolution of the VLA B array helps us to resolve the structure in the two sources: the well-known 3C 28 (in the west) and the head–tail radio source (J0056+2627) to the northeast.

3.3. VLA L-band B Configuration

The Abell 115 L-band B-array VLA data were first run through the standard CASA calibration and editing processes. Editing tasks like flagdata and rflag were used to flag the bad data. Three out of twenty-seven antennas, along with some channels, were flagged. The calibration was done using tasks setjy and gaincal. The gain solutions were checked using plotcal. The calibrated target data were separated from the multisource data set with the task split. The imaging was done by the CASA task clean choosing a cell size of 1". Briggs weighting was used with robust parameter $-1$. Wide-field imaging was done in CASA using the W-projection algorithm with 128 W-projection planes. The image was restored with restoring beam $3''2 \times 2''8$ with a beam position angle of 78°. The rms noise is $\approx 45 \mu$Jy/beam near the center of the image. The results from the VLA B-array L band are shown in Figure 5. It is evident from this figure that the resolution of the VLA B array helps us to resolve the structure in the two sources: the well-known 3C 28 (in the west) and the head–tail radio source (J0056+2627) to the northeast.

3.4. Radio Spectral Index and Mach Number

It is evident from Figure 3 that the diffuse emission is best captured with the VLA D-array and GMRT 610 MHz analysis with a broader restoring beam. We then calculate the spectral index for the radio emission bridge between 3C 28 and the head–tail radio source (J0056+2627) to the northeast; we obtain an average spectral index of $-1.1 \pm 0.2$. With a 45" restoring beam, the bridge is unresolved in the transverse direction. However, the quality of the archival radio data prevents us from going any further with this analysis and creating a spectral index map of the region. In order to do so, we need new radio observations of this field at the L and P
bands with the VLA. The upgraded capabilities of the VLA will allow us to get a spectral index map of this “bridge.”

If we are viewing a shock front oriented edge-on, the radio spectral index ($\alpha$) should be sensitive to the prompt emission from the shock front (Skillman et al. 2013), given by $\alpha = \alpha_{\text{prompt}} = (1 - s)/2$, where $s$ is the spectral index of the accelerated electrons given by $n_e(E) \propto E^{-s}$ (Hoett & Brüggen 2007). The theory of diffusive shock acceleration for planar shocks, at the linear test-particle regime, predicts that this radio spectral index is related to the shock Mach number by

$$M^2 = \frac{2\alpha - 3}{2\alpha + 1},$$

where $\alpha$ is the radio spectral index ($S_\nu \propto \nu^\alpha$; Blandford & Eichler 1987; Hoett & Brüggen 2007; Ogrean et al. 2013). Given the orientation of the features, we estimate a Mach number for the edge-on case. For prompt emission case and a spectral index within the relic region of A115 ($\alpha = -1.1$), the resulting Mach number is 2.1. This is consistent with the estimates of the shock Mach number at the relic position computed by Botteon et al. (2016) using the X-ray data.

4. X-Ray Temperature Structure and Dynamics

The X-ray surface brightness morphology, coupled with the high-fidelity temperature map, strongly suggest a likely dynamical scenario, at least as projected on the sky. The addition of the optical redshifts of the member galaxies indicates the relative line-of-sight motion as well. Barrena et al. (2007) analyzed optical redshift and photometric data for 115 galaxies, all of which were members of A115-N and A115-S. Their analysis strongly indicates two separate distributions of galaxies, A115-N, with a velocity dispersion of $\sigma_v \approx 1000$ km s$^{-1}$, and A115-S, with $\sigma_v \approx 800$ km s$^{-1}$. The analysis suggests that the subclusters are moving toward one another along the line of sight with relative velocity $V_r \approx 1600$ km s$^{-1}$.

