DIFFERENT METHODS OF FORMING COLD FRONTS IN NONMERGING CLUSTERS

RENATO DUPKE
University of Michigan, Ann Arbor, MI 48109

RAYMOND E. WHITE III
University of Alabama, Tuscaloosa

AND

JOEL N. BREGMAN
University of Michigan, Ann Arbor

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ABSTRACT

Sharp edges in X-ray surface brightness with continuous gas pressure called cold fronts have often been found in relaxed galaxy clusters such as Abell 496. Models that explain cold fronts as surviving cores of head-on subcluster mergers do not work well for these clusters, and competing models involving gas sloshing have been recently proposed. Here, we test some concrete predictions of these models in a combined analysis of density, temperature, metal abundances, and abundance ratios in a deep Chandra exposure of Abell 496. We confirm that the chemical discontinuities found in this cluster are not consistent with a core merger remnant scenario. However, we find chemical gradients across a spiral “arm” discovered at 73 kpc north of the cluster center and coincident with the sharp edge of the main cold front in the cluster. Despite the overall SN Ia iron mass fraction dominance found within the cooling radius of this cluster, the metal enrichment along the arm, determined from silicon and iron abundances, is consistent with a lower SN Ia iron mass fraction (51% ± 14%) than that measured in the surrounding regions (85% ± 14%). The “arm” is also significantly colder than the surroundings by 0.5 – 1.6 keV. The arm extends from a boxy colder region surrounding the center of the cluster, where two other cold fronts are found. This cold arm is a prediction of current high resolution numerical simulations as a result of an off-center encounter with a less massive pure dark matter halo, and we suggest that the cold fronts in A496 provide the first clear corroboration of such model, where the closest encounter happened ~0.5 Gyr ago. We also argue for a possible candidate dark matter halo responsible for the cold fronts in the outskirts of A496.

Subject headings: cooling flows — galaxies: clusters: individual (Abell 496) — intergalactic medium — X-rays: galaxies: clusters

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1. INTRODUCTION

One of the most interesting features discovered by Chandra satellite observations of galaxy clusters are the sharp X-ray surface brightness discontinuities, accompanied by jumps in gas temperature called “cold fronts” (e.g., Markevitch et al. 2000; Vikhlinin et al. 2001; Mazzotta et al. 2001). The temperature and density jumps happen in such a way as to maintain the gas pressure continuous across the front, and therefore, they are not created by shocks. They were originally interpreted as being the result of subsonic (transonic) motions of head-on merging substructures with suppressed thermal conduction (Markevitch et al. 2000, 2001; Vikhlinin et al. 2001).

The above-mentioned merger core remnant model is theoretically justified (e.g., Bialek et al. 2002; Nagai & Kravtsov 2003; Heinz et al. 2003; Mathis, et al. 2005; Poole et al. 2006) and holds relatively well for clusters that have clear signs of merging, such as 1E 0657-56 (Markevitch et al. 2002) and A3667 (Vikhlinin et al. 2001). However, these models do not work well for the increasing number of cold fronts (sometimes multiple cold fronts in the same cluster) found in apparently nonmerging clusters such as A496 (Dupke & White 2003, hereafter DW03), A1795 (Markevitch et al. 2001), and RX J1720.1+2638 (Mazzotta et al. 2001). This prompted the development of other models for cold front generation, such as oscillation of the cD and the low entropy gas around the bottom of the potential well (Lufkin et al. 1995; Fabian et al. 2001; DW03), hydrodynamic gas sloshing (Ascasibar & Markevitch 2006, hereafter AM06), or dark matter peak oscillation due to scattering of a smaller dark matter system (Tittley & Henriksen 2005). For very recent review, see Markevitch & Vikhlinin (2007).

