A Chandra view of the multiple merger in Abell 2744

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ABSTRACT
We present a Chandra observation of the merging cluster of galaxies Abell 2744. The cluster shows strong evidence for an ongoing major merger which we believe to be responsible for the radio halo. X-ray emission and temperature maps of the cluster, combined with the spatial and redshift distribution of the galaxies, indicate a roughly north–south axis for the merger, with a significant velocity component along the line of sight. The merger is occurring at a very large velocity, with $M = 2–3$. We estimate the mass ratio of the merging subclusters to be of the order of unity. They are nearing their closest approach to each other, but with a significant impact parameter. In addition, there is a small merging subcluster toward the north-west, unrelated to the major merger, which shows evidence of a bow shock. A hydrodynamical analysis of the subcluster indicates a merger velocity corresponding to a Mach number of $\sim 1.2$, consistent with a simple infall model. This infalling subcluster may also be re-exciting electrons in the radio halo. Its small Mach number lends support to turbulent reacceleration models for radio halo formation.

Key words: acceleration of particles – shock waves – turbulence – galaxies: clusters: individual: Abell 2744 – intergalactic medium – X-rays: galaxies: clusters.

1 INTRODUCTION

One of the largest contributions that Chandra has made in its first few years of operation is in the study of merging clusters of galaxies. The unprecedented spatial resolution of the satellite has made possible the study of detailed physics of cluster interactions. Cold fronts – the sharp leading edges of moving cool cores of gas from clusters – along with their associated bow shocks have been imaged for the first time using Chandra. From these measurements, the dynamics of cluster mergers have been determined (e.g. A2142, Markevitch et al. 2000; A3667, Vikhlinin et al. 2001a; 1E 0657-56, Markevitch et al. 2002). These analyses at high spatial resolution have also made it possible to demonstrate the suppression of conduction in clusters (Ettori & Fabian 2000; Vikhlinin, Markevitch & Murray 2001b), to determine the dark matter distribution on small scales (Vikhlinin & Markevitch 2002). The resolution of Chandra has also provided the basis for the first measurement of a direct correlation between cluster merger shocks and diffuse radio emission in clusters (Markevitch & Vikhlinin 2001).

Abell 2744, also known as AC 118, is a rich (Abell richness class 3), luminous [$L_X (0.1–2.4 \text{ keV}) = 22.05 \times 10^{44} \text{ erg s}^{-1}$; Ebeling et al. 1996] cluster at moderate redshift ($z = 0.308$; Couch & Newell 1984). It hosts one of the most luminous known radio haloes which covers the central 1.8 Mpc of the cluster, as well as a large radio relic at a distance of about 2 Mpc from the cluster centre (Giovannini, Tordi & Feretti 1999; Govoni et al. 2001a,b). Because of the presence of the radio halo and relic, Abell 2744 has been known to be undergoing a merger, but the details of the merger have been rather murky. Abell (1958) classified the spatial distribution of its galaxies as ‘regular,’ but it has no dominant bright galaxy or galaxies, so its Bautz–Morgan class is III (Bautz & Morgan 1970).

Observations of the cluster with ROSAT shed some light on the merger, showing the presence of a second peak in the X-ray brightness a little less than 1 Mpc to the north-west of the main peak. This second peak is much smaller and presumably much less massive than the main cluster, although it could have been stripped of much of its gas if it had already passed through the main cluster. The radio halo extends in the direction of this second peak, leading to the impression that the merger of the large main cluster and this smaller subcluster to the north-west is the cause of the radio halo, perhaps accelerating electrons via turbulence in its wake.

Our observation of the cluster with the higher resolution made possible by Chandra disproves this picture for the formation of the halo. Although a merger does indeed appear to be responsible for the radio halo, in fact it appears to be created by a merger between two subclusters with a small mass ratio, while the very small subcluster to the north-west is only beginning its descent into the potential of the two much larger subclusters and has only a small effect on the non-thermal emission.

We assume $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ throughout, for which 1 arcsec $= 5.58 \text{ kpc}$ and $d_L = 1970 \text{ Mpc}$. All errors are quoted at 90 per cent confidence unless otherwise stated.