The defining features of the X-ray temperature map, shown in Figure 2, are the two cold, bullet-like structures in the north and south, with temperatures in the cold gas of $3.5 \leq T_X \leq 5$ keV, and the hot, amorphous region between them, with X-ray temperatures as fitted in the ACB map ranging up to 15–20 keV. The overall dynamical picture seems to be that the two subclusters are moving both toward one another along the line of sight (as suggested by the optical data) and moving past each other in the plane of the sky (as suggested by the X-ray data). Given the elongated X-ray appearance, the northern subcluster appears to be moving to the west and slightly south, while the southern subcluster is moving to the north and east. We explored this interpretation by extracting spectra from the data.

In Figure 4, we show a set of regions, guided by features in the ACB map, that we have extracted spectra from (using specextract) and fitted with XSPEC. The regions were chosen to isolate areas of interest in the ACB temperature map. Regions A and G contain the cold, X-ray-bright cores of A115-N and A115-S, respectively. Regions B and H were chosen to cover what appears to be cold gas stripped from the clusters by their motion and pressure effects, and indicating the direction of relative motion. Region D covers the very hot central region between the clusters, and Regions C, E, and F were chosen in order to quantify the temperature profile between A115-N and A115-S on either side of the hot region in the center. The spectra were fit with an APEC model including photoelectric absorption from galactic neutral hydrogen. The $N_H$ column density was fixed at the value from Stark et al. (1992), $5.2 \times 10^{20}$ cm$^{-2}$, as in the ACB map fits. The metallicity was left as a free parameter, except in the case of the hot central region, where only poor fits to the metallicity could be obtained. With the exception of the hot central region (region D in Figure 4) whose spectral fit we describe later in this section, we fit the spectrum in the energy range 0.7–8.0 keV. The spectral fits are shown in Table 2.

In light of the dynamical picture we described above, it is not straightforward to interpret the faint, hot region between the subclusters. Morphologically, this feature is not obviously consistent with either other observed shock features in galaxy cluster X-ray observations or the appearance of shocks in numerical simulations of galaxy clusters. Interestingly, while working on this manuscript, an X-ray study of Abell 141 that shows morphological similarity to A115 (Caglar 2018) appeared. It should be noted that though morphologically this hot region does not appear shock-like, its relative position compared to the two subclusters is where we might expect a shock given the likely dynamical scenario. Since this feature does not appear as prototypically shock-like, we have looked in detail at this feature. We used the ACB temperature map as a guide to discover this and other features. To verify the temperature in that region, we also have extracted a spectrum from an elliptical region covering the hot region in between the clusters. In the hot region, we modified the spectral fitting slightly, in that we fixed the metallicity at $Z_\odot = 0.2$, but the temperature fit was relatively insensitive to the choice within the range of the local fitted values around it. Additionally, we fit the spectrum in the 0.7–5.0 keV band, as we see a flattening of the spectrum at high energy due to the contribution of the noise. We fit a bulk temperature in this region (marked region “D” in Figure 4) of $T_X = 11.03 \pm 1.74$ keV.

We have also examined the X-ray emission in the region of the radio relic, as was done in Botteon et al. (2016). Figure 5 shows the X-ray surface brightness and radio contours, overlaid on the optical data. One can clearly see the location of 3C 28 and the head–tail radio source (J0056+2627). The red contours, extending from west to east away from 3C 28 at the center of A115-N, are 1.5 GHz radio contours from the VLA B+D array, showing the location of the extended emission of the radio relic. If the relic is indeed being illuminated because of the shock acceleration of a preexisting population of particles, we need to understand how the presence of a shock at that location is consistent with the dynamics of the cluster. Shock-accelerated particle populations cool quickly by synchrotron radiation, and so the expectation is that the location of the relic will be almost precisely coincident with the shock accelerating the particles. While we do not see strong evidence for a shock at that location in the X-ray data, it is admittedly very faint. Botteon et al. (2016) make an argument for the evidence of a shock from the X-ray data near the radio relic. However, what is not immediately obvious is what dynamical scenario should result in a shock at that location. We address the dynamics in later sections.