Cold fronts are found with relatively high frequency. A review of Chandra archival images finds that more than 40% of the observed clusters have cold front-like features, and their presence may have significant physical impact in the physics of their host cluster cores, such as gas heating, generation of bulk and turbulent velocities, constraining conduction, etc. The significance of cold fronts’ influence on cluster physics depends on how they are being generated. Therefore, it is important to determine which mechanisms actually produce cold fronts. Abell 496 provides an excellent opportunity to test different scenarios for cold front generation, given its physical and observational characteristics. A496 is a typical bright, nearby (z = 0.032), apparently relaxed cold core cluster. The X-ray peak coincides very well with the cD optical centroid. The gas temperature varies from 5–6 keV in the outer regions to 2–3 keV in the central arcmin (e.g., Tamura et al. 2001, DW03). The presence of a central abundance enhancement has been established with previous instruments including Ginga and Einstein (White et al. 1994), ASCA (e.g., Dupke & White 2000a), BeppoSAX (Irwin & Bregman 2001), and XMM-Newton (Tamura et al. 2001), showing an overall radial enhancement from ~0.2–0.25 solar in the outer regions to...
~0.4–0.7 solar in the central arcminute. Furthermore, Dupke & White (2000a) also discovered radial gradients, for the first time, in various elemental abundance ratios, which indicates that the gas in the central 2′–3′ has a higher proportion of SN Ia ejecta (~70%) than the outer parts of the cluster. This was confirmed by more sensitive spectrometers on-board XMM-Newton (Tamura et al. 2001).

As pointed out by DW03, different models for cold front formation can be discriminated through the analysis of chemical gradients across the front. If the cold front is due to a head-on merger core remnant, we should expect the front to be accompanied by a specific discontinuity of elemental abundance ratios (e.g., Mushotzky et al. 1996; Dupke & White 2000a, 2000b). The expected discontinuity in this case would be symmetric with respect to the merger axis and asymmetric with respect to the direction perpendicular to the merger axis. This kind of analysis can be performed best with Chandra, given its high angular resolution. DW03 performed a chemical analysis of the cold front in Abell 496. With an effective exposure of ~9 ks they were able to determine abundance ratio profiles only on large semi-annuli, covering a region larger than that of the cold front itself. The distribution of iron, silicon, and oxygen abundances showed radial gradients, but there were no clear discontinuities uniquely related to the cold front itself, pointing out the weaknesses of the remnant merging core model when applied to A496. Here we report the results of a deeper observation of that cluster that allowed us to produce high quality maps of the gas parameters and to compare more closely the observations with the predictions given by different models for cold front formation. All distances shown in this paper are calculated assuming a $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$, unless stated otherwise. At the distance of this cluster $1'' \approx 0.66$ kpc.

2. DATA REDUCTION

Abell 496 was observed by Chandra ACIS-S3 in 2004 July for 76 ks (Fig. 1a). The cluster was centered on the S3 chip. We used Ciao 3.2.0 with CALDB 3.0 to screen the data. After correcting for a short flarelike period, the resulting exposure time in our analysis was 59.6 ks. A gain map correction was applied together with PHA and pixel randomization. ACIS particle background was cleaned as prescribed for VFAINT mode. Point sources were extracted and the background used in spectral fits was generated from blank-sky observations using the acis_bkgrd_lookup script. Here we show the results of spectral fittings with XSPEC V11.3.1 (Arnaud 1996) using the apec and Vapr thermal emission models. Metal abundances are measured relative to the solar photospheric values of Anders & Grevesse (1989). Galactic photoelectric absorption was incorporated using the wabs model (Morrison & McCammon 1983). Spectral channels were grouped to have at least 20 counts per channel. Energy ranges were restricted to 0.5–9.5 keV. The spectral fitting errors are 1 $\sigma$ confidence, unless stated otherwise. This was applied both to the annular distribution (Fig. 2) and to the two-dimensional maps (Fig. 3).