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2 OBSERVATION AND DATA REDUCTION

The data were taken on 2001 September 3 in a single observation of \( \sim 24\,800 \) s using the ACIS-S detector on Chandra, with the focus on the S3 chip. The data were taken in Very Faint (VF) mode, in order to allow for additional rejection of particle background events.\(^1\) Very Faint mode data retains 5 × 5 pixel islands for each event, thereby making it possible to identify charged particle events that would appear to be valid photon events using the standard 3 × 3 pixel islands. This additional filtering of background events was performed, then the data were filtered on the standard ASCA grades 0, 2, 3, 4 and 6. Observations with Chandra are frequently affected by background flares where the background increases over the quiescent level. We checked for flares using the S1 chip, which is quite sensitive to flares and is far enough away from the focal point of the detector to be essentially devoid of source photons. No flares occurred during our observation.

We used the period D blank-sky background files for background correction. The background files were also screened using the VF mode filtering. We checked the quiescent background rate in our data by measuring the event rate on the S3 chip in PHA channels 2500–3000, where the sensitivity to photons is extremely small, and compared it to the rate in the same PHA channels in the blank-sky background files. The background level in our data was \( \sim 19 \) per cent below the nominal quiescent background level in the blank-sky files, which include data from the beginning of period D when the quiescent level was slightly higher than the average for that period. We therefore corrected the background by the ratio of these quiescent rates when subtracting the background in our subsequent analysis. Despite this small correction, the background level in our data is consistent with the nominal quiescent level in PHA channels 2500–3000 at the date of the observation, to within the observed scatter of the nominal level. Throughout this analysis, we used the calibration products in CALDB 2.17. We assume the Galactic absorbing column of 1.6 × 10\(^{20}\) cm\(^{-2}\) in all spectral fits.

3 X-RAY PROPERTIES

3.1 X-ray Image

We show a raw Chandra image, binned into 2-arcsec pixels, in Fig. 1. Fig. 2 shows an adaptively smoothed version of the same image. The adaptively smoothed image was constructed using the CIAO tool CSMOOTH with a minimum signal-to-noise ratio of 3 and a maximum of 5. The blank-sky background image and exposure map were both smoothed using the same kernel as for the source image. These smoothed images were then used to correct the source image. A monoenergetic exposure map was used, with energy at 0.8 keV – the peak of the emission in the central 2.25 arcmin of the cluster.

The Chandra image shows two distinct components to the cluster: a large, irregular main cluster and a much smaller subcluster to its north-west (see Fig. 2). The main cluster, while fairly strongly peaked, does not fall off in surface brightness uniformly in all directions. Rather, it shows four ‘ridges’ of emission extending to the north (hereafter ridge A; see Fig. 3), north-west (ridge B), south-west (ridge C) and south (ridge D). These ridges provide strong evidence, even in the absence of other information, that the cluster is out of hydrostatic equilibrium. All the ridges except ridge D extend at least 1 arcmin out of the centre, whereas the north ridge extends nearly 2 arcmin. These three ridges also show significant curvature, possibly suggesting internal angular momentum and turbulence within the main cluster. Even the ridges are not completely continuous: ridges A and D have secondary surface brightness peaks away from the central peak of the main cluster, at roughly R.A. = 00\(^{h}\)14\(^{m}\)19.5, Dec. = −30\(^{\circ}\)24′09′ and R.A. = 00\(^{h}\)14\(^{m}\)20.5, Dec. = −30\(^{\circ}\)22′45′, respectively. These secondary peaks are clearly visible in Fig. 2. We suspect that these may be identified with the cool cores of merging subclusters, as we will discuss below.

At large radii, the substructure in the main cluster lessens. By a distance of \( \sim 2.1 \) arcmin from the cluster centre, the surface brightness distribution falls off approximately uniformly in all directions except that of the north-west subcluster. In a \( \beta \)-model fit to a ROSAT PSPC image of the cluster, Govoni et al. (2001b) find both an unusually large core radius of \( r_c \sim 640 \) kpc and an unusually steep value for \( \beta \). Their fit excludes the subcluster. The core they find encompasses exactly the ‘ridges’ in the centre of the main cluster, as is evident from the Chandra data. The core radius they found may also have been broadened slightly by the large point spread function of ROSAT. We have fit a radial surface brightness profile, centred on the same point as that used in Govoni et al. (2001b) (R.A. = 00\(^{h}\)14\(^{m}\)18.7, Dec. = −30\(^{\circ}\)23′16′), with a single-component \( \beta \)-model, excluding the region of the north-west subcluster. We find the best-fitting parameters to be \( r_c = (474 \pm 33) \) kpc and \( \beta = 0.79 \pm 0.06 \) (1\( \sigma \) errors). The Chandra image shows that the cluster is too far from equilibrium, particularly in its core, for the parameters of the \( \beta \)-model fit to have any useful physical meaning.