4.1. Shocks and Temperature Features in the ICM

We have run an automated shock finder on the surface brightness and spectral temperature maps, identical to the procedure described in Datta et al. (2014) and Schenck et al.
High-quality surface brightness and spectral temperature maps can be probed using this technique, which is adapted from a similar calculation used in numerical simulations (Ryu et al. 2003; Skillman et al. 2008). In numerically simulated clusters, we can find shocks using the full three-dimensional properties of the gas. The conditions for determining whether a given volumetric element of the simulation is the location of a shock are

\[
\nabla \cdot \mathbf{v} < 0 \\
\n\nabla T \cdot \nabla K_S > 0 \\
\nT_2 > T_1 \\
\rho_2 > \rho_1.
\]

where \(\mathbf{v}\) is the velocity field, \(T\) is the temperature, \(\rho\) is the density, and \(K_S = T/\rho^{-1}\) is the entropy. The Mach number of the shock is then defined by the temperature jump, using the Rankine–Hugoniot shock jump conditions, to be

\[
\frac{T_2}{T_1} = \frac{(5M^2 - 1)(M^2 + 3)}{16M^2}
\]

In X-ray images, all shock observables are projected on the sky. Therefore, for observational data, we must use two-dimensional projected X-ray surface brightness and temperature maps. Hence, the technique is modified to account for that. In this modified scenario, the shock finder calculates the jump in temperature and surface brightness in \(N\) evenly placed directions centered on a given pixel. The shock finder then accepts those pixel pairs between which the conditions \(T_2 > T_1\) and \(S_{X2} > S_{X1}\) (where \(S_{X2}\) and \(S_{X1}\) represent the downstream and upstream X-ray surface brightness, respectively, and the

\begin{table}[h]
\centering
\caption{Spectral Temperature Fits}
\begin{tabular}{llll}
Region & Name & \(T_X\) (keV) & \(Z_e\) \\
\hline
A & N Core & 3.01 ± 0.03 & 0.29 ± 0.02 \\
B & N Tail & 5.30 ± 0.10 & 0.22 ± 0.03 \\
C & N Inter & 6.90 ± 0.45 & 0.15 ± 0.06 \\
D & Hot Central & 11.03 ± 1.7 & fixed \\
E & E Middle & 8.82 ± 0.78 & 0.46 ± 0.09 \\
F & S Middle & 7.44 ± 0.42 & 0.31 ± 0.07 \\
G & S Core & 4.31 ± 0.15 & 0.29 ± 0.05 \\
H & S Tail & 4.00 ± 0.08 & 0.28 ± 0.03 \\
\hline
\end{tabular}
\end{table}

Note. Spectral fit for temperature and chemical abundance relative to solar for the regions shown in Figure 4. The X-ray spectral fitting for these regions is described in Section 4.
The Mach number for each successful pixel pair is noted. The Mach number with the maximum value is chosen to be the resultant Mach number for that given pixel. The full details of the method are described in Datta et al. (2014) and Schenck et al. (2014).

The automated shock finder identifies only one region where there are pixels consistent with a shock, and that is in the area we interpret as leading the motion of A115-N. The shock finder identifies a number of pixels in the image as shocks, with Mach numbers ranging from $M \approx 1$ to $M \approx 3$. This area of the map has very low surface brightness, and the temperature map, by the nature of the method, has aggregated pixels over some relatively large area of the map. Again, as before, using the ACB map and shock finder as a guide, below we explore more deeply with extractions in those regions.

We explored the region identified as a shock in the above analysis. First, we used a projected pressure map derived from the X-ray surface brightness and temperature maps. The projected pressure maps were generated by taking the square root of the X-ray surface brightness as a proxy for the projected density and multiplied it by the temperature fit to the X-ray spectra, represented by the ACB map. We then generated a projected pressure profile across the region identified as a shock, and it is shown in the orange boxed region and line in Figure 6. In the region upstream of the northern subcluster, we see a steep drop in pressure. The other parts of the X-ray map where we might have expected to find evidence of a shock are the regions to the northeast of A115-S (leading its motion) and to the northeast of both subclusters, in the location of the radio relic. We explored the pressure profile across the northern radio relic in the area where Botteon et al. (2016) suggest they detect a shock. In Figure 6, we show the projected pressure profile across that northern radio region (in green). In front of the southern subcluster (the region shown by the blue box and line), we see no such discontinuity, just a gradual decline in pressure. This is also true across the northern radio relic region. However, as noted in earlier sections, orientation and projection effects can act to diminish the observed surface brightness and X-ray temperature contrast at the location of a shock.