In order to obtain an overall distribution of the spectral parameters we used an adaptive smoothing code that selects extraction regions based on a fixed minimum number of counts per cell (here we used 3000 counts for temperatures and global abundances and 7000 for individual abundances) to maintain the range of statistical fitting errors more or less constant throughout. The intercell spacing is fixed at a fraction of the radius of the surrounding cells, and in general there is significant cell to cell overlap except for the cells with smallest size. The overlap of extraction regions is therefore stronger in low surface brightness regions, away from the core of the cluster. We plot the distribution of region sizes in Figures 3e and 4e, to give an estimate of the local smoothing kernel size. The code produces a matrix with best-fit values and different cell sizes. The best-fit values used here are defined as the midpoint of the 68% confidence errors. In order to make the contour plots, this matrix is mapped into a square matrix with equal cell sizes using an interpolation routine. This is done by computing a new value for each cell in the regular matrix weighing by the values of the adjoining cells in the matrix included within some defined search radius (minimum of 3 cells.

Fig. 1a

Fig. 1a — (a) Exposure corrected Chandra image of Abell 496 smoothed in DS9 ver. 4.0 with a Gaussian function with 3 pixel kernel radius. Black arrows show the position of the northern, southern, and eastern main cold fronts. (b) Same as (a), but with the PIE sectorial extraction regions used in the radial analysis of the cold fronts. X-ray contours are also overlaid and are the same as in Figs. 2 and 3. The outermost contour corresponds to ACIS-S3 chip border. [See the electronic edition of the Journal for a color version of this figure.]
in 4 adjacent quadrants). The closest measured values usually have the most influence on calculating the value of a cell. The computation is based on the Kriging method (for a description see, e.g., Davis 1986, p. 383), which calculates the weights from a semi-variogram developed from the spatial structure of the data, where $h$ is the number of intervals between the values of the regionalized variable $X$ taken at locations $i$ and $i + h$, and $n$ is the total number of points. The number of cells of the mapped matrix was artificially increased to three times the maximum length of the original matrix for purposes of improving image quality for analysis. This is responsible for the small "square domains" that appear in Figures 3a, 3c, 4a, and 4c. The values outside the CCD border contours are also an effect of the smoothing algorithm and should be ignored.

3. RESULTS

3.1. Cold Fronts and Temperature Distribution

Figure 1a shows the exposure-corrected smoothed X-ray image of A496. One can clearly see the sharp surface brightness edge toward the north, described in DW03. One can also see two other brightness edges (to the southwest and southeast) that meet at nearly right angles. This suggests the presence of multiple cold fronts in this cluster. To analyze the nature of these edges we used the set of extraction regions shown in Figure 1b. The radial distance units are pixels and 1 pixel $\approx 0.5^\circ \approx 0.33$ kpc. Errors are $1\sigma$ confidence. Vertical lines indicate the position of the cold fronts. (b) Individual iron and metal abundance ratio radial distributions. Results from spectral fittings using a wabs(apec) spectral model of same regions as in (a) and the same color code. The values of Si/Fe, S/Fe, and Si/S for the north (hexagon) and west (diamond) directions had 2 added to their original values for clarity. The reduced $\chi^2$ values for the spectral fittings shown are typically 0.7–0.96, with typically 180–250 dof. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2a

**NORTH/ EAST/ SOUTH/ WEST EDGES**

Radius (Pixel = 0.5 Arcsec)

Fig. 2b

**NORTH/ EAST/SOUTH/ WEST EDGES**

Radius (Pixel = 0.5 Arcsec)

Fig. 2.—(a) Temperature and density profiles: exposure corrected surface brightness (top) and best-fit gas temperature (bottom) radial distributions along the line of symmetry of the sharp edge (cold fronts) indicated in Fig. 1b, north (diamonds), east (triangles), south (squares), and west (circles) using a wabs(apec) spectral model. The vertical lines indicate the position of the cold fronts using the notation: triangles = dashed, squares = dotted, circles = dot-dashed, and diamonds = double-dot-dashed. The extraction regions correspond to those shown in Fig. 1b. The radial distance units are pixels and 1 pixel $\approx 0.5^\circ \approx 0.33$ kpc. Errors are $1\sigma$ confidence. Vertical lines indicate the position of the cold fronts. (b) Individual iron and metal abundance ratio radial distributions. Results from spectral fittings using a wabs(apec) spectral model of same regions as in (a) and the same color code. The values of Si/Fe, S/Fe, and Si/S for the north (hexagon) and west (diamond) directions had 2 added to their original values for clarity. The reduced $\chi^2$ values for the spectral fittings shown are typically 0.7–0.96, with typically 180–250 dof. [See the electronic edition of the Journal for a color version of this figure.]