About 2.7 arcmin (\( \sim 900 \) kpc projected distance) to the north-west of the main cluster is a much smaller subcluster. At that distance, the subcluster is still well within the X-ray halo of the main cluster, which extends out to a radius of at least 11 arcmin as detected by ROSAT (Govoni et al. 2001b). The subcluster exhibits a sharp, curved eastern edge that is particularly distinct on its north-east side, with a surface brightness contrast across the edge of 1.7 ± 0.2 (1\( \sigma \)) and is hence very statistically significant. From there, it fans out to the west, getting more diffuse with increasing distance from the

\(^1\) http://cxc.harvard.edu/cal/Links/Acis/acis/Cal.prods/vfbkgrnd/index.html
\(^2\) http://asc.harvard.edu/contrib/maxim/bg/
east edge. These features indicate that the subcluster is moving from west to east, while its gas is swept back by ram pressure from the intracluster medium (ICM) of the main cluster. This characteristic ‘fan’ shape of the subcluster is typical of smaller subclusters being ram-pressure stripped by interaction with a larger cluster (cf. Kempner, Sarazin & Ricker 2002; Markevitch et al. 2002). As can be seen in Fig. 1, the fan of emission of the subcluster is brighter to one side (the north) than to the other. The contours in Fig. 2 are also compressed on this side, indicating that the brightness falls off more steeply than it does on the south side of the subcluster. This morphology is similar to that of the south subcluster in Abell 85 (Kempner, Sarazin & Ricker 2002), which is quite similar in terms of both the mass ratio and the current separation of the constituent clusters. The ‘bullet’ subcluster in 1E 0657-56 (Markevitch et al. 2002) also shows this sort of asymmetry.

3.2 The north-west subcluster

As mentioned above, the raw image shows tentative evidence that the north-west subcluster contains a ‘cold front’ similar to those seen by Chandra in other clusters (e.g. A2142, Markevitch et al. 2000; A3667, Vikhlinin et al. 2001a; 1E 0657-56, Markevitch et al. 2002), although the temperature contrast across the brightness discontinuity is only about 20 per cent. A longer observation with better photon statistics would be required to definitively identify the brightness discontinuity as a cold front. Also visible is a possible indication of a bow shock about 90 kpc ahead of the tentative cold front (see Fig. 3). Approximating the core as a sphere, the ratio of the stand-off distance of the shock to the radius of curvature of the cold core is determined only by the Mach number of the shock. Following Moekel (1949), this diagnostic indicates a Mach number of ∼1.2. The stand-off distance one measures, however, is highly sensitive to projection. That is, if the velocity of the subcluster has a significant line-of-sight component, we will have underestimated the stand-off distance, and thereby overestimated the Mach number. Furthermore, this method is exact only for a perfect sphere, although the tentative cold front is unlikely to deviate from this too much, at least on its leading edge.

The photon statistics are too poor to do a properly deprojected analysis of the electron densities across the tentative cold front. There are, however, other methods for measuring the velocity of the subcluster. The surface brightness jump across the putative bow
shock provides an approximate diagnostic of the velocity of the subcluster. We approximate the square root of the ratio of brightnesses on either side of the shock as the ratio of densities, that is, \((I_{\text{SS}}/I_{\text{SB}})^{1/2} \approx \rho_1/\rho_2\), which, in turn, is equal to the inverse of the shock compression. From this, we determine the shock compression to be \(C = 1.3 \pm 0.2\), which implies a Mach number of \(\mathcal{M} = 1.2 \pm 0.2\) (both 1\(\sigma\)). From the image, we can also roughly determine the opening angle of the Mach cone to be about 55–60\(^\circ\), which implies a Mach number of 1.15–1.22. Thus, although the evidence of a bow shock is certainly not conclusive from the image, the consistency of the various diagnostics lends credence to the suggestion of a bow shock.

These various independent diagnostics for the velocity of the subcluster are all consistent with each other to within the measurement errors, all finding \(\mathcal{M} \approx 1.2\). This is a good indication that the merger axis is not highly inclined to the plane of the sky. This is quite similar to the velocities found for the other merging subclusters mentioned above. As a sanity check, we also calculated the velocity for a collisionless point mass at the projected radius of the subcluster, falling from the turnaround radius into an isothermal potential with a mass of \(2.70 \times 10^{15} \, M_\odot\) (Girardi & Mezzetti 2001). This simplistic model puts the velocity of the test particle at \(\mathcal{M} = 1.2\), given the measured temperature of the main cluster of 9.3–9.7 keV in the vicinity of the subcluster. This is also consistent with our measured velocity. We should note, however, that this velocity should be treated as an upper limit for this particular model, because projection effects would increase the actual separation of the subcluster and decrease its velocity. Furthermore, the fan-like shape of the subcluster indicates that the effects of ram pressure on the gaseous content of the subcluster are significant, further reducing its likely velocity compared to our simple model. Therefore, the model is only useful in setting the general scale of the velocity of the subcluster, and for this purpose it is completely consistent with our data.