Figure 5. Optical map of A115 using SDSS data, overlaid with 1.5 GHz radio contours showing 3C 28, the head–tail source (J0056+2627), and the radio relic. Black contours represent the 0.5–8.0 keV Chandra X-ray surface brightness and represent the same values as depicted in Figure 2. Blue contours are constructed with VLA B data having a beam size of 3\'2 \times 2\'8 in position angle 79° and are at 1.5%, 4.25%, 12.75%, 42%, and 85% of the peak emission. The red contours are from previous VLA C+D-array data as published in Botteon et al. (2016) and are at 0.06%, 0.10%, 0.16%, 0.18%, 0.26%, and 0.40% of the peak emission. The restoring beam of the image is 15'' \times 14'' in position angle −35°. The colorbar is in units of nanomaggies (1 nanomaggy = 3.631 \times 10^{-6} Jy).
In the direction of motion of A115-N, where the shock detector identifies some pixels as part of a shock, the X-ray surface brightness is quite low. As a consequence, the region from where pixels are selected for an X-ray spectral fit by both the WVT and ACB methods (both using a signal-to-noise threshold of 50 for their regions) is quite large. Therefore, it is difficult to extract a reasonable spectral fit to the regions either in front of or behind the identified shock location. However, we can quite easily extract a surface brightness profile across this region ahead of the deduced motion of A115-N, and that is shown in Figure 7. The regions from where the surface brightness is extracted are shown in the annular wedge regions in the map, also in Figure 7. The fifth region in from the outer part of the shock feature shows a steep increase in surface brightness profile across the feature identified as a shock by the automated shock finder. Note the steep increase in the fifth bin from the right, just behind the identified shock. The 1σ error is shown while the units are in counts per pixel squared.

Figure 6. Relative projected pressure profiles from the X-ray surface brightness and temperature maps across three interesting features—upstream of the northern and southern subclusters, and in the location identified by previous studies as a shock across the radio relic feature. Our automated shock finder, described in the text, finds evidence for a shock in the X-ray image in the region to the east of the northern subcluster, where our profile is taken (marked with the orange line). The overview image (right) is of the relative pressure difference. X-ray surface brightness contours are depicted in cyan at 1%, 1.8%, 2.58%, 4%, and 5.1% of the peak emission. VLA C+D contour lines are depicted in white at 0.06%, 0.10%, 0.16%, 0.18%, 0.26%, and 0.40% of the peak emission. VLA B+D contour lines (only shown in the northern subcluster thumbnail) are depicted in black at 1.5%, 4.25%, 12.75%, 42%, and 85% of the peak emission.

Figure 7. Left panel: ACB temperature map of the northern subcluster (A115-N) overlaid with contours of the X-ray surface brightness (black) and Mach number of identified shocked pixels (cyan). Mach contours are located at 1, 1.25, 1.5, and 1.75. The surface brightness contours are at 1%, 1.8%, 2.58%, 3.38%, 4.17%, and 4.96% of the peak emission. The white contours are the annular wedge regions from where the surface brightness is extracted for the radial profile. Right panel: radial profile across the feature identified as a shock by the automated shock finder. Note the steep increase in the fifth bin from the right, just behind the identified shock. The 1σ error is shown while the units are in counts per pixel squared.
brightness, by a factor of roughly two. This is the location where the shock finder identifies a shock, and the profile shows that location to be plausible. Better X-ray data may allow a good spectral fit, spatially resolved in this region. However, the current data do not permit that at this time.