1 Tanaka et al. (2006) finds an additional cold front in this cluster 4' to the south, out of the field of view of our observation.
Fig. 3.—Results from an adaptive smoothing algorithm with a minimum of 3000 counts per extraction region (circular) and fitted with an absorbed VAPEC spectral model. The gridding method used is a correlation method that calculates a new value for each cell in the regular matrix from the values of the points in the adjoining cells that are included within the search radius, using the Kriging method (e.g., Davis 1986), see § 2 for details. We also overlay the X-ray contours shown in Fig. 1 on top. North is up. The units are pixels and 1 pixel = 0.57 = 0.33 kpc. The outermost contour corresponds to ACIS-S3 chip border and is centered at RA = 68.4084°, decl. = −13.261°. Values outside the CCD borders are an effect of the smoothing algorithm and should be ignored. The parameters mapped are (a) temperature and (c) abundance. The regions of (and surrounding) the cold arm are shown in (a) and (c) as polygons. (b) and (d) show the adaptively smoothed 1σ error maps for temperatures and abundances, respectively. Panel 1e shows a color contour plot of the radii of the spectral extraction regions used to determine the parameters shown in (a)–(d). It basically gives an idea of the resolution, or smoothing kernel radius, of the 2D maps above. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 4.—Individual metal abundance ratios. Same notation as in Figure 3, but for the silicon to iron ($a, b$) and silicon to sulfur ($c, d$) ratios. Panel 2e shows, analogously, the radii of the spectral extraction regions used to determine the parameters in Figs. 3a–3d. [See the electronic edition of the Journal for a color version of this figure.]
nearly at the same radial distance \(r \sim 64\) kpc as the northern one and is, apparently, an extension of the northern front. We can also see that the two edges near the core, labeled east \(r \sim 16\) kpc and south \(r \sim 22\) kpc, have the temperature jumps characteristic of cold fronts. There is also a marginally significant cold front to the east at \(r \sim 106\) kpc.

Following DW03, we measured the radial distribution of metal abundance ratios toward the directions of the main fronts (edges). We used “PIE” extraction regions that were chosen in such a way as to have the same opening angle as the cold front of interest. In the radial distributions there are no clear significant systematic relations between the changes in Fe abundance or abundance ratios and cold fronts. The changes seen can be mostly associated with overall (global) radial trends. Globally, the Fe abundance shows a radial decline from supersolar near the cluster’s center to subsolar in the outer core regions. At the very center, \(r \lesssim 10''\) \((\sim 7\) kpc), there is a statistically significant abundance dip described in \(\S\) 3.2. The radially averaged value in the central 23 kpc is 0.93 \pm 0.04 solar (with asymmetric variations from 0.8 to 1.2 solar) and in the outer (130 \pm 50) kpc is 0.75 \pm 0.04 (with asymmetric variations from 0.47 to 0.86 solar).

The results for the ratios involving Si, S, and Fe are shown in Figure 2a, where the color code is the same as that used in Figure 2a. In the abundance ratio plots we added “2” to the values shown in Table 1. The temperature of the cold arm is \(\sim 3.2\) keV. The temperatures on the surrounding regions of the cold arm are \(3.5 \pm 0.1\) keV toward the inner and \(4.1 \pm 0.2\) keV toward the outer cluster regions, respectively. The cold arm is definitely associated with the northern cold front and to a lesser extent with the western cold front. It departs from a boxy low temperature region, the edges of which appear to coincide with the southeastern and southern cold fronts near the cluster’s core, although the temperature edges in these weaker cold fronts are less well defined than that of the main cold front. From Figure 2b it can be seen that the overall temperature error in the cold arm region is around \(0.1\)–\(0.2\) keV. The higher temperatures near the southern CCD border are not well constrained (with errors \(\gtrsim 1\) keV).