### 3.3 Temperature structure

As might be expected from the complex structure in the X-ray image, the temperature structure in the cluster is quite complex as well. Fig. 4 shows the temperature structure of the cluster in the

![Figure 3](image3.png)

Figure 3. Gaussian-smoothed, 0.3–6 keV image of Abell 2744. The cold front and bow shock are indicated in red. The surface brightness ridges and cool cores are also labelled.

![Figure 4](image4.png)

Figure 4. Temperature map of Abell 2744 made with adaptively binned spectra. The pixel size in the image is 6.9 arcsec. The binning length ranges from 29.3 arcsec in high signal-to-noise areas to 63 arcsec in the outer parts of the cluster. Pixels with negative fractional error in the temperature of >15 per cent (90 per cent confidence) have been masked out for clarity. Contours from Fig. 2 are shown for reference.

The final image shows several regions of 8–13 keV gas in the core of the cluster, surrounded by 6–7 keV gas. The 6–7 keV gas extends out to a radius of about 740 kpc, and even further in the direction of the north-west subcluster. Outside that radius, there is some evidence that the temperature drops even further, although the photon statistics are only good enough to make such a determination in one small area to the north-east. The upper limit on the temperature in this region is nowhere greater than 5 keV, whereas the lower limit at smaller radii is nowhere less than about 5.5 keV (both 90 per cent confidence), so the temperature difference is real. However, deeper observations with a larger field of view are needed to confirm this drop in temperature at large radii, particularly because the temperature drop to the north-east could be a local phenomenon, given the patchiness of the temperature structure throughout the cluster.

Two fingers of cooler gas extend into the centre of the cluster. The higher-contrast one coincides with the south surface brightness ‘ridge’ (ridge D), whereas the lower-contrast one follows ridge A. Both are oriented roughly north–south. In both cases, these fingers of cool emission terminate with the bright peaks of emission in higher signal-to-noise areas of the data. The temperature map was created using the adaptive binning algorithm described in Houck & Denicola (2000). The algorithm bins the data to a minimum of 800 counts in each extracted spectrum, while also minimizing the sizes of the extraction regions. The maximum allowed size of an extraction region was 63 \times 63\,\text{arcsec}^2. Regions of this size with fewer than 800 counts were excluded from this analysis. The response matrices were generated on a 32 \times 32\,\text{grid in chip coordinates. The ancillary responses were generated on a 16 \times 16\,\text{grid in the coordinates of the binned output image. The systematic errors introduced by this binning are much smaller than the statistical errors in the temperature measurements. The systematic error is approximately 1 per cent. Each pixel in the output map is 6.9 \times 6.9\,\text{arcsec}^2. Each spectrum was corrected for background using a spectrum from a matching region in the blank-sky background field discussed in Section 2. Regions containing point sources were eliminated from the source and background event lists. For clarity, we masked out all pixels in the final output image with negative fractional errors >15 per cent (90 per cent confidence). Typical fractional errors in the temperature map are ~9 per cent (90 per cent confidence).
each ridge. The regions of hottest temperature in the core of the cluster correspond to the other surface brightness ridges. Whereas ridges corresponding to the hotter gas, particularly ridges B and C, are relatively sharp narrow features, the cooler ridges are somewhat broader. Ridge A is especially broad. We note, however, that the hottest region, just east of the cluster centre, is not identified with any surface brightness enhancement. Another hot region, the finger of hot gas extending due south out of the cluster centre, also is uncorrelated with a surface brightness enhancement.

The gas in the north-west subcluster, as discussed above, is significantly cooler than the ambient gas surrounding it.

4 GALAXY POPULATIONS AND DISTRIBUTION

Abell 2744 is a so-called Butcher–Oemler cluster (Butcher & Oemler 1978a,b; Butcher & Oemler 1984), with an anomalously large fraction of blue galaxies compared with present-day clusters. The cluster has a marked deficiency of elliptical galaxies, a high percentage of spirals and a normal percentage of S0 galaxies (Couch et al. 1998). Two large elliptical galaxies fall at the centre of the galaxy population, just south-east of the peak of the X-ray emission, although they are not significantly more luminous than the next brightest galaxies. The spatial distribution of the galaxies, in fact, is roughly centred on these two galaxies rather than on the peak of the X-ray gas, although neither of these two galaxies is morphologically identified as a cD (Couch et al. 1998).