4.2. Comparing to Numerical Simulations

For comparison, and to help deduce the dynamics of A115, we show synthetic observations of galaxy clusters simulated in a cosmological context using the cosmological N-body/hydrodynamic simulation code Enzo\(^{10}\) (Bryan et al. 2014). The merger dynamics in the simulations are an excellent guide for determining the observable consequences of typical subcluster interactions. The simulations used for this purpose are described in detail in Hallman & Jeltema (2011). The simulation used here is for a universe volume of 128 \(h^{-1}\) Mpc (comoving) on a side, on a 256\(^3\) root grid. The simulation is evolved in a ΛCDM cosmological model from an Eisenstein & Hu (1999) power spectrum from \(z = 99\) to \(z = 0\), with a maximum of five levels of adaptive mesh refinement. This results in a peak spatial resolution of 15.6\(h^{-1}\) comoving kpc. We refine on both dark matter and baryon overdensities of 8.0. This particular simulation does not include the effects of metal line cooling, as has been done in other prior works. In this case, we are using the simulated clusters to understand the large-scale dynamics and observable effects outside the cluster core, where cooling times are typically long. Such simulations serve as a guide for understanding the range of merger interactions we expect in a cosmological context.

In Hallman & Jeltema (2011), we extracted 16 simulated clusters at \(z = 0\) whose masses exceeded \(M_{\text{200}} \geq 3 \times 10^{14} M_\odot\). The objects of highest virial mass in the simulation are similar in mass to A115. For the current study, we make use of the synthetic observations of these 16 clusters. For each of the identified clusters at \(z = 0\), we extracted a volume around that cluster in a series of 132 snapshots in time, equally spaced (\(\delta t = 0.22\) Gyr) in the redshift interval 0 \(\leq z \leq 0.9\). For each of these time outputs, using the yt\(^{11}\) toolkit (Turk et al. 2011), we created synthetic 0.3–8.0 keV X-ray images and spectroscopic-like temperature (\(T_{\text{sl}}\)) maps (see Rasia et al. 2005). The X-ray emission is calculated using the CLOUDY\(^{12}\) software (Ferland et al. 1998). The projections are of an 8\(h^{-3}\) Mpc\(^3\) volume centered on the cluster, and thus each image is an 8\(h^{-2}\) Mpc\(^2\) field. This exposes not only the merger activity within the cluster virial radius, but also the larger cosmological environment of the cluster, allowing us to understand how various observable effects originate.

4.2.1. Similarities to A115 in Numerical Galaxy Clusters

In the simulation data, we see features that are consistent with the inferred dynamics of A115, as well as with the temperature and surface brightness substructure. When two merging subclusters pass each other in the simulations, both drive bow shocks into the other subcluster’s ICM. Additionally, these shocks then interact as they travel outward from the subclusters and collide. This combination of the two subcluster’s bow shocks can heat the gas between the clusters, leaving an observable structure even after the leading edge of the bow shock has propagated into a less dense, X-ray-faint location ahead of the cluster. Figure 8 shows the evolution of such a feature, using the synthetic X-ray temperature maps generated in our prior work. The surface brightness contours represent a dynamic range of 1000 from brightest to faintest, which is similar to the dynamic range of the Chandra X-ray images. The outer edge of the bow shock from the subcluster, to the right of each image, is in a very faint region of the image, and so would be very difficult to detect. The three panels from left to right are three stages in the cluster evolution, separated by approximately 220 Myr in time. To the right of each image, there is a cooler subcluster traveling toward the top of the image, with a heated region in front of it, representing shock-heated gas. Between the subclusters, you can see a hotter region, with a relatively flat surface brightness profile, very similar to what we see in A115.

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\(^{10}\) http://enzo-project.org

\(^{11}\) http://yt-project.org/

\(^{12}\) http://www.nublado.org/
Although this is not a model of A115, it may represent a similar dynamical scenario based upon the morphological similarities that we see. These features are quite common in cluster mergers in numerical cosmological simulations, and we believe that a similar scenario is very likely responsible for the hot region between A115-N and A115-S. It is likely that the interaction of the edge of the two interfering bow shocks has heated the gas to high temperature, and that the upstream parts of the shock, as well as those away from the center of the merger, are in locations where the X-ray surface brightness is too low to detect them.