There are significant indications of a “cold tail” \((T \sim 4\) keV) starting 2.3′ southwest of the cluster’s center extending to 4.2′ to the south of the cluster that is associated with a low Fe abundance region (Fig. 3c). The abundance along the cold tail is approximately half of the surrounding regions values of \(\sim 1.2\) solar. This “cold tail” seems to extend to the south for more 5′ (Tanaka et al. 2006). A similar cold tail was found on the opposite side of the cold front in the cluster 2A0335+096 (Tanaka et al. 2006). The Fe abundance map is also inhomogeneous (Figs. 3c and 3d). There is an overall abundance gradient, which is steeper toward the northern regions. In particular the transition from sub- to supersolar abundances happens at a radius of \(100'' \sim 140''\) from the center in all directions but the south. In general, the Fe abundance within the cold front spatial scales \((r < 60\) kpc) is supersolar, with the exception of the very central 8 kpc, where an abundance “dip” is found. The Fe abundance in the central dip

| Region \(^b\) | Temperature (keV) | Fe (solar) | Si (solar) | S (solar) | Si/Fe (ratio) | S/Fe (ratio) | Si/S (ratio) | \(\chi^2\) (dof) |
|--------------|------------------|------------|------------|-----------|--------------|--------------|--------------|----------------|
| Inner......... | 3.55 \pm 0.11    | 0.86 \pm 0.08 | 0.88 \pm 0.23 | 1.44 \pm 0.35 | 1.03 \pm 0.29 | 1.68 \pm 0.43 | 0.61 \pm 0.22 | 211/204 |
| Arm ........... | 3.08 \pm 0.07    | 0.77 \pm 0.07 | 1.60 \pm 0.20 | 1.43 \pm 0.26 | 2.08 \pm 0.32 | 1.86 \pm 0.38 | 1.12 \pm 0.25 | 176/177 |
| Outer.......... | 4.68 \pm 0.22    | 0.75 \pm 0.13 | 0.72 \pm 0.57 | 2.16 \pm 0.74 | 0.96 \pm 0.78 | 2.89 \pm 1.10 | 0.29 \pm 0.24 | 167/171 |

\(^a\) From vabo (Valec) model.
\(^b\) Shown in Figs. 3a, 3c, 4a, and 4c.

\(^2\) It should be noted that even though the radial trends found for ratios that include S are, in general, similar to those derived from other ratios, the absolute values of the S abundance seem to be overestimated with respect to SN Ia and II yield models. To place it within the theoretical models the values measured would need a systematic negative correction. This does not change the conclusions of this paper, since we are looking at relative chemical changes across cold fronts. For a discussion about the discrepancies found between observed sulfur yields and model predictions see, e.g., Dupke & White (2000a) and Baumgartner et al. (2005, and references therein).
reaches a minimum of $0.55 \pm 0.3$ solar (an average of $0.8 \pm 0.03$ solar in a circular region 10.5 kpc in radius) and in the immediately surrounding regions achieves a maximum of $\sim 1.7 \pm 0.4$ solar (with an average of $1.1 \pm 0.04$ solar within an annulus with radius between 11 and 22 kpc). There is a secondary, marginally significant, abundance dip with similar spatial scales $35''$ to the north-northwest, where the abundance decreases from $\sim 1.3$ to $\sim 0.7$ solar with a characteristic error of $0.3$ solar. Central metal abundance dips have been found in other clusters [e.g., A2199 (Johnstone et al. 2002), Centaurus (Sanders & Fabian 2002), and Perseus (Schmidt et al. 2002)], and the mechanisms that generate them are a matter of current debate. Suggested scenarios include resonant scattering (cf. Sanders & Fabian 2006), extremely inhomogeneous metal abundances (Morris & Fabian 2003), artifacts appearing from fitting single temperature models to multi-temperature gas (Buote 2000) and buoyant transport to higher radii (Brighenti & Mathews 2005). None of these mechanisms are adequate to explain off-center abundance dips, which are probably related to previous AGN activity. An extended analysis of off-center abundance dips in clusters is provided elsewhere (R. A. Dupke et al. 2008, in preparation). Metal abundances are in general high toward the southern regions, with the exception of the regions coincident with the southern cold tail.