To the north-west, in the direction of the subcluster, Andreon (2001) identifies a clump of galaxies which was associated with the X-ray subcluster. The X-ray emission from the subcluster is actually somewhat farther north-west than the concentration of galaxies. If the subcluster were falling straight into the main cluster, one would expect the collisionless galaxies to precede the collisional ICM as ram pressure from the interaction with the main cluster slows the descent of the subcluster into the main cluster potential. The morphology of the X-ray gas is largely in agreement with this interpretation, as we will discuss in greater detail in Section 5.

An extensive catalogue of galaxy redshifts in Abell 2744 was compiled by Couch & Sharples (1987) and Couch et al. (1998). The distribution in redshift space of the combined sample from both these sources deviates significantly from a single Gaussian, as noted by Couch et al. (1998) for their subsample. With the addition of the sample from Couch & Sharples (1987), the distribution becomes murkier, but is still clearly non-Gaussian. While the sample is relatively small – only 72 galaxies – the distribution is noticeably bimodal. Girardi & Mezzetti (2001) find one peak at \( z = 0.3014 \) and the other peak at \( z = 0.3148 \). From this, we see that the merger has quite a high velocity along the line of sight: \( \Delta c z = 4000 \text{ km s}^{-1} \).

This unusually large merger velocity strongly suggests that the two subclusters are at or near their closest approach to one another. The extremely large line-of-sight component of the velocity also indicated that the merger is occurring largely, though not entirely, along the line of sight. As we will show in Section 5, a small transverse component to the merger is necessary to explain the data.

The further north of the two brightest ellipticals, at R.A. = \( 0^\circ\!0^\prime\!0^\alpha 14^m 20^s 6, \) Dec. = \( -30^\circ\!24^\prime\!00^\alpha 0 \), has a redshift of \( z = 0.318 \pm 0.00033 \) (Couch & Sharples 1987), which is at the peak of the bluer component of the distribution. The further south of the two bright ellipticals, at R.A. = \( 0^\circ\!0^\prime\!0^\alpha 14^m 22^s 0, \) Dec. = \( -30^\circ\!24^\prime\!20^\alpha 0 \), has a redshift of \( z = 0.318 \pm 0.00033 \) (Couch & Sharples 1987), which is near the peak of the redder component of the distribution. Girardi & Mezzetti (2001) also found that this combined set of galaxies was well-fitted by a bimodal distribution, with velocity dispersions of \( 1121^{+176}_{-158} \) km s\(^{-1}\) and \( 682^{+75}_{-72} \) km s\(^{-1}\), respectively, for the bluer and redder components. These velocity dispersions correspond to \( 8.0^{+2.1}_{-1.7} \) keV and \( 3.0^{+0.9}_{-0.6} \) keV. Girardi & Mezzetti (2001) also fit these redshifts with a single Gaussian with a velocity dispersion that implies a virial temperature of \( \sim 20 \) keV, more than twice the observed temperature through most of the cluster. They also note that the X-ray and lensing masses for the cluster are highly discrepant, which further suggests that the cluster is out of equilibrium and that a single cluster model for the galaxy velocities is therefore inappropriate.

The two populations in redshift space are also somewhat segregated on the sky. Fig. 5 shows the spatial distribution of galaxies from the two populations, using \( z = 0.31 \) as the dividing line. The set of galaxies with measured redshifts is not uniformly sampled in all directions from the cluster centre. In order to have a sample with equal north–south and east–west extent, we took only those galaxies within 2.7 arcmin of the centre of the field used by Couch & Sharples (1987). This eliminated two galaxies with \( z < 0.31 \) and three with \( z > 0.31 \) from our sample. Like the two large ellipticals, the bluer galaxies tend to be segregated to the north, whereas the redder galaxies tend to be segregated to the south. The mean positions of the two populations, plotted as diamonds in Fig. 5, illustrate the spatial segregation. A Kolmogorov–Smirnov test confirms this north–south segregation of the two populations with \( > 90 \) per cent confidence. Thus, although the data are suggestive of a spatial segregation, they are by no means conclusive. We should also note that this sample of galaxies only covers the central 900 kpc, so any cluster galaxies at larger distances could alter the spatial distribution. We suspect that the true centroid of the approaching galaxies, i.e. those with \( z < 0.31 \), would in fact change, given a more complete sample of galaxies from a larger field, because the centroid we measure is so close to the centre of the field and because they fill the field so completely. The receding galaxies, on the other hand, are a smaller population on the whole, so we...
have probably sampled a larger percentage of it within our field of view.