4.3. Establishing the Location of the Bow Shock in A115-N

In order to determine the plausibility of this hypothesis, here we use estimates of the shock Mach number and stand-off distance to see if the location of the central hot region is consistent with this interpretation. We calculate the location of the bow shock around the northern subcluster of A115 using Moeckel’s method (Moeckel 1949, hereafter M49),13 which is also summarized for cluster purposes in Appendix B of Vikhlinin et al. (2001, hereafter V01). We employ the shock-finder’s map of A115 to draw an asymptotic line to the part of the bow shock detected in this manner. This can be seen in the top panel of Figure 9. The curved cyan contours in this panel represent the shock contours. The black dashed line represents the asymptotic line of the bow shock. Using the surface brightness map (represented as white contours), we determine the subcluster’s direction of movement (black solid line). This allows us to obtain the angle \( \phi \sim 36^\circ \) for the northern cluster (for reference, see Figure 9 in V01), which provides us with a Mach number of the subcluster, \( M \sim 1.7 \), using the relation \( \phi = \arctan(M^2 - 1)^{-1/2} \).

To calculate the hyperbola function representing the bow shock, we require both \( M \) and the stand-off distance \( x_0 \). To obtain the latter, we proceed as follows. Since this object does not have a well-defined shoulder, we can locate the so-called body sonic point \( S_b \) (the point on the surface of the body where the flow speed equals the speed of sound, marked with a green star in each panel of Figure 9) by using the relation between the angle \( \theta \) (formed between the line of movement and the asymptote to the shoulder) and \( M \), as found in Figure 4 of M49. Using this angle, we find \( S_b(x_b = 549 \text{ kpc}, y_b = 103 \text{ kpc}) \) on the surface of the subcluster. The coordinate origin is where the three black lines meet.

From Figure 7 in M49, selecting the curve that assumes an axially symmetric body with respect to the line of movement, as well as the continuity method, we obtain \( L/y_b \sim 1 \) (which is only a function of the body speed, i.e., \( M \), calculated above to be \( \sim 1.7 \)). We can then find the shock detachment distance \( L = x_b - x_0 \), and finally the shock stand-off distance \( x_0 = 445 \text{ kpc} \).

Given \( M \) and \( x_0 \), we can now model the bow shock as the hyperbola shown by the white solid line in the top panel of Figure 9. Due to the uncertainty in the assumption of the shape of the moving object, we repeat the calculation, choosing instead the two-dimensional body plus the continuity method curve from Figure 7 of M49. We then obtain \( x_0 = 272 \text{ kpc} \) and the white dashed line in the top panel of Figure 9. We use these two cases to bracket a region (shaded white) where we might expect to find the true, underlying bow shock. Gutierrez & Krawczynski (2005) also drew a bow-shock estimation from the surface brightness map in their Figure 7, which is roughly consistent with our result.

Note that we encouragingly find that the bow-shock region south of the northern object goes through the hot spot between the two subclusters. We can also obtain the sound speed in the cluster assuming a temperature of 10 keV, \( \sim 1594 \text{ km s}^{-1} \), giving \( \sim 2710 \text{ km s}^{-1} \) for the northern subcluster (using \( M \sim 1.7 \); or 1127 km s\(^{-1}\) and 1916 km s\(^{-1}\), respectively, assuming 5 keV). Recall that from Barrena et al. (2007) that the colliding line-of-sight velocity between the subclusters is \( \sim 1600 \text{ km s}^{-1} \).

4.4. Estimating the Location of the Assumed Bow Shock in A115-S

Since for the southern subcluster we do not have any visible residual of the bow shock, we cannot follow the first part of the method used for A115-N. Let us assume, however, that our argument holds and that the asymptotic line for the southern subcluster is aligned with that of the northern subcluster (black dashed line over the central hot region between the subclusters), as shown in the bottom panel of Figure 9. We also morphologically establish the direction of movement as going through the subcluster as indicated by the black solid line crossing it. With these two lines, from this point on we can proceed as described in the previous subsection. For this subcluster, we then obtain \( \phi \sim 50^\circ \) and calculate \( M \sim 1.3 \), which is lower than that of the northern subcluster and thus consistent with the dynamical measurements of Barrena et al. (2007).