We also performed an analysis of the 2D distribution of the elemental abundance ratios in this cluster. Different metal enrichment mechanisms act with different efficiencies at different cluster locations and produce different SN type ejecta signatures. Therefore, elemental abundance ratios can be used as “fingerprints” to trace the gas history, better than metal abundances alone. The abundance ratio maps involving the best-determined abundances (Si, S, and Fe) are shown in Figures 4a and 4c. The 1 $\sigma$ errors of the quantities are shown in Figures 4b and 4d, and give an idea of the significance level of the measured quantity in the region of interest. Since our best-fit values are defined as the midpoint of the 1 $\sigma$ error bars, we use only values with fractional errors smaller than 100% to create the 2D square images. This is done to avoid biases in the interpolation to produce the smoothed color contours that would be caused by upper/lower limits, where the error bars can be highly asymmetrical. The spatial resolution of the map is not good enough to completely resolve the cold arm with a characteristic smoothing kernel size of $\sim 30$–50 pixels, or $15''$–$25''$. Nevertheless, as corroborated by direct measurements of the regions of interest (Table 1), it can be seen that, in general, the cold arm is accompanied by enhanced abundance ratio values (lower SN $\text{Fe}$ mass fraction than the surroundings). This is mostly visible in the Si/Fe map, which shows an average variation from $\sim 1$ to 2, or equivalently, from 85% to 51% SN $\text{Fe}$ mass fraction, respectively, in the regions surrounding the cold arm, and the regions along the cold arm. The characteristic error is $\sim 0.4$ ($\sim 14\%$ in SN $\text{Fe}$ mass fraction). Sulfur abundances are higher than expected, and abundance ratios are off-scale when compared to the theoretical predictions of Nomoto et al. (1997a, 1997b) for SN Ia and II yields. However, the trend of S/Fe is similar to that of Si/Fe and to place the limits within theoretical bounds, we need to apply a constant positive correction of $\sim 0.4$ to S/Fe, placing the and the corresponding S negative correction $\sim 0.4$–0.8 within the errors (see footnote 2).

4. DISCUSSION: THE NATURE OF COLD FRONTS IN ABELL 496

The analysis of the core of A496 presented in this paper reveals several new features that were not observed previously: a large multiplicity of cold-front features (at least three cold fronts); a spiral cold arm seen in the temperature map, which is clearly associated with the main (northern) cold front; strong indication of spiral (or circular) chemical arms associated with the main cold front; a cold, metal-poor tail extending toward the direction opposite to the main cold front; an overall central abundance enhancement with a small-scale “dip” at the core; and marginal evidence for other off-center abundance dips. The multiplicity of cold fronts, together with the spiral pattern of the chemical gradients, seem to rule out the scenario in which the cold front(s) in this cluster are created by a head-on merging remnant core. Although gas sloshing has been invoked to explain cold fronts in apparently relaxed clusters, there have been very few observable predictions that can be used to discriminate the details of different sloshing mechanisms proposed in the literature. Very recently, AM06 performed high-resolution numerical hydrodynamical simulations specifically designed to investigate the effects of scattering of lower mass dark matter halos (with and without gas) by clusters of galaxies. One of the results from their work was that the subhalo flyby induces a variable gas velocity field in the ICM of the main cluster that generates ram pressure near the cluster gas core and produces cold fronts, accompanied by significant amount of substructures seen in the gas 2D temperature distribution.