The only two systematic catalogues of redshifts for this cluster have concentrated on the central few arcmin of the cluster and have not included the north-west subcluster. Consequently, it is not possible to determine the line-of-sight velocity of the north-west clump of galaxies relative to the main cluster, or even to confirm based on velocity that they are a distinct population belonging to a separately evolved cluster. A clue to determining their identity comes instead from their near-infrared luminosity functions, which trace the stellar masses of the galaxies. The faint end of the luminosity function of the north-west clump is flatter than that of the main cluster (Andreon 2001). This larger dwarf fraction is consistent with the galaxies having evolved in a less dense environment than that of the main cluster (Oemler 1974; Dressler 1978; Lopez-Cruz et al. 1997). We therefore confirm with some certainty the association of the north-west clump of galaxies with the subcluster detected in X-rays.

5 DISCUSSION

5.1 Dynamical history

The discussion that follows is an attempt to form a consistent picture for the dynamical history of the merger based on a confluence of the X-ray, optical and radio data.

The X-ray brightness and temperature structure of the main cluster are extremely complex, particularly in the central 0.5 Mpc. The ridges in the X-ray brightness emission are largely correlated with features in the temperature structure. The cooler ridges are both oriented north–south, along the same axis as the centroids of the two galaxy populations discussed in Section 4. Both ridges show some curvature, and in opposite directions, consistent with being the wakes of the two subclusters if their interaction has a non-zero impact parameter. Furthermore, these two ridges show secondary surface brightness peaks, each about 0.75 arcmin (250 kpc) from the central peak of the main cluster, and each significantly cooler than the surrounding gas. These secondary brightness peaks with extended ridges of emission trailing away from the cluster centre combined with the cold temperature of this gas relative to the rest of the cluster lead us to interpret the cooler ridges of bright emission to be the wakes of cooler gas from the cores of the respective subclusters, stripped by ram pressure through the earlier stages of the merger. Similarly, we interpret the two brightness peaks to be the cool cores of the respective subclusters. The fact that the cool wakes are visible at all demonstrates that the merger is not occurring entirely along the line of sight, but must have at least a small transverse component.

The hotter ridges are seen in the region where the gas should be the most strongly compressed ahead of the moving cool cores of the two subclusters. The velocity derived from the galaxy redshifts implies a Mach number for the merger of ~2.6, using the temperature of the ambient cluster gas determined at the radius of the subcluster in Section 3.2 (9.3 keV). This Mach number is actually a lower limit because the temperature has probably been boosted by merger shocks by a factor of ~1.5–2 (Ricker & Sarazin 2001) compared to its original value, and because the velocity derived from the galaxy redshifts excludes the transverse component of the velocity. Both of these factors would increase the actual strength of the shocks produced in the merger. In any case, the temperature jump across an $M_\triangleq 2.6$ merger shock would be a factor of 3. A fit to the northern cool core using a two-temperature MEKAL model (Kaastr 1992; Liedahl, Osterheld & Goldstein 1995), with the hotter temperature fixed to that of the surrounding hot gas, finds a temperature of the cool core of $4.6^{+2.0}_{-1.2}$ keV compared with a temperature of the surrounding hot gas of $10.6^{+2.3}_{-1.5}$ keV. This temperature contrast is consistent with the predicted shock heating to within the (sizeable) errors. The two regions of hot gas which are not correlated with surface brightness enhancements (see Section 3.3) could result from shocks that are largely perpendicular to the line of sight, and therefore do not appear as sharp features in the X-ray image.

The cool core to the north of the cluster centre (the south-moving subcluster) is both larger and brighter than the south core. This suggests that it is the more massive of the two. This assertion may be corroborated by the galaxy populations: Girardi & Mezzetti (2001) found that the bluer population of galaxies, which has its centroid near the main X-ray peak, has a higher velocity dispersion than the redder population, which has its centroid further south. The mass ratio derived from the velocity dispersions is ~4:1. Assuming that the gas has not yet decoupled from the dark matter and the galaxies, we would expect the positions of the cool cores and the galaxies to be correlated. This is probably a safe assumption because the merger appears to be at an earlier stage than, say, Abell 3667, in which the gas and dark matter are still coupled (Vikhlinin & Markevitch 2002).