To obtain the stand-off distance \( x_0 \), from Figure 4 of M49 and using \( M \sim 1.3 \), we have \( \theta \sim 25^\circ \). Positioning this angle in the bottom panel of Figure 9 (between the black and cyan solid lines) we obtain \( x_0 = 616 \text{ kpc} \) and \( y_0 = 59 \text{ kpc} \), and following the same calculation and assumptions as before, \( x_0 = 528 \text{ kpc} \). The white solid line shows the hyperbola corresponding to the assumed bow shock in A115-S, with this being an axially symmetric object. Assuming instead a two-dimensional shape of the subcluster, we find \( x_0 = 219 \text{ kpc} \) and the white dashed line. This and the previous hyperbola bracket the white shaded region where we might find the bow shock.

4.5. The Shock Hypothesis

In summary, the calculations of the shock stand-off distance and location strengthen our hypothesis, derived from morphological similarity to numerical simulations, that the location of the central hot spot can plausibly be attributed to the presence of the two bow shocks from the motion of the two subclusters. Between the subclusters, where there is high enough gas density to generate significant X-ray emission, we can see the hot gas. In the outer parts of the subclusters, and also upstream of the subcluster motion, the gas density is lower, and the X-ray features we expect for a shock are not visible.

5. The Radio Relic and Its Relationship to the X-Ray

Prior work discussing the radio relic in A115 describes two possible scenarios for the origin of the extended radio emission. In Govoni et al. (2001) and Gutierrez & Krawczynski (2005), the initial hypothesis was that the extended radio emission, which has subsequently been left behind by the motion of the

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13 Technical note available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930082597.pdf
Figure 9. Location of the bow shocks in the northern (top panel) and southern (bottom panel) subclusters, as shown by the white shaded regions. Sections 4.3 (for the northern subcluster) and 4.4 (for the southern subcluster; note the additional assumption taken in this case) describe in detail how we obtain in each case the white solid hyperbola representing the location of the bow shock when assuming axial symmetry of the subcluster in the direction of movement (black solid line), through the determination of the angles $\phi$ and $\theta$, and the body sonic point $S_B$ (marked with a green star). The white dashed hyperbola comes from the same calculation but assuming instead a two-dimensional shape (see M49) of the moving object. We might expect the bow shock to be approximately bracketed by these two curves. These results support the plausibility of our hypothesis that the interaction of the two bow shocks in the center of the cluster drives the observed high temperature that is otherwise unexplained. The X-ray surface brightness contours in both images are represented by white solid lines at 1%, 1.8%, 2.58%, 4%, and 5.1% of the peak emission. Both images are measured in keV.
cluster, is coming from accelerated particles ejected from 3C 28 and other nearby radio galaxies and associated galaxies. The other scenario, described in Botteon et al. (2016), is that the relic is associated with a shock, accelerating the particles to higher energy, causing them to radiate. These scenarios are not exclusive. This feature could result from a particle population that was ejected from the local radio galaxies and then reaccelerated by a merger shock. Shock acceleration theory (and recent observational evidence) suggests that accelerating a preexisting population of particles with a nonthermal distribution is more efficient than accelerating particles out of the tail of a thermal distribution (Brunetti & Jones 2014; van Weeren et al. 2017).

What is most relevant to this work is determining the plausibility of either scenario, based on the apparent dynamics of the cluster. Below, we explain the presence of a shock at the location and orientation of the radio relic based on a reasonable dynamical scenario. Also, we investigate whether the radio data support the shock hypothesis or are consistent with the idea that this is simply stripped radio plasma, with no reacceleration process.

The morphology of shocks in merging numerical clusters seems to be in some cases consistent with the shape and location we see in A115. This feature could in fact be consistent with the dynamical picture deduced from X-ray and optical data. In Figure 8, one can also see the outer part of the bow shock from the cold subcluster. This region would very likely not be visible in the X-ray observation of such a cluster, as it is in a region of very low X-ray surface brightness. However, should that portion of the bow shock propagate through a region of accelerated particles, one might expect Fermi processes to reaccelerate those particles to higher energy, and they may become visible as synchrotron sources.