A common feature in most cases analyzed by AM06 was the presence of cold spiral arms coinciding with the cold fronts close to the main cluster’s core, which were long-lasting. In particular, their case for a dark matter perturber produces properties very similar to those observed in A496. In AM06 a pure dark matter halo with 1/5 of the mass of the main cluster flies by with an impact parameter of 500 kpc and with closest approach at $t \approx 1.37$ Gyr. We show part of Figure 7 of AM06, for the epoch corresponding to 1.9 Gyr (Fig. 5a). The image is inverted vertically to be compared directly to the temperature map of A496 in Figure 2a. The size of the box is 250 kpc, similar to the size of ACIS-S3 CCD borders at the redshift of the cluster ($\sim 320$ kpc). The cold front(s) can be seen when comparing the temperature map with the surface brightness map (Fig. 21 of AM06). The main cold front coincides with the large spiral cold arm extending horizontally. The spatial scale is very similar to that of the cold arm in A496. Their simulations also seem to indicate the presence of milder cold fronts in the opposite side closer to cluster’s core. These are clear predictions that are corroborated well by A496 and strongly suggest that a dark matter halo flyby created the cold fronts in this cluster. Furthermore, there is a larger scale, diffuse cold extension of the main arm also toward the south of the main cold front, which is a consequence of the ram pressure caused by the gas velocity field induced by the DM halo flyby. This suggests that the same process that creates the main cold front may also be associated with the formation of the southern cold tail seen in A496. The existence of such pure DM subhalos is not completely unexpected, since the intergalactic gas originally belonging to the subhalo could have been stripped in an earlier phase of the encounter with the main cluster. AM06 simulations of gaseous DM subclump passages produces a variety of substructures visible in temperatures and surface brightness maps, which are not seen in A496, and are not favored within the limited cases simulated. Future addition of metallicity distributions to cluster merger simulations should help to constrain the characteristics of the perturber.

A prediction of this scenario is the presence of a DM halo in the outskirts of the cluster without significant X-ray emitting gas. From the simulations, the position of that clump at the present epoch (corresponding to a simulation epoch of 2 Gyr) would be in the north, in the same general direction of the main cold front. It is reasonable to assume that galaxies would tend to trace their host
DM subhalo. A recent wavelet analysis of the member galaxies of A496 within a 1.5h\(^{-1}\) Mpc radius (Flin & Krywult 2006), found a secondary in all wavelet scales analyzed, to the northwest of the core of A496, roughly consistent with the position where the DM perturber was likely to be found in the AM06 simulation (toward the north). We illustrate this in Figure 5b, where we show the positions of the dark matter clump at 1.34, 1.43, 1.51, and 4.2 Gyr, taken from merging four of the nine images of AM06’s Figure 3. We overlap part of Figure 5 of Flin & Krywult (2006), which illustrates the position of the galaxy subclump for a wavelet scale of 129 kpc.

If we scale the ratio of masses of the main cluster to that of the DM perturber from the AM06 simulation parameters and, conservatively, use for A496 the mass of \(4.2 \times 10^{14} M_\odot\) (Durret et al. 2000), the perturber should be very massive (0.84 \(\times 10^{14} M_\odot\)). This is almost 3 times more massive than HCG62 (Morita et al. 2006), the brightest HCG in the Ponman et al. (1996) survey. Such a group, if not unusually depleted of gas, would easily be detected by current X-ray instruments at the A496 redshift. ROSAT All-Sky Survey (RASS) exposures of that region (\(R < 500\) from A496) fail to detect a significant X-ray excess from any extended sources as expected by the gasless dark matter perturber scenario described here. The excess count in a square region 180” on the side centered in Flin & Krywult’s (2006) subclump is 15 \(\pm 18\) background subtracted counts. However, RASS exposures are too short (\(\sim 250\) s) to place any significant constraints on the amount of X-ray emitting gas. Future combination of weak lensing and deeper X-ray observations of that substructure with current satellites should be able to corroborate this prediction.

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