THERMAL AND NONTHERMAL EFFECTS IN MERGING CLUSTERS OF GALAXIES

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Abstract

This thesis presents several studies of merging clusters of galaxies at X-ray and radio wavelengths, and analyzes the observable effects of mergers on the intracluster medium (ICM). It focuses primarily on nonthermal radio halos and relics and on the thermal effects of moving cold cores of gas propagating through the ICM.

We present a systematic search for diffuse radio halos and relics in all of the Abell clusters that are visible in the Westerbork Northern Sky Survey. We found 7 candidates for which we provide the first evidence of diffuse radio emission. We also investigate the correlation between cluster X-ray luminosity and radio power of halos and discuss the implications of this correlation for future surveys.

An analysis of Abell 2199 sets strong upper limits on the radio flux from the cluster. These limits are used to constrain the cluster magnetic field by requiring consistency between the radio flux and the hard X-ray (HXR) flux observed by BeppoSAX, assuming that the HXR excess is inverse Compton scattering of cosmic microwave background photons by relativistic electrons in the ICM. The magnetic field must be very weak in order to avoid producing an observable radio halo. We also consider a nonthermal bremsstrahlung model for the HXR excess.

In X-rays, we present an analysis of a highly asymmetric cluster merger from a Chandra observation of Abell 85. The merger shows significant disruption of the less massive subcluster from ram pressure. A cold core, coincident with the cD galaxy, is observed in the subcluster. We derive dynamical information from the motion of the cold core through the main cluster’s ICM and construct a consistent kinematic model for the merger based on this dynamical analysis.

Also in X-rays, we present an analysis of a Chandra observation of Abell 2034. The cluster has signatures of an ongoing merger, including a cold front and significant
heating of the intracluster medium. We again derive dynamical information from the cold front. Emission to the south of the cluster, previously thought to be a merging subcluster, may be a moderate redshift background cluster seen in projection.
Acknowledgments

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Chapter 1

General Introduction
1.1 Introduction

Clusters of galaxies are the largest organized structures in the Universe. They span a range in total mass up to several times $10^{15} M_\odot$ and several thousand galaxies. Clusters were originally discovered as overdensities of galaxies in optical images. One of the earliest systematic surveys for clusters of galaxies was the Ph.D. thesis of George Abell (Abell 1957, 1958), which catalogued over 2700 clusters in the northern sky using plates from the Palomar Observatory Sky Survey (POSS). The Abell catalog, subsequently updated to include the southern sky (Abell, Corwin, & Olowin 1989), remains the most widely used optically selected catalog of clusters. It is adopted as the source sample for the survey detailed here in chapter 2. In 1966, X-ray emission was first detected from a cluster (Byram, Chubb, & Friedman 1966; Bradt et al. 1967) in an early X-ray observation of M87 in the nearby Virgo cluster. Clusters have subsequently been shown to be highly luminous X-ray sources, with typical luminosities of $10^{43}$ to more than $10^{45}$ ergs s$^{-1}$. This large luminosity comes from hot intracluster gas, which accounts for a large fraction of the visible mass of clusters. In rich clusters, $\gtrsim 20\%$ of the mass is in the form of this hot, X-ray emitting intracluster gas, while a few percent is in galaxies, and the remainder is dark matter. With the majority of the mass, the dark matter dominates the gravitational potentials of clusters.

The most widely accepted model for the formation of clusters of galaxies is the so-called “hierarchical merger” model. This model assumes that clusters initially form out of the gravitational collapse of density fluctuations in the early Universe, which are assumed to be more numerous and of greater density contrast on smaller scales. The structures formed in these small perturbations then merge to form larger objects. This process is repeated over and over, to hierarchically form large clusters. This process
is well described by a formalism first proposed by Press & Schechter (1974). Starting with a density perturbation spectrum, $\sigma(M)$, this formalism allows one to calculate both the number of clusters of a given mass and their merger rate, both as a function of redshift. One possible perturbation spectrum, which matches the observations on scales the size of clusters, is that produced by Cold Dark Matter (CDM) models. (A recent variation on this is the $\Lambda$CDM model, which includes the addition of a Cosmological Constant, $\Lambda$.) CDM models assume that the non-radiative dark matter, which makes up most of the gravitational mass in the Universe, consists of dynamically “cold” material. Since the dark matter is dynamically cold, small-scale perturbations do not diffuse away as they would if the dark matter were “hot,” but instead persist on top of larger scale perturbations. These models also generally assume that the dark matter is completely non-interacting, that is, that it does not interact with either visible matter or with itself other than gravitationally. Measurements of the number density of clusters per unit volume provide one of the best measurements of the normalization of the fluctuation spectrum. The normalization of the spectrum is generally parameterized as $\sigma_8$, which is the rms density fluctuation on a scale of $8\,h^{-1}\,\text{Mpc}$, where the Hubble constant is $H_0 = 100\,h\,\text{km\,s}^{-1}\,\text{Mpc}^{-1}$. For a given present day abundance of clusters, the merger rate depends most strongly on $\Omega_M$, the mean matter density in the Universe in units of the critical density needed to close the Universe. Therefore, a determination of the current rate of cluster mergers can serve as a measurement of the mass density of the Universe.

Major mergers, in which two clusters of galaxies with a total mass of $\sim 10^{15}\,M_0$ collide with a velocity of $\gtrsim 2000\,\text{km/s}$, release a total kinetic energy of $\sim 10^{64}$ ergs and are the most energetic events in the present Universe. A large fraction of the energy in the hot gas that is released in a merger, $\gtrsim 10^{63}$ ergs, goes into hydrodynamic
shocks driven into the hot gas in the cluster, dissipating the kinetic energy of the gas. These merger shocks (sometimes referred to as “accretion” shocks in the context of the accretion of smaller subclusters out of large scale structure) have several major effects, both thermal and nonthermal. The major thermal effect is heating of the intracluster medium (ICM), which contributes to the high temperature of this gas. Major nonthermal effects include the acceleration of charged particles to relativistic energies through first order Fermi acceleration, and the generation of turbulence in the shocks’ wakes. This turbulence may also serve to accelerate charged particles, although the mechanism for turbulent acceleration is less well understood.

Merger shocks should be visible at both X-ray and radio wavelengths. In X-rays, they should be visible as sharp temperature and surface brightness discontinuities, where the gas is both heated and compressed by the shock. Since the X-ray emissivity increases in proportion to the square of the gas density, the compressed gas behind the shock could appear significantly brighter than the unshocked gas even for the relatively low Mach number shocks expected in mergers. Since shocks are relatively thin, nearly two-dimensional surfaces, these jumps will only be easily observable if the shock surface is roughly parallel to the line of sight. In addition to these distinct X-ray signatures, the relativistic charged particles accelerated by a shock will emit radio synchrotron radiation in the presence of the cluster’s magnetic field. Since the synchrotron lifetimes of these particles are much less than the cluster crossing times of the shocks, one would expect to see diffuse synchrotron emission in the vicinity of merger shocks. A number of merging clusters, some of them discussed in this thesis, contain emission consistent with this picture. These sources are known as “radio relics” for the historical reason that when they were first discovered they were assumed to be relic radio emission from extinct radio galaxies.\footnote{This nomenclature has persisted, despite the growing evidence that they are in fact connected...}
The same electrons that produce this synchrotron radiation should also undergo Inverse Compton (IC) scattering off the Cosmic Microwave Background, producing emission at extreme ultraviolet (EUV) through gamma-ray wavelengths. While this IC emission is expected to be much fainter than the thermal emission from the ICM from energies of a fraction of a keV up to \( \sim 10 \) keV, it should contribute significantly to the overall flux at EUV and hard X-ray wavelengths. The contribution of IC to the X-ray emission will be greater if one can resolve the regions where the relativistic particles are generated. Thus, we might be able to observe IC emission with X-ray observatories such as *Chandra* and *XMM-Newton*, which are fairly sensitive above about 4 keV where the contribution from IC could be a significant fraction of the total in localized regions. Satellites with very hard X-ray detectors such as *BeppoSAX*, which is sensitive at energies up to about 100 keV, have an even better chance of detecting IC from radio relics, although their spatial resolution at these energies is still too poor to draw direct connections between X-ray and radio structures. Given the limited collecting area of *Chandra* and *XMM-Newton* at energies above 10 keV, where IC would begin to dominate the overall emission, spatially resolved detection of IC emission may have to wait for future X-ray observatories that combine higher spatial resolution with sensitivity to hard X-rays.