As to the second question—whether the radio data support the shock reacceleration scenario—unfortunately, the quality of the data prohibits a definitive analysis. What we expect in a shock-accelerated scenario is that the radio spectral index will vary spatially, depending on the exact location of the shock. At the location of the shock, the spectral index will be flatter, and behind the shock, as the highest energy particles radiate their energy away more quickly than those at lower energy, the spectral index will steepen. There are examples from other radio relics, when there is high-quality, high-resolution radio data available. If a shock is sweeping through the radio-emitting plasma, we would expect a spectral index gradient perpendicular to the long axis of the relic feature (see, e.g., van Weeren et al. 2010). However, if this radio-emitting plasma is simply stripped from the radio galaxies and passively advected away, what we would expect is that the spectral index gradient will be parallel to the long axis of the feature and in the direction of motion of the radio galaxies.

6. Summary and Conclusions

As discussed in Barrena et al. (2007), there are a number of features in the optical and X-ray data that support the description of the initial stages of a major merger occurring between the two subclusters of Abell 115. We are able to further corroborate this scenario, consistent with the prior X-ray observations of A115 (e.g., Forman et al. 1981; Shibata et al. 1999; Gutierrez & Krawczynski 2005; Botteon et al. 2016), through more detailed X-ray and radio observations, as well as comparing our results with relevant hydrodynamical simulations.

Figure 10. Pictorial representation of the dynamical scenario in A115. The subclusters are orbiting each other in the process of merging. The red lines represent the location of shocks, the black arrows represent the past and current motion of the subclusters, and the blue ellipses represent the region of each subcluster core. The radio relic results from the Fermi acceleration of a relic population of cosmic rays ejected from the local radio galaxies and advected behind the motion of A115-N. The curved remnant of the earlier bow shock, similar to what we see in simulations, continues to propagate into the relic plasma after A115-N has changed its motion. The interaction of the bow shocks of A115-N and A115-S produces a hot region between the subclusters.

The dynamical scenario we have described here is shown pictorially in Figure 10. The subclusters are orbiting each other in the process of merging. The red lines represent the location of shocks, the black arrows represent the past and current motion of the subclusters, and the blue ellipses represent the region of each subcluster core. The radio relic results from the Fermi acceleration of a relic population of cosmic rays ejected from the local radio galaxies and advected behind the motion of A115-N. The curved remnant of the earlier bow shock, similar to what we see in simulations, continues to propagate into the relic plasma after A115-N has changed its motion. The interaction of the bow shocks of A115-N and A115-S produces a hot region between the subclusters.

Both prior works, and this analysis, suggest that the A115 merger results in a hot X-ray region between the clusters, which we interpret as a feature resulting from interacting bow shocks. High-energy particles, accelerated in 3C 28 and the head–tail radio source (J0056+2627), are spread out behind A115-N, along the direction of motion. It has been suggested by Forman (2017) that hydrodynamic forces associated with the motion of the radio galaxies through the ICM are responsible for the morphology. Here, we suggest, consistent with the interpretation of the X-ray data by Botteon et al. (2016), that a shock at the location of the radio relic, in our scenario as part of the leading bow shock of A115-N, has reaccelerated these particles accounting for the radio emission along the arc-like structure between and behind the two radio galaxies.
Though these conclusions are highly plausible, there are some additional observations that could make this case more definitively. Primarily, the addition of high-quality, high-resolution, multifrequency radio observations of the relic could strongly constrain whether the shock acceleration scenario is correct. In particular, the availability of high-quality, wide bandwidth 350 MHz and 1.4 GHz observations, using the B, C, and D array configurations of the JVLA, would allow for resolved spectral index maps of the relic. These could be used to determine whether the spectral index gradient is perpendicular to the putative shock or whether the spectral index variation is more consistent with a scenario where the radio plasma is ejected from the radio galaxies and simply ages via synchrotron cooling as it advects away.

Also, deep X-ray observations of the region around the relic, as well as in the regions where one might expect the outer parts of the bow shocks resulting in the X-ray hot spot, might clear up that interpretation as well.

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