The data are inconclusive here, however. The projected separation of the south cool core from the centroid of the redder galaxies is a mere 60 kpc, but the separation of the centroid of the bluer galaxies from the north cool core is 250 kpc. These centroids are biased, however, by the relatively small area on the sky over which the galaxies have redshifts available in the literature. We therefore conclude that the spatial distributions of the galaxies are a poor test for determining the connection between the X-ray cores and the galaxy populations. The velocity dispersions are a more reliable test, however, and they appear to indicate that the north cool core has a negative line-of-sight velocity relative to the rest frame of the cluster, whereas the south core has a positive line-of-sight velocity in the same frame.

The cool wakes behind the cores, particularly to the north, give more insight into the dynamical history of the merger. The northern wake has significant curvature, indicating that the merger has a non-zero orbital angular momentum. Put another way, this shows that the merger is not head on, but has a non-zero impact parameter. Unfortunately, it is difficult to place even a meaningful lower limit on the value of the impact parameter because the cool wake of the south subcluster is too short to determine the transverse component of its direction of motion, and the direction implied by the wake of the north subcluster brings it into the south subcluster head on.

5.2 Radio halo

The radio halo in Abell 2744 is one of the most luminous and most well-studied (Govoni et al. 2001a,b). The bulk of the diffuse radio emission is centred on the main cluster, with a radius of about 3 arcmin. The cluster also hosts a radio relic at a projected distance of almost 2 Mpc from the cluster centre. We will confine our discussion here to the halo, because the relic is too far from the ACIS focus for our data to contain many source photons from that region.

Fig. 6 shows an image of the radio halo taken with the Very Large Array (VLA) at 20 cm, superimposed on the raw Chandra image. The offset between the peaks of the X-ray and radio images noted in Govoni et al. (2001a) is probably not real, as the peak of the radio emission is resolved into several smaller peaks at slightly higher resolution than that of our Fig. 6 (Govoni et al. 2001b), the brightest of which is coincident with the X-ray brightness peak to within a few arcsec.
The strong correlation between the X-ray and radio surface brightnesses that was found using lower-resolution ROSAT data by Govoni et al. (2001a) is also visible in our higher-resolution data. We note some particularly interesting correlations: all the surface brightness ridges, both the cool ones and the hot ones, are correlated with brightness enhancements in the radio. The north-west subcluster is also correlated quite strongly with the radio halo. Also of note is a strong anticorrelation between the radio brightness ridge to the south of the cluster and the X-ray brightness. This feature in the radio image, however, follows exactly the temperature enhancement in the same region which we discussed above. If the high temperature of this gas is indeed due to a shock in that region, then the enhanced radio brightness there is most likely the result of current acceleration of cosmic ray electrons by the shock. Similarly, the other hot regions, which are more clearly indicative of shocks from their X-ray brightnesses, show enhanced radio emission. Given the large Mach number inferred above for the merger, the merger shocks should be strong enough to accelerate electrons to the energies necessary to produce the observed radio emission (Gabici & Blasi 2003).

The cool wake from the northern (south-moving) subcluster also shows enhanced radio emission. (The south wake shows no enhancement, but the bright radio point source in that part of the image makes it impossible to rule out enhanced diffuse emission.) Again, this probably indicates that cosmic ray electrons are currently being accelerated in these regions. No shocks are likely to exist in the cool stripped gas, so some other mechanism of particle acceleration is needed. Fujita, Takizawa & Sarazin (2003) demonstrated that turbulent resonant acceleration can generate the necessary electrons to produce radio halo emission, as long as a population of trans-relativistic electrons is already present. Such a population is clearly present, as indicated by the presence of large-scale diffuse radio emission. However, the velocity of the merger in Abell 2744 is so large that the time-scale for the persistence of turbulence is small compared with the time required to re-accelerate these electrons if the radio emitting electrons have $\gamma \sim 10^3$--$10^5$. Electrons with $\gamma \gtrsim 10^5$ have radiative lifetimes of $\lesssim 10^9$ yr (Sarazin 1999), whereas the turbulent time-scale is at most $5 \times 10^8$ yr and perhaps even $\lesssim 10^8$ yr according to the simulations of Fujita et al. (2003), assuming the component subcluster masses derived by Girardi & Mezzetti (2001). It is also possible that the enhanced emission in the cool stripped gas is not due to current particle acceleration, but to a weaker magnetic field than is present in the rest of the cluster, thereby reducing the rate of synchrotron losses of the electrons. This could be the result of a stretching of the magnetic field as the gas is stripped from the core of the subcluster. Unfortunately, the actual mechanism for enhancing the radio emission cannot be distinguished using the currently available data. A direct detection of the magnetic field could be made from a spatially resolved detection of inverse Compton emission, which would enable us to determine if the enhancement is due to current particle acceleration or to a locally weaker magnetic field. Either of these mechanisms, however, will have the same observable effect in the radio: the spectral index in the regions of enhanced emission should be flatter than that in the rest of the cluster because the electrons will have suffered fewer synchrotron losses. This should be easily measurable using lower-frequency data with the same spatial resolution as the 20-cm data.

The north-west subcluster shows further evidence for particle acceleration, or, more likely, re-acceleration. As can be seen in Fig. 6, the radio halo emission extends to the north-west to cover the region of the north-west subcluster completely. Two possible scenarios can explain this extension of the radio halo to the north-west.

The first scenario is simple shock acceleration from the observed bow shock ahead of the infalling subcluster. Other infalling subclusters with Mach numbers as small as that observed in Abell 2744 do not show any evidence of diffuse radio emission (e.g. Abell 85, Kemper et al. 2002). Gabici & Blasi (2003) demonstrated that, even in the case of a cluster with a pre-existing population of suprathermal electrons, weak shocks such as the bow shock in question produce an energy spectrum of accelerated electrons that is too steep to explain the observed radio emission. This predicted lack of radio emission is consistent with observations of other infalling subclusters, and thus we find it unlikely that the bow shock in Abell 2744 is responsible for producing the observed radio emission.

The second scenario assumes that a pool of ‘seed’ electrons at mildly relativistic energies exists, which can be accelerated to the necessary energies. A population of suprathermal electrons does indeed exist in much of the cluster, as the existence of the radio halo demonstrates, but its presence at radii beyond the edge of the 20-cm radio emission is less obvious. As has been seen in other clusters with radio haloes, the spectra of the haloes steepen with radius, so the haloes appear much larger at lower frequencies (e.g. Coma, Giovannini et al. 1993; Deiss et al. 1997; for a theoretical explanation, see Brunetti et al. 2001). Therefore it is quite likely that a population of electrons exists at the radius of the infalling subcluster, the energies of which are too low to emit synchrotron radiation at 20 cm. Unfortunately, the lack of data at longer wavelengths for Abell 2744 makes it impossible to verify this assumption at present. As long as Abell 2744 is not unique, it should have the necessary seed electrons at the radius of the subcluster. The model of Fujita

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$^{3}$ This assumes both that variations in the magnetic field strength are resolved and that the relativistic electrons are distributed similarly to the field lines. Coherent structures over tens of kiloparsecs observed in Faraday rotation maps (e.g. Eilek & Owen 2002) give some hope for the former, but the latter remains a tenuous assumption.
et al. (2003), discussed above, is most efficient at re-accelerating electrons in exactly this sort of situation, i.e. a large mass ratio merger at an early stage where the merger velocity is still small. Thus, turbulent re-acceleration of seed electrons could also account for the extent of the halo across the subcluster. In principle, these two scenarios could be distinguished by detailed spectral index maps of the halo in the vicinity of the subcluster. In the first scenario, the halo would show a spectral index gradient from the flattest part near the bow shock, where the electrons are currently being accelerated, to the wake of the subcluster, where the electrons would be passively aging. The second scenario would create a more uniform spectral index, because electrons are being accelerated throughout the wake of the subcluster.

6 SUMMARY

We have presented a new Chandra observation of Abell 2744 which shows that the main cluster is in a highly disturbed state. Temperature and surface brightness variations are observed on all scales along with the cool cores of the constituent subclusters amid strong $(M \gtrsim 2)$ merger shocks. The bimodal distribution of the member galaxies and the morphology of the radio halo provide further evidence that the cluster is undergoing a major merger. We propose a dynamical scenario for the merger which involves a merger of two subclusters, currently near their closest approach to each other, with a mass ratio near unity and a non-zero impact parameter. A significant component of the merger axis is estimated to be along the line of sight.

We have also studied the small merging subcluster to the north-west and estimate an infall velocity of $M \sim 1.2$. We also demonstrate that this subcluster is not responsible for the bulk of the disturbed nature of the ICM of the main cluster. None the less, its effect on the extremely powerful radio halo of the cluster is significant, at least in the immediate vicinity of the subcluster. We conclude that turbulent re-acceleration of electrons in the wake of the subcluster is probably responsible for the extension of the radio halo across the subcluster. Future radio observations of the subcluster at lower frequencies should be able to determine or strongly constrain the formation mechanism of the radio halo.

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