Another phenomenon associated with cluster mergers and observed at radio wavelengths is the set of sources known as “radio halos.” As with radio relics, they are diffuse synchrotron sources, believed to be powered by electrons accelerated during a merger. Halos, however, are much larger, with sizes on the order of a megaparsec. Also, unlike relics, they have not been directly connected observationally with merger shocks. More recently, a hybrid picture of their formation has been proposed wherein the synchrotron emitting electrons originate in a population of suprathermal electrons in the relic lobe of an extinct radio galaxy and are reaccelerated by a merger shock (Brüggen et al. 2002; Enßlin & Brüggen 2002). Despite the awkwardness of the term, I will use it throughout this thesis for the sake of consistency with previously published work on the subject.
shocks. Halos are centrally located in clusters, and their surface brightness tends to be correlated fairly closely with the cluster X-ray emission (Giovannini & Feretti 2000). This correlation, along with their tendency to be found in later stage mergers, suggests that the acceleration mechanism for the relativistic electrons is more distributed than are the merger shocks. For example, the electrons might be accelerated by turbulence generated in mergers. I will discuss a number of radio halo and relic sources in Chapter 2.

In addition to these effects of mergers that are directly or indirectly tied to merger shocks, dynamical features associated with cluster cooling flows have also been observed in merging clusters, using the high angular resolution of the Chandra X-ray Observatory. Cooling flows develop naturally in relaxed clusters when the cooling time of the gas in the cluster core is less than the age of the cluster. Because the cooling rate is proportional to density squared, the gas at the cluster center will cool the fastest, and will then flow inward due to the higher pressure exerted on it by the hotter exterior gas. Prior to the launch of Chandra in December 1999, it was believed that merger shocks might disrupt cooling flows in clusters with all but the steepest gravitational potentials. However, given the low Mach numbers of merger shocks, it was also considered possible that the cores of cooling flows would persist despite the shocks. This latter picture has been confirmed by Chandra observations. The discovery of “cold fronts” formed at the leading edges of these cold cores as they move through ICM (e.g. Markevitch et al. 2000) has been the single most dramatic discovery made by Chandra in the study of merging clusters of galaxies. In Chapters 4 and 5 of this thesis, I will discuss my own observations of cold fronts using data from Chandra.
1.2 Structure of the Thesis

Chapter 2 presents a search for radio halos and relics in all Abell clusters north of $\delta = 30^\circ$, using the Westerbork Northern Sky Survey. Seven new candidate sources were found in addition to blindly “rediscovering” all the known sources that fell into the sample of clusters. I discuss the properties of the individual sources as well as some properties of and correlations among the population as a whole. These include an estimation of selection bias in determining the final sample, and a discussion of a simplified model which attempts unsuccessfully to reproduce the observed population of halos and relics. The consequences of the selected bias for future surveys is also considered. This chapter was previously published as an article in the *Astrophysical Journal*. The full citation for the article is “Radio Halo and Relic Candidates from the Westerbork Northern Sky Survey,” Kempner, J. C., & Sarazin, C. L. 2001, ApJ, 548, 639 (Copyright 2001, American Astronomical Society; reproduced by permission of the AAS).

Chapter 3 presents radio measurements of the cluster of galaxies Abell 2199. It was written in response to a claimed detection of a hard X-ray excess in this cluster (Kaastra, Bleeker, & Mewe 1998; Kaastra et al. 1999). Two possible explanations for this X-ray excess were suggested: Inverse Compton of relativistic electrons off the Cosmic Microwave Background, or nonthermal bremsstrahlung by a population of suprathermal electrons. If the first explanation were correct, the same electrons should produce a radio halo or relic that would be visible in surveys of the sky at radio wavelengths. This hypothesis is tested in this chapter. The measurements of the radio properties of this cluster were done in part as a test of a possible technique to be used in Chapter 2. However, this technique ended up not being useful for application to the large sample of clusters used in the other study. Also presented
in this chapter is an application of the nonthermal bremsstrahlung model developed in Sarazin & Kempner (2000) to the parameters of Abell 2199 in an attempt to reproduce the observed X-ray emission. The consequences of the IC model and the nonthermal bremsstrahlung model for a physical description of the cluster are also discussed. This chapter was previously published as an article in the *Astrophysical Journal*. The full citation for the article is “Limits On the Diffuse Radio and Hard X-ray Emission of Abell 2199,” Kempner, J. C., & Sarazin, C. L. 2000, ApJ, 530, 282 (Copyright 2000, American Astronomical Society; reproduced by permission of the AAS).

Chapters 4 and 5 present analyses of *Chandra* observations of two merging clusters, Abell 85 and Abell 2034, respectively. Chapter 5 covers many details of the cluster Abell 2034, including its global properties and a hydrodynamical analysis of the merger using information from an observed cold front. In contrast, Chapter 4 focuses narrowly on a single merging subcluster in Abell 85. I present in this latter chapter a detailed analysis of the hydrodynamics of the interaction and construct a model for the merger in full spatial and velocity dimensions. I also discuss possible explanations for the observed suppression of hydrodynamic instability in the subcluster and of conduction across the observed cold front. Lastly, I briefly explore the interaction of the merger with a radio source which appears to be connected with the subcluster.

Chapter 4 has been submitted to the *Astrophysical Journal* for publication with the title “Chandra Observations of Abell 85: Merger of the South Subcluster.” The paper is co-authored by J. C. Kempner, C. L. Sarazin, & P. M. Ricker.

Lastly, Chapter 6 discusses some general conclusions and directions for future study.
Chapter 2

Radio Halo and Relic Candidates from the Westerbork Northern Sky Survey
Abstract

We have undertaken a systematic search for diffuse radio halos and relics in all of the Abell clusters that are visible in the Westerbork Northern Sky Survey (WENSS). In this survey we found 18 candidates, 11 of which are already known from the literature, and 7 for which we provide the first evidence of diffuse radio emission. All the clusters in this sample show other evidence for a recent or ongoing merger. We also investigate the correlation between cluster X-ray luminosity and radio power of halos. We develop a very simple model for merger shocks that reproduces the sense of this correlation, although it is probably not as steep as the correlation in the data. We discuss the implications of X-ray–radio correlations for future detections of radio halos.
2.1 Introduction

A number of clusters of galaxies are known to contain large-scale diffuse radio sources which have no obvious connection to the clusters' population of galaxies. These sources are referred to as radio halos when they appear projected on the center of the cluster, and are called relics when they are found on the cluster periphery. Because of projection effects, the distinction between halos and relics is physically debatable, but does provide a convenient classification for their discussion. It is also possible that halos and relics in fact have different physical origins, as we discuss below. Halos (and relics; we will use "halos" hereafter for brevity) are believed to be produced by synchrotron emission from a population of relativistic electrons which have been accelerated or reaccelerated, possibly by shocks in the intracluster medium (e.g., Jaffe 1977; Roland 1981; Schlickeiser, Sievers, & Thiemann 1987). These shocks may be the product of cluster mergers. In fact, all known halos are found in clusters which show other signs of being in some stage of a merger (e.g., Feretti 1999; Schuecker & Böhringer 1999). In the early stages of mergers, halos are often found on the border between the subclusters, where the cluster gas is first being shocked (e.g., Abell 85; Slee & Reynolds 1984). In more advanced mergers, more conventional centrally located halos (e.g., Coma) and peripheral relics (e.g., Abell 3667) are found.

The most common explanation of the physical origin of halos and relics is that they originate from particle acceleration in merger shocks, but other theories have been suggested. Enßlin et al. (1998) suggest that relics may trace shocks created in the initial structure formation of the Universe. Liang et al. (2000) posit that turbulent reacceleration may maintain the population of cosmic rays necessary to produce a halo after they have been accelerated initially by merger shocks. There is also disagreement over whether the cosmic ray electrons are accelerated directly
from the thermal population or are re-accelerated cosmic rays previously produced in
starbursts and AGN. Alternately, the secondary electron model (Dennison 1980; Blasi
& Colafrancesco 1999 and references therein) proposes that the necessary electrons
are created as a result of interactions between cosmic ray protons and the intracluster
gas. The secondary electron model is unique in that it does not require a merger to
create a radio halo.

Halos and relics are rare phenomena, with only about 10–20 having been known
until quite recently. With the completion of the NRAO VLA Sky Survey (NVSS:
Condon et al. 1998) and Westerbork Northern Sky Survey (WENSS: Rengelink et al.
1997), systematic searches for additional sources have been possible, yielding about 25
new halos and relics. Evidence on the exact origin of halos and relics is still unclear,
mostly because of their small numbers. With a larger sample, however we can begin
to determine if the merger shock picture of their formation is correct, and perhaps
even disentangle the different mechanisms for halo and relic formation, if they are in
fact different phenomena.

We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout this paper.

\section*{2.2 Sample and Source Selection}

We conducted our search for new halos and relics using the publicly available images
of the WENSS. The survey has an angular resolution of $54'' \times 54'' \csc \delta$ at declination
$\delta$, a typical noise level of 3.6 mJy beam$^{-1}$, and covers the sky north of $\delta = 30^\circ$.

Our search was strictly limited to galaxy clusters in the ACO catalog (Abell 1958;
Abell et al. 1989) that fall within the region covered by the WENSS. This gave us a
sample of 1001 clusters up to a redshift of $\sim 0.3$. With the good $(u,v)$ coverage of
the survey, the images were sensitive to extended structures of up to $1^\circ$ in diameter.
We were therefore able to detect cluster-wide halos with a typical size of 1 Mpc at redshifts $z \gtrsim 0.01$, which covers the entire Abell catalog. Sources 1 Mpc in size do not become unresolved by the WENSS beam until a redshift much greater than the limit of the Abell catalog.

We searched for diffuse sources using images from the WENSS on their own as well as using these images overlaid on images from the Digital Sky Survey (DSS). Our criteria for a positive detection were that the sources had to $a)$ have regions of surface brightness greater than the 2σ level, $b)$ be resolved, $c)$ not be associated with an optically identified galaxy, $d)$ not be clearly associated with a known extended radio galaxy, and $e)$ not be an obvious blend of unresolved sources. We used images from the NVSS, and from the FIRST survey where available (Becker et al. 1995) to check for the existence of point sources. In clusters within about 1° of a very bright (peak-flux-to-rms $\gtrsim 800$) source, uncleaned sidelobe structure had the potential for causing confusion, but the large sizes of the WENSS images enabled us to identify these cases and avoid confusion. We further compared the WENSS images to images from the ROSAT All-Sky Survey (RASS: Voges 1992; Trümper 1993) for information about the X-ray morphology of the clusters.

For sources which are resolved but smaller than about 1°, the WENSS is surface brightness limited. Figure 2.1 shows the mean surface brightnesses of the sources in our sample as a function of redshift. The dashed line is the nominal 1σ surface brightness limit of WENSS (3.6 mJy beam$^{-1}$). The mean surface brightness was determined for each source by spreading its integrated flux evenly over a convex region which just encloses the 2σ surface brightness contours for that source. In reality, however, few of the sources fill this region completely, and most of them have splotchy surface brightness distributions with peaks which are much higher than this
Fig. 2.1.— Mean surfaces brightnesses and redshifts are shown for the detected sources, with halos indicated by squares and relics by triangles. The mean surface brightness assumes that the flux is distributed over a convex region which just encloses the 2σ surface brightness contours. The nominal 1σ surface brightness limit of the WENSS (3.6 mJy beam$^{-1}$) is indicated by the dashed line.

average value. This is the reason that our survey limit on the mean surface brightness appears to be slightly below the WENSS noise limit. Note that our cluster survey would not be sensitive to sources which are very close or very large ($\gtrsim$1°) or sources which are very small or very distant, which would be unresolved ($\lesssim$1').
2.3 Halo and Cluster Candidates

Using the criteria detailed above, we found a sample of 16 clusters containing candidate halos or relics. Of this sample, 7 were not known prior to this study, while 9 had previously been discovered. Of the previously known halos and relics which fell into our sample, all but one (Abell 2218, see §2.4) were detected in this study. Abell 2218 is included in our analysis for completeness. The halo in Abell 2218 was not detected because it was nearly unresolved in WENSS. Five of the seven new detections are associated with clusters which are not part of the Ebeling et al. (1996) catalog of X-ray bright clusters, and therefore were not in the NVSS sample (Giovannini, Tordi, & Feretti 1999) that comprises about half of the previously known halos and relics in our sample.

Table 2.1 lists the candidate clusters. For each cluster, we list the name, redshift $z$, position, X-ray luminosity in the 0.1–2.4 keV rest frame energy range, Rood-Sastry (1971) class, Bautz-Morgan (1970) class, radio morphology, and whether the cluster halo/relic had been detected previously. Data in columns 2, 3, and 4 are taken from Ebeling et al. (1996) except where noted. The X-ray luminosities in column 5 came from the literature (sources noted), except for A 796, where the luminosity was determined from the RASS flux. Column 8 gives the morphology of the radio source: “H” for a halo, “R” for a relic, and “u” for uncertain. According to convention, we classified diffuse sources as halos if they were centered on the cluster and as relics if they appeared on the cluster periphery. Sources whose status as a halo or relic are uncertain were labeled as such. These include faint sources, sources which may be a blend of unresolved sources, and sources which have tentative but not obvious associations with optical sources. Uncertain sources comprise about half of our sample of new detections.
Table 2.1. Properties of Clusters Containing Halo and/or Relic Candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>z</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>$L_X$ (0.1−2.4 keV) ($\times 10^{44}$ erg s$^{-1}$)</th>
<th>RS$^a$</th>
<th>BM$^b$</th>
<th>Morphology$^c$</th>
<th>Previously Detected?</th>
</tr>
</thead>
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<tr>
<td>A 665</td>
<td>0.1818</td>
<td>08 30 47.4</td>
<td>+65 51 14</td>
<td>14.78$^d$</td>
<td>I c</td>
<td>III:</td>
<td>H</td>
<td>y</td>
</tr>
<tr>
<td>A 667</td>
<td>0.282$^e$</td>
<td>08 42 57.6</td>
<td>+36 21 59</td>
<td>16.30$^f$</td>
<td>F</td>
<td>II-III</td>
<td>u</td>
<td>n</td>
</tr>
<tr>
<td>A 725</td>
<td>0.0921$^e$</td>
<td>09 01 10.1</td>
<td>+62 37 20</td>
<td>0.80$^h$</td>
<td>I c</td>
<td>...</td>
<td>R</td>
<td>n</td>
</tr>
<tr>
<td>A 773</td>
<td>0.2170</td>
<td>09 17 54.0</td>
<td>+51 42 38</td>
<td>12.35$^d$</td>
<td>B</td>
<td>II-III</td>
<td>H</td>
<td>y</td>
</tr>
<tr>
<td>A 786</td>
<td>0.1241$^i$</td>
<td>09 28 49.7</td>
<td>+74 47 55</td>
<td>1.53$^i$</td>
<td>F</td>
<td>...</td>
<td>R</td>
<td>y</td>
</tr>
<tr>
<td>A 796</td>
<td>0.1475$^i$</td>
<td>09 28 00.0</td>
<td>+60 23 00</td>
<td>1.38$^i$</td>
<td>C</td>
<td>III</td>
<td>u</td>
<td>n</td>
</tr>
<tr>
<td>A 1240</td>
<td>0.1506$^i$</td>
<td>11 23 37.6</td>
<td>+43 05 52$^k$</td>
<td>1.36$^i$</td>
<td>C</td>
<td>III</td>
<td>R+R</td>
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<tr>
<td>A 1452</td>
<td>0.0630$^i$</td>
<td>12 03 38.8</td>
<td>+51 44 18</td>
<td>...$^i$</td>
<td>C</td>
<td>...</td>
<td>u</td>
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<td>F</td>
<td>...</td>
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<td>0.1712</td>
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<td>L</td>
<td>II</td>
<td>H</td>
<td>y</td>
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<td>+33 29 12</td>
<td>6.86$^i$</td>
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<td>II-III</td>
<td>R</td>
<td>n</td>
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<td>A 2061</td>
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<td>3.92$^i$</td>
<td>L</td>
<td>III</td>
<td>R</td>
<td>n</td>
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<td>A 2218</td>
<td>0.1710</td>
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<td>+66 12 59</td>
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<td>C</td>
<td>II</td>
<td>H</td>
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<td>F</td>
<td>III</td>
<td>u</td>
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<td>A 2255</td>
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<td>II-III</td>
<td>H</td>
<td>y</td>
</tr>
<tr>
<td>A 2256</td>
<td>0.0581</td>
<td>17 04 02.4</td>
<td>+78 37 55</td>
<td>6.99$^d$</td>
<td>B</td>
<td>II-III</td>
<td>H+R</td>
<td>y</td>
</tr>
<tr>
<td>A 2319</td>
<td>0.0555</td>
<td>19 21 05.8</td>
<td>+43 57 50</td>
<td>12.99$^d$</td>
<td>cD</td>
<td>II-III</td>
<td>H</td>
<td>y</td>
</tr>
</tbody>
</table>

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$RS types are as follows: cD = single cD galaxy; B = “binary,” two dominant galaxies; F = “flat,” no dominant galaxy; C = “clumpy” spatial distribution of galaxies; L = “linear” distribution of galaxies; I = “irregular” galaxy distribution.

$^b$Bautz-Morgan types are as follows: type II clusters have no cD galaxy but have one or more Virgo-type giant ellipticals; type III clusters have no dominant galaxies; type II-III are intermediate; a colon after the type indicates an uncertain type estimate.

$^c$Radio morphology notation: H = halo; R = relic; u = uncertain.

$^d$Feretti 2000

$^e$Crawford et al. 1995

$^f$Ebeling et al. 1998

$^g$Owen, Ledlow, & Keel 1995

$^h$Böhringer et al. 2000

$^i$Struble & Rood 1987

$^j$Redshift estimated using the method described by Ebeling et al. 1996; these clusters' positions are taken from Abell 1958 except where another reference is indicated.

$^k$David, Forman, & Jones 1999

$^l$Ebeling et al. 1996
### Table 2.2. Properties of Halo and Relic Candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>$S_{907}$ (mJy)</th>
<th>$S_{1400}$ (mJy)</th>
<th>$\alpha$</th>
<th>$P_c$ (10$^{24}$ W Hz$^{-1}$)</th>
<th>RA (J2000)</th>
<th>Dec. (arcmin)</th>
<th>$L_{AS}$ (kpc)</th>
<th>$L_{LS}$ (kpc)</th>
<th>Distance (Mpc)</th>
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<tbody>
<tr>
<td>A 665</td>
<td>108 ± 17</td>
<td>16 ± 2</td>
<td>-1.30 ± 0.25</td>
<td>17.61 ± 0.10</td>
<td>08 30 58</td>
<td>+65 50</td>
<td>8.0</td>
<td>1900</td>
<td>...</td>
</tr>
<tr>
<td>A 697</td>
<td>29 ± 6</td>
<td>7 ± 2</td>
<td>-0.97 ± 0.28</td>
<td>11.16 ± 0.18</td>
<td>08 42 56</td>
<td>+36 22</td>
<td>2.9</td>
<td>920</td>
<td>...</td>
</tr>
<tr>
<td>A 725</td>
<td>76 ± 9</td>
<td>6 ± 1</td>
<td>-1.73 ± 0.35</td>
<td>3.10 ± 0.18</td>
<td>09 01 29</td>
<td>+62 38</td>
<td>3.2</td>
<td>440</td>
<td>0.31</td>
</tr>
<tr>
<td>A 773</td>
<td>35 ± 7</td>
<td>8 ± 1</td>
<td>-1.02 ± 0.26</td>
<td>7.85 ± 0.11</td>
<td>09 18 04</td>
<td>+51 42</td>
<td>5.3</td>
<td>1400</td>
<td>...</td>
</tr>
<tr>
<td>A 786</td>
<td>319 ± 22</td>
<td>104 ± 3</td>
<td>-0.77 ± 0.06</td>
<td>21.85 ± 0.04</td>
<td>09 22 16</td>
<td>+75 00</td>
<td>8.2</td>
<td>1400</td>
<td>5.0</td>
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<tr>
<td>A 796</td>
<td>53 ± 15</td>
<td>8 ± 3</td>
<td>-1.34 ± 0.60</td>
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<td>+60 23</td>
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<tr>
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<td>8 ± 1</td>
<td>-0.96 ± 0.26</td>
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<td>11 23 28</td>
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<td>4.0</td>
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<td>A 1240S</td>
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<td>-1.11 ± 0.27</td>
<td>6.22 ± 0.13</td>
<td>11 23 47</td>
<td>+43 01</td>
<td>4.6</td>
<td>960</td>
<td>1.5</td>
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<tr>
<td>A 1452</td>
<td>54 ± 15</td>
<td>14 ± 3</td>
<td>-0.92 ± 0.32</td>
<td>0.96 ± 0.17</td>
<td>12 03 18</td>
<td>+51 45</td>
<td>7.9</td>
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<tr>
<td>A 1758</td>
<td>55 ± 11</td>
<td>11 ± 2</td>
<td>-1.13 ± 0.31</td>
<td>21.52 ± 0.14</td>
<td>13 32 44</td>
<td>+50 32</td>
<td>4.3</td>
<td>1300</td>
<td>...</td>
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<tr>
<td>A 1914a</td>
<td>114 ± 29</td>
<td>20 ± 3</td>
<td>-1.19 ± 0.34</td>
<td>16.07 ± 0.13</td>
<td>14 25 58</td>
<td>+37 48</td>
<td>6.8</td>
<td>1500</td>
<td>...</td>
</tr>
<tr>
<td>A 2034</td>
<td>44 ± 9</td>
<td>8 ± 2</td>
<td>-1.17 ± 0.36</td>
<td>2.60 ± 0.19</td>
<td>15 10 17</td>
<td>+33 31</td>
<td>5.7</td>
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<td>0.35</td>
</tr>
<tr>
<td>A 2061</td>
<td>104 ± 15</td>
<td>19 ± 3</td>
<td>-1.17 ± 0.23</td>
<td>2.85 ± 0.12</td>
<td>15 20 06</td>
<td>+30 29</td>
<td>7.7</td>
<td>920</td>
<td>2.1</td>
</tr>
<tr>
<td>A 2218</td>
<td>9 ± 4</td>
<td>1 ± 0.6</td>
<td>-1.46 ± 1.04</td>
<td>1.33 ± 0.53</td>
<td>16 35 46</td>
<td>+66 12</td>
<td>1.5</td>
<td>340</td>
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</tr>
<tr>
<td>A 2219</td>
<td>19 ± 6</td>
<td>2 ± 1</td>
<td>-1.44 ± 0.82</td>
<td>5.27 ± 0.44</td>
<td>16 40 11</td>
<td>+46 44</td>
<td>2.9</td>
<td>810</td>
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</tr>
<tr>
<td>A 2255a</td>
<td>360 ± 44</td>
<td>18 ± 5</td>
<td>-2.06 ± 0.57</td>
<td>11.47 ± 0.37</td>
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<td>7.6</td>
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</tr>
<tr>
<td>A 2256R</td>
<td>1105 ± 107</td>
<td>190 ± 19</td>
<td>-1.25 ± 0.17</td>
<td>17.69 ± 0.08</td>
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<td>15.8</td>
<td>1450</td>
<td>0.66</td>
</tr>
<tr>
<td>A 2256H</td>
<td>126 ± 32</td>
<td>32 ± 6</td>
<td>-1.28 ± 0.35</td>
<td>2.83 ± 0.16</td>
<td>19 21 11</td>
<td>+43 56</td>
<td>6.6</td>
<td>580</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

*a*Discrete sources superposed on diffuse emission have been masked out as described in the text.

*b*Power calculated by assuming the spectral index of −1.9 given by Costain et al. 1972 with an associated error of ±0.3.
In Table 2.2, we list the properties of the halo and relic candidates themselves. Clusters with multiple sources have one entry for each source. Columns 2 and 3 list the WENSS and NVSS fluxes, respectively, as determined by the WENSS 2σ surface brightness contours. In clusters where point sources were superposed on the likely extent of the diffuse emission, we could not satisfactorily subtract off those sources due to substructure in the beam. Instead, we masked out the sources and added a systematic error to our measurement which assumes that the surface brightness in the masked regions is equal to the average in the unmasked area. This may in some cases underestimate the actual error if sidelobes from these sources are present in the unmasked area, or if the surface brightness in the masked region differs significantly from the mean. Col. 4 gives the spectral index α derived from these fluxes. Here, the radio power $P_\nu$ varies with frequency as $P_\nu \propto \nu^\alpha$. Col. 5 lists the monochromatic radio power of the source at 327 MHz in the cluster rest frame. The derived spectral index is used to correct for the redshift, assuming that the same spectral index holds for lower observed frequencies. The position in columns 6 and 7 is the estimated center of the diffuse source. Columns 8 and 9 list the largest angular size $LAS$ of the source and the corresponding largest linear size $LLS$ at the redshift of the cluster, both evaluated at 327 MHz. Column 10 gives the projected distance of the source from the cluster center (see Table 2.1) for relic sources only.

In the cases of many of the well studied and more diffuse sources, they are more extended than we observe them to be in either the WENSS or the NVSS. These sources contain very low surface brightness emission around their edges, and what we see are only the brighter cores. Therefore both our size measurements and our flux measurements are known to be underestimated in some cases and may be in others as well.
Fig. 2.2.— For each cluster in Table 2.1, contours from the WENSS and NVSS radio images are given, superposed on the DSS optical images. The radio contours shown are 2, 3.5, 5, 7, 10, 15, 30, 50, 100, 200, 500, & 1000 times the local rms. The 3.5σ negative contour is also shown. Typical rms levels are 3.6 mJy beam⁻¹. Most of the images are approximately 12′×12′; all include the cluster center.
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
Figure 2.2 Continued
WENSS and NVSS radio contours of the clusters in Table 2.1 are shown in Figure 2.2, superposed on DSS optical images. The images are of variable size, although most are approximately $12'\times12'$. All include the cluster center listed in Table 2.1 and extend to include the radio emission of interest.

2.4 Notes on Individual Sources

A 665. The halo is detected at better than the 6σ level in the WENSS, only slightly less significantly than in the NVSS. The spectral index we find is consistent with the lower limit of $\alpha < -0.6$ found by Moffet & Birkinshaw (1989).

A 697. The diffuse emission is located in the cluster center and extends to the NW. The peak of the emission is roughly coincident with the X-ray centroid of the cluster. The absence of point sources in this region in the FIRST survey and the lack of bright ellipticals in the DSS suggest that the diffuse emission is in fact real, despite its low flux. Because of the large uncertainties in its flux, however, we will consider it to be uncertain until deeper, more detailed observations can be made.

A 725. The brightest radio source in the cluster is associated with the bright elliptical at the cluster center. The relic is seen as an arc of diffuse emission to the NE of this source. The X-ray gas as seen in the RASS is slightly elongated along the axis connecting the relic and the cluster center. It has one of the steepest spectra of any source in our sample.

A 773. The diffuse emission is quite splotchy and irregular in the WENSS image but is detected at the 5σ level. Its existence had been previously known from the NVSS (Giovannini et al. 1999).

A 786. This relic (upper right corner in Figure 2.2) is at an unusually large projected distance ($\sim 5$ Mpc) from the center of the cluster. Its association with the
cluster is based on the relic being coincident in projection with two galaxies of similar redshift to that of the cluster. The cluster is a member of Rood Group #27 (Rood 1976), although the other Abell clusters in the group lie to the southwest of A 786. Based on the presence of the galaxies at the position of the relic, the supercluster also is likely to extend to the northwest.

The cluster’s X-ray morphology indicates that it is a double cluster, with the position given in Table 2.1 lying between the two X-ray clusters.

The spectral index we measure is consistent with the value determined by Harris et al. (1993).

A 796. The centrally located diffuse emission in this cluster is quite large and has very low surface brightness. Deeper imaging will be needed to confirm the presence of a halo in this cluster.

A 1240. Two roughly symmetric relics are found in this cluster. They are indicated in Table 2.2 by their positions relative to the cluster center, north or south. They appear to either side of the cluster center at projected distances of ~1.3 and ~1.5 Mpc. To compare the radio morphology with that of the X-ray emitting intra-cluster gas, we extracted a pointed ROSAT PSPC observation from the archive. This 11.9 ksec exposure (RP900383) was aimed at another target, and A 1240 is located about 27' from the center of the field. As a result of the poorer angular resolution and supporting rib structure at this location in the detector, the image is of lower quality than if the field had been centered on A 1240. The X-ray image was corrected for particle background and exposure using the HEASARC ftools software package. The resulting X-ray image in the R4R7 (roughly, 0.5-2.0 keV) band was adaptively smoothed with a minimum signal-to-noise ratio of 3 per smoothing beam.

The smoothed image is shown in Figure 2.3, superposed with the WENSS con-
Fig. 2.3.— Adaptively smoothed ROSAT PSPC image of Abell 1240 (greyscale) with superposed WENSS image contours. The greyscale is a square root scaling and ranges from 0 to $2 \times 10^{-4}$ counts sec$^{-1}$ pixel$^{-1}$; the pixels are $15'' \times 15''$. The radio image is shown in 2- and 3.5-σ surface brightness contours.
tours. The ROSAT observation of the cluster show a double X-ray morphology consistent with a slightly asymmetric merger. Both of the radio relics are located on the edge of the cluster X-ray gas; both have similar luminosities and spectra. The axis of symmetry of the relics is roughly aligned with the apparent axis of the merger. Hydrodynamic simulations of off-center mergers (Ricker & Sarazin 2001) show a similar slight misalignment of the axis connecting the merger shocks with that of the cluster centers. Although projection effects introduce some uncertainty, the location of the relics is consistent with the expected location of merger shocks. This cluster joins Abell 3667 and Abell 2345 in a growing class of clusters with symmetric double radio relics.

A 1452. This possible halo is quite large, but not very powerful. It has relatively low surface brightness and is fairly splotchy. Deeper imaging is needed to confirm the presence of diffuse emission in this cluster.

A 1758a. The brightest source is identified with a Narrow Angle Tail galaxy (Odea & Owen 1985) with the tail pointing to the SE. The bulk of the remaining emission is resolved into two sources in the FIRST image, but the faint emission to the south of these and between these and the tailed galaxy may be diffuse emission unrelated to the point sources, or it may be a blend of fainter point sources. The presence of diffuse emission is therefore considered uncertain.

A 1914. A very steep spectrum source has been known to exist in this cluster for quite some time (e.g., Kulkarni et al. 1990). The center of this cluster contains a number of point sources visible in the FIRST images, at least two of which overlap the radio halo. Accurately masking the point sources in the WENSS image was difficult due to their small separation, so the actual error in our measurement may be slightly greater than that quoted in Table 2.2.
A 2034. The extended emission is located north of the cluster center. It is coincident with a discontinuity in the X-ray surface brightness which may indicate the presence of a merger shock. Forthcoming observations of the cluster with XMM-Newton and Chandra will be able to confirm the existence of a merger shock at this location.

A 2061. The diffuse emission in this cluster is visible as two closely separated sources $\sim 18'$ SW of the cluster center. The two regions are most likely part of a single radio relic. The FIRST survey shows two point sources: one just south of the relic, the other just north. This second source is too faint to be clearly visible in the WENSS, but is obvious in the NVSS.

As the cluster’s RS type indicates, it is quite elongated, with the position angle of the galaxy distribution extending in the direction of the relic. The X-ray gas also has a bimodal distribution (Crawford et al. 1999). The RASS image shows that this extension has the same orientation as that of the optical galaxy distribution.

A 2218. This fairly small halo was first detected by Moffet & Birkinshaw (1989). It is nearly unresolved in WENSS and is quite faint, causing it to be missed by our survey, but we include it here for the sake of completeness. This was the only halo or relic found in the literature which was part of our initial sample but which we failed to detect in the WENSS.

A 2219. This possible halo was first discovered in the NVSS (Giovannini et al. 1999) but was considered uncertain. The WENSS data improve the situation somewhat, as the halo candidate appears at slightly better than the 3$\sigma$ level as an arc of emission to the west and NW of the cluster. The emission to the SW that is visible in the NVSS appears to be a blend of point sources which are resolved by the FIRST survey, but these sources cannot explain the diffuse emission to the NW. Since
the halo candidate was still not detected with a high signal-to-noise, we continue to consider this candidate as uncertain.

A 2255. The spectral index we measure is consistent with the integrated $\alpha \sim -1.7$ derived by Feretti et al. (1997a). The somewhat steeper value we find is probably caused by including the “hole” region in which there is no significant emission at 20 cm. This cluster also contains a relic (e.g., Burns et al. 1995) which is not visible in either the WENSS or NVSS images at a level which is considered significant.

A 2256. This cluster contains perhaps the most spectacular diffuse radio source in our sample. It contains a large radio relic to the west of the cluster. We find a steeper spectral index for the relic than that reported by Rottgering et al. (1994), although the increased sampling of short $(u, v)$ spacings in the WENSS as compared to their observations at 90 cm with the VLA B-array probably accounts for the discrepancy.

We also observe a central radio halo which was detected by Bridle & Fomalont (1976) at 610 MHz, and which is easily visible in the WENSS. Because of its very low surface brightness (it is rarely brighter than 2 mJy beam$^{-1}$ in the WENSS image) and its ultra-steep spectrum, this halo has largely been ignored by subsequent studies of A 2256, which have instead focused on the relic and the numerous head-tail galaxies in the cluster. Costain, Bridle, & Feldman (1972) found the spectral index of A 2256 between 22.25 and 81.5 MHz to be $-1.9$, suggesting the presence of a centrally located ultra-steep spectrum source. Their data also suggest that this source is of comparable size to, or slightly bigger than the observed extent of the halo at 327 MHz. Based on this steep spectral index and the halo’s flux at 610 MHz (Bridle & Fomalont 1976), we would expect a flux more than 2.5 times what we observe at 327 MHz. However, since the halo is quite faint and is perhaps slightly larger than is evident from the WENSS image, our measurement should be taken as a lower limit to the actual flux
of the halo. The flux of the halo at 1400 MHz is expected to be below the sensitivity of the NVSS, and indeed it is not seen there at all.

The halo and relic measurements are listed separately in Table 2.2 and are named accordingly.

A 2319. This halo was studied extensively by Feretti et al. (1997b). It is much more extended than it appears in either the WENSS or NVSS, so much of the total flux in the halo is missing in our measurements from both surveys.

### 2.5 The Radio–X-ray Correlation

#### 2.5.1 Correlations for Clusters with Radio Detections

We now consider the correlation between the radio power of a cluster halo or relic and the cluster’s other properties. We begin by limiting our statistical analyses to the radio measurements done in this study, because of the difficulty of developing a consistent sample of low-frequency radio data on radio halos and relics based on previous observations. Most previous large surveys of these objects have been done at 20 cm. We then discuss correlations at higher frequencies and attempt to apply them to our 327 MHz data.

We find no significant correlation between the radio power of the source and the RS type or the Abell Richness class of the cluster. The distribution of halo/relic candidates in redshift space is uniform, but given the small number of clusters in which we detect diffuse radio emission, this result is probably not meaningful.

We do not find a correlation between radio power and X-ray luminosity when halos and relics are considered together (Figure 2.4). When considered separately, we find a correlation coefficient of $r = 0.56$ for halos, consistent with no correlation. This
may, however, be a result of missing flux from having few short baselines, as more complete data at 1.4 GHz (Feretti 2000; Liang et al. 2000) do show a correlation. Relics show no sign of a correlation either, although the X-ray data for these clusters is quite poor. It should be noted that the clusters in which we find the first evidence of diffuse radio emission all display relatively faint halos or relics and generally have X-ray luminosities which are comparable to or slightly fainter than those of clusters already known to have halos or relics. With better radio data for these sources, they may extend the correlation found at 1.4 GHz.

2.5.2 A Simple Merger Model for the Radio–X-ray Correlation

We now consider a very simple analytic model for the radio luminosity as a function of X-ray luminosity, on the assumption that the radio emitting electrons are accelerated in cluster mergers. In general, a cluster of mass \( M \) may undergo mergers with clusters or groups having any mass \( M' \leq M \). (We take the mass \( M \) to apply to the larger subcluster in the merger.) However, mergers with much smaller subclusters are unlikely to produce very strong shocks with large energy fluxes. Thus, we consider only major mergers with \( M' \approx M \), and for simplicity we assume that the mergers are symmetric (\( M' = M \)). Mergers occur with a distribution of impact parameters \( b \), which can affect the strength of the shocks produced (e.g., Ricker & Sarazin 2001). To simplify the model, we assume that the mergers occur with \( b = 0 \) (zero impact parameter, or a head-on merger). A distribution of values of \( M' \) and \( b \) should introduce dispersion into the correlation between X-ray and radio luminosities, but should not affect the correlation itself. Let us characterize each of the subclusters by the mass \( M \), characteristic radius \( R \), and velocity dispersion \( \sigma \).
Fig. 2.4.— Monochromatic radio power at 327 MHz in the cluster rest frame plotted against X-ray luminosity in the 0.1–2.4 keV rest frame band. The solid line is the best fit to the halo data, using a fixed logarithmic slope of 2.15 derived from the 20 cm data in Feretti (2000).
To begin with, we assume that the radio emitting electrons have short lifetimes and are accelerated by cluster merger shocks. Radio observations of Galactic supernova remnants indicate that shocks at velocities similar to those in cluster mergers convert \( \sim 3\% \) of the shock energy flux into accelerating relativistic electrons (e.g., Blandford & Eichler 1987). Thus, we will assume that the rate at which energy is deposited by accelerating cosmic ray electrons \( \dot{E}_{CR} \) is

\[
\dot{E}_{CR} = f_{CR} \dot{E}_{\text{shock}},
\]

where \( \dot{E}_{\text{shock}} \) is the rate at which energy is being deposited in merger shocks, and \( f_{CR} \approx 0.03 \) is the fraction of the shock energy that goes into accelerating cosmic rays, and is assumed to be constant. Assume the two subclusters approach with a velocity \( v \). Then, the rate of energy deposition by shocks is approximately

\[
\dot{E}_{\text{shock}} \approx \frac{1}{2} \rho_{\text{gas}} v^3 A,
\]

where \( \rho_{\text{gas}} \) is the pre-shock density of the thermal gas in the intracluster medium (ICM), and \( A \sim \pi R^2 \) is the cross-sectional area of the merger shocks. The merger velocity of subclusters is determined by their infall velocity from the turnaround radius in the Hubble flow, and is close to the escape velocity. Thus, \( v^2 \sim GM/R \).

The average density of the thermal gas is

\[
\rho_{\text{gas}} = \frac{M_{\text{gas}}}{4\pi R^3/3},
\]

where \( M_{\text{gas}} \) is the total gas mass in the cluster. We write the gas mass as

\[
M_{\text{gas}} = f_{\text{gas}} M,
\]
where $f_{\text{gas}}$ is the cluster gas fraction. The X-ray observations of rich clusters indicate that $f_{\text{gas}} \approx 0.2 \approx \text{constant}$ (e.g., Arnaud & Evrard 1999).

We will assume that the magnetic field strength $B$ in the cluster radio source is $\lesssim 3 \mu$G, so that the main loss process for the radio emitting electrons is inverse Compton (IC) scattering of cosmic microwave background photons. Then the lifetime of an electron with an energy of $\gamma m_e c^2$ is (e.g., Sarazin 1999)

$$t_{IC} = 7.7 \times 10^9 (1 + z)^{-4} \left( \frac{\gamma}{300} \right)^{-1} \text{yr}. \quad (2.5)$$

The average frequency of synchrotron radiation produced by an electron with a Lorentz factor of $\gamma$ is $\langle \nu_{\text{rad}} \rangle = (55/96)(\sqrt{3}/\pi)\gamma^2(eB/m_e)\sin \theta$, where $\theta$ is the pitch angle of the electron (e.g., Rybicki & Lightman 1979). This gives

$$\langle \nu_{\text{rad}} \rangle \lesssim 560 \left( \frac{\gamma}{10^4} \right)^2 \left( \frac{B}{1 \mu\text{G}} \right) \text{MHz}, \quad (2.6)$$

so that the electrons which produce the radio emission we observe have $\gamma \gtrsim 10^4$ and short lifetimes $t_{IC} \lesssim 2 \times 10^8$ yr. Since these times are shorter than the durations of cluster mergers, one expects to find radio emission only during the merger. This result has been found previously based on more detailed models (e.g., Sarazin 1999; Takizawa & Naito 2000).

The total energy in cosmic ray electrons is then

$$E_{CR} \sim t_{IC} \dot{E}_{CR} \propto f_{CR} f_{\text{gas}} \frac{M}{R} \left( \frac{M}{R} \right)^{5/2}. \quad (2.7)$$

It is also useful to replace the radius $R$, which is poorly defined observationally, with the gas temperature $T$. The gas in clusters is in hydrostatic equilibrium, which implies
that

\[ T \propto \sigma^2 \propto \frac{GM}{R}. \]  

(2.8)

The total energy of cosmic ray electrons then varies as

\[ E_{CR} \propto \frac{f_{CR} f_{gas}}{(1 + z)^4} T^{5/2}. \]  

(2.9)

Alternatively, we can use the cluster X-ray luminosity \( L_X \) to parameterize the size of the cluster. The X-ray luminosity–temperature relationship is approximately \( L_X \propto T^3 \) (e.g., Arnaud & Evrard 1999). Thus, the energy in relativistic electrons varies as

\[ E_{CR} \propto \frac{f_{CR} f_{gas}}{(1 + z)^4} L_X^{5/6}. \]  

(2.10)

The diffuse radio emission from a cluster depends both on the population of relativistic electrons and on the magnetic field. We consider two simple models for the variation in the field strength from cluster to cluster. First, we assume that the magnetic field is constant from cluster to cluster. In this case, electrons with the same energy or Lorentz factor produce radio emission at the same frequencies in all clusters, and the total magnetic energy density is the same in all clusters. Then, the radio luminosity \( L_{radio} \propto E_{cr} \), so that the radio power at an emitted frequency \( \nu \) varies as

\[ P_{\nu} \propto \dot{E}_{\text{shock}} \propto L_X^{5/6} \propto T^{5/2}. \]  

(2.11)

These relations are too flat to fit the observed relations (Fig. 2.4; Feretti 2000; Liang et al. 2000).

As an alternative model, we assume that the magnetic field varies from cluster to cluster in such a way that the magnetic pressure is a fixed proportion of the gas
pressure in the intracluster medium. This might occur as a result of turbulence generated in merger shocks. Then, the magnetic field strength varies as

\[ B^2 \propto \rho_{\text{gas}} T \propto f_{\text{gas}} \frac{M}{R^3} T \propto f_{\text{gas}} \frac{T^4}{M^2}. \]  

(2.12)

Assuming that clusters form from large scale structure and that the gas is hydrostatic implies that the cluster mass and gas temperature are related by \( M \propto T^{3/2} \) (Bryan & Norman 1998), and this is consistent with the observations of clusters (Horner, Mushotzky, & Scharf 1999). This implies that

\[ B \propto (f_{\text{gas}} T)^{1/2}. \]  

(2.13)

Varying the magnetic field also varies the energy of the electrons which contribute to the radio emission at a given observing frequency \( \nu \) according to equation (2.6), and this affects the number of electrons effective at synchrotron emission at this frequency. We assume that the electron population is a power-law in \( \gamma \), with \( N(\gamma) \, d\gamma = N_1 \gamma^{-p} \, d\gamma \) being the total number of electrons with energies in the range \( \gamma \) to \( \gamma + d\gamma \). We determine the power-law index \( p \) from the observed radio spectral index \( \alpha \), which gives \( p = 1 - 2\alpha \). Although the spectral indices vary from cluster to cluster, we assume that there is no consistent variation with cluster X-ray luminosity \( L_X \) or temperature \( T \). We assume the electron populations is in steady-state, which implies that the total number of particles or the normalization of the electron spectrum varies as

\[ N_1 \propto E_{CR} \propto f_{CR} f_{\text{gas}} T^{5/2}. \]  

(2.14)
From synchrotron theory, the radio power at a frequency $\nu$ varies as

$$P_\nu \propto \nu_B N (\nu/\nu_B)^\alpha,$$

(2.15)

where $\nu_B \equiv eB/(2\pi m_e c) \propto B$ is the cyclotron frequency. This leads to

$$P_\nu \propto f_C R f_{\text{gas}}^{(3-\alpha)/2} T^{-3-\alpha/2} \propto L_X^{1-\alpha/6}.$$

(2.16)

These relations between radio power $P_\nu$ and $L_X$ or $T$ are somewhat steeper than those produced by a constant magnetic field (eq. 2.11), but are only a small improvement in terms of fitting the data. We first tried varying $\alpha$, and found a best fit for $\alpha = -7$, which is unreasonably steep. We then fit the $L_X-P_\nu$ data in Feretti (2000) using this relation for several values of $\alpha$ that are consistent with our data. An example of these fits is shown in Figure 2.5. Since the slope is not very sensitive to $\alpha$, we show a fit for only one typical value—other values give a similar fit. This fit differs from the best fit by about 2.5$\sigma$.

For the purposes of considering the radio detectability of halos, it is worth considering how the radio surface brightness $I_\nu$ and radio halo size might vary with X-ray luminosity or temperature. The physical radius of a cluster is expected to vary with temperature as $R \propto T^{1/2}$ (e.g., Mohr et al. 1999). If the temperature vs. X-ray luminosity relation is $L_X \propto T^3$ as assumed above, the cluster size varies as $R \propto L_X^{1/6}$. If we assume that the size of the radio halo is proportional to the cluster size $R$, then $I_\nu \propto T^{3/2} \propto L_X^{1/2}$ for a fixed magnetic field, and $I_\nu \propto T^{(4-\alpha)/2} \propto L_X^{(4-\alpha)/6}$ when the magnetic pressure increases in proportion to the gas pressure. These relations are even flatter than those for the radio power.
Fig. 2.5.— Monochromatic power at 1.4 GHz of well-studied radio halos from Feretti (2000) as a function of X-ray luminosity. The solid line is a least squares fit to the data assuming a power-law relation. The dotted line is a fit using our simple shock model for $\alpha = -1.3$. 
2.5.3 Limits from Clusters with Radio Non-Detections

The discussion so far has concentrated on the radio–X-ray correlations for clusters with detected radio halos. However, radio halos are relatively rare, and most clusters do not show diffuse radio emission at a detectable level. In a model where the radio-emitting electrons are accelerated during cluster mergers this is easily understood, since these electrons have short lifetimes and will only be present during the period of stronger merger hydrodynamical interaction. Since clusters showing X-ray evidence for strong merger shocks are also relatively rare and all radio halo clusters appear to be undergoing mergers, this can explain, at least qualitatively, the low rate of occurrence of radio halos and relics.

We also find that luminous halos and relics are generally not found in clusters with low X-ray luminosities. The NVSS radio survey at 20 cm found a similar result (Giovaninni et al. 1999). This relationship between X-ray luminosity and the detection of a halo or relic appears in several other forms, as well. The Abell clusters north of $\delta = 30^\circ$ that fall into the Ebeling et al. (1996) X-ray–bright cluster sample comprise less than 20% of our initial sample, but make up 65% of the clusters in which we find diffuse emission. If X-ray luminosity and the radio halo luminosity were uncorrelated and the halo detection rate from the Ebeling et al. (1996) sample held for fainter clusters, we would expect to find a radio halo or relic in about 200 of the clusters we studied.

Surely, some of the low X-ray luminosity clusters in the Abell catalog are also undergoing mergers, and may have particle acceleration. Why are these lower luminosity clusters not detected in radio? The observations of clusters indicate that there is a steep correlation of radio power with X-ray luminosity or temperature; our simple merger shock model also implies a steep correlation, although probably not as steep
as the data. Here, we consider the possibility that the failure to detect radio halos in low X-ray luminosity clusters results from this correlation and the radio sensitivity of our survey. We assume that the correlation between radio halo and X-ray luminosity seen for bright clusters (Feretti 2000) continues to lower X-ray luminosities.

The surface brightness sensitivity limit of our search technique is taken to be that of the WENSS, shown in Figure 2.1. We determine the predicted surface brightnesses of clusters as a function of X-ray luminosity $L_X$ and redshift. For a cluster with a given X-ray luminosity, we used the radio power vs. X-ray luminosity relation (Figure 2.4) to determine its radio power at 327 MHz.

To determine the predicted mean radio surface brightness of the halo, we also need to know its physical size. It seems likely that that bigger clusters, which have larger X-ray luminosities, will also have larger radio halos. For example, it may be that radio halo sizes are proportional to the overall sizes of clusters. As discussed in § 2.5.2, this leads to the radio halo size varying with X-ray luminosity roughly as $R \propto L_X^{1/6}$. In our sample of radio halos, there is no clear evidence for a variation of the size of the halo with the X-ray luminosity of the cluster. However, it may be that our sample is too small, or that the sizes deduced from the WENSS images are too uncertain. Figure 2.6 plots the sizes of the radio halos from the sample in Feretti (2000) as a function of the cluster X-ray luminosity. This sample does show some evidence for a size-luminosity relationship. The dashed curve is the best-fit relation which follows the cluster radius vs. X-ray luminosity relation, $R \propto L_X^{1/6}$. The solid curve is the best-fit power-law relation with an arbitrary exponent. This best-fit corresponds roughly to $R \propto L_X^{1/2}$.

The sizes shown in Figure 2.6 are largest linear size ($LLS$) values. Typically, the regions covered by the radio halos are not circular. For the halo sources in our
Fig. 2.6.—Largest linear radio size vs. X-ray luminosity for the halos in Feretti (2000). The solid line is the best least squares fit to the data for a power-law relationship. The dotted line is the best fit with an exponent of 1/6, which would apply if the radio halo size was proportional to the cluster size.
survey, the average area of the source (the area used to determine its mean surface brightness in Figure 2.1) is given by $0.37(\text{LLS})^2$. We use the same factor to determine the predicted area of a source of a given X-ray luminosity; its mean surface brightness at 327 MHz in the cluster rest frame is then determined by dividing the predicted radio power $P_{327}$ by the predicted area of the halo. For the observed radio power and radio size vs. X-ray luminosity relations, the predicted mean radio surface brightness is a monotonically increasing function of the X-ray luminosity.

For a cluster at a redshift of $z$, the observed surface brightness at an observing frequency of 327 MHz is reduced by a factor of $(1+z)^{-3+\alpha}$. We assume a typical spectral index of $\alpha = -1.3$ to determine the observed surface brightness. This observed mean surface brightness was compared to the surface brightness limit of our survey (Figure 2.1), and the X-ray luminosity of the faintest detectable cluster was determined. This limiting $L_X$ is plotted versus redshift as the solid curve in Figure 2.7. This limit is incorrect for very small redshifts where the halos may be too large in angular size, and at very large redshift where the halos might be unresolved. The sense of these differences is to make the clusters harder to detect.

It is clear that the detections are roughly consistent with the survey sensitivity and the radio–X-ray correlations. Abell 2255 is the only cluster to lie at or below the limit, but as Figure 2.4 shows, this cluster deviates substantially from the best-fit $L_X-P_\nu$ relation with a low X-ray luminosity given its radio power. It is clear that radio halos in fainter X-ray clusters ($L_X \lesssim 5 \times 10^{44}$ ergs s$^{-1}$) would be too weak to be observed, if they follow the radio–X-ray correlations observed for brighter clusters. Of course, there may be other selection effects affecting the detection rates of clusters. For example, some of the radio halo detections have resulted from deep radio observations of Sunyaev-Zel’dovich clusters to remove radio sources (e.g., Moffet &
Fig. 2.7.— X-ray luminosity of halo clusters in the 0.1–2.4 keV rest frame as a function of redshift. The solid curve gives the lower limit on cluster X-ray luminosity for a detection of a halo with $\alpha = -1.3$ in the WENSS survey, assuming the halo radio power and size vary with X-ray luminosity as shown in Figures 2.4 and 2.6.
Birkinshaw 1989; Liang et al. 2000). Since the S-Z clusters tend to be selected as the hottest, highest X-ray luminosity clusters, this might explain part of the correlation of radio halo detections with cluster X-ray temperature or luminosity.

2.6 Conclusions

We have discovered 7 new candidate radio halos and relics in a search of Abell clusters in the WENSS. We also confirm the presence of diffuse emission in 7 clusters and find further evidence of such emission in 2 more clusters where the presence of a halo has been posited but remains uncertain. Our search technique detected all but one previously known source that fell within our sample. More detailed radio observations of the new radio halos and relics would be very useful to accurately determine their structure.

We argue that radio halos or relics are only found in clusters which are currently undergoing a cluster merger. All the clusters in our sample show evidence for a merger from either their X-ray surface brightness distribution or their galaxy distribution. This can explain the relative rarity of diffuse radio emission in clusters.

We also find weak evidence for the observed correlation between monochromatic power of radio halos and cluster X-ray luminosity. We present a very simple model for the correlation of radio power with X-ray luminosity or temperature in clusters which are currently merging, on the assumption that the radio-emitting electrons are accelerated by merger shocks. We consider two cases for this model: one in which the magnetic field is the same for all clusters and one in which the field varies as a fixed proportion of the gas pressure. The latter model is marginally more successful at fitting the data. This argument predicts a strong radio-X-ray luminosity correlation, although not as steep as the one observed at 20 cm.
Our survey is the first to look for halos in a large sample of clusters with low X-ray luminosity. In general, radio halos and relics are not found in low X-ray luminosity clusters. We argue that this is the result of the steep radio power vs. X-ray luminosity correlation. If this is true, many more low luminosity clusters could be detected as diffuse radio sources if the sensitivities of the surveys could be greatly increased. Clearly, deeper imaging with high sensitivity at short \((u, v)\) spacings is necessary to test whether the \(P - L_X\) correlation holds at lower X-ray luminosities.

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Chapter 3

Limits on the Diffuse Radio and Hard X-ray Emission of Abell 2199
Abstract

The Westerbork Northern Sky Survey (WENSS) and the NRAO/VLA Sky Survey (NVSS) were used to determine an upper limit to the diffuse radio flux from the nearby cluster Abell 2199. For the entire cluster, this limit is $<3.25$ Jy at 327 MHz from WENSS; for the inner 15' radius, the limit is $<168$ mJy at 1.4 GHz. These limits are used to constrain the cluster magnetic field by requiring that the radio flux be consistent with the hard X-ray (HXR) flux observed by BeppoSAX, assuming that the observed HXR excess is due to inverse Compton (IC) scattering of cosmic microwave background photons by relativistic electrons in the intracluster gas. We find that the magnetic field must be very weak ($<0.073$ $\mu$G) in order to avoid producing an observable radio halo. We also consider the possibility that the HXR excess is due to nonthermal bremsstrahlung (NTB) by a population of suprathermal electrons which are being accelerated to higher energies. We find that a NTB model based on a power-law electron momentum distribution with an exponent of $\mu \approx 3.3$ and containing about 5% of the number of electrons in the thermal ICM can reproduce the observed HXR flux.
3.1 Introduction

Abell 2199 is a nearby \((z = 0.0303)\) X-ray cluster. It contains a cooling flow which is centered on the cD galaxy NGC 6166, which is also a strong radio source (3C 338). Recent X-ray observations of the cluster with BeppoSAX (Kaastra, Bleeker, & Mewe 1998; Kaastra et al. 1999) found evidence for an excess of hard X-rays above that expected from the thermal emission of the hot intracluster gas. There are several possible interpretations of this hard tail to the X-ray luminosity. One is that the excess is caused by inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by highly relativistic cosmic ray electrons located in the intracluster medium (ICM) (Rephaeli 1979; Kaastra et al. 1999). Another is that the excess is produced by nonthermal bremsstrahlung (NTB) by subrelativistic but suprathermal electrons which are undergoing acceleration in the ICM (Kaastra et al. 1998; Enßlin, Lieu, & Biermann 1999; Sarazin & Kempner 2000). If the first explanation is correct, the same relativistic electrons should produce diffuse radio synchrotron emission as long as the ICM contains a magnetic field which is not too small. As a test of the IC model, we search for diffuse radio emission from this cluster using the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) and the NRAO/VLA Sky Survey (NVSS; Condon et al. 1998). We assume \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\) and \(q_0 = 0.5\) throughout.

3.2 Limits on Diffuse Radio Halo

We searched for diffuse radio emission from Abell 2199 using the WENSS 92 cm radio survey and the NVSS radio survey at 20 cm. The WENSS images have a synthesized beam of \(54'' \times 85''\) at the declination of Abell 2199. The typical noise level is 3.6 mJy
beam$^{-1}$. WENSS interferometer observations should be sensitive to radio emission on scales of less than $\sim 1^\circ$. The NVSS synthesized beam is $45'' \times 45''$. The typical noise level is 0.45 mJy beam$^{-1}$. The NVSS is sensitive to emission on scales of less than 15'. At the redshift of Abell 2199, a typical cluster core radius of 200 kpc corresponds to 3.5', while an Abell radius of 3 Mpc subtends 58'. Thus, the WENSS observations should be sensitive to a diffuse radio halo in the cluster if it is smaller than the cluster Abell radius, while the NVSS should be sensitive to a halo smaller than 775 kpc.

The WENSS survey gives a source catalog (Rengelink et al. 1997), which contains 22 sources which lie within half a degree (the largest angular scale not resolved out by the interferometer used in the survey) of the center of the cluster. We adopt the position of the central cD galaxy NGC 6166, R.A. = 16$^h$26$^m$55.4, Dec. = +39$^\circ$39'37'', as the center of the cluster. The strongest radio source is 3C 388 which is associated with the central cD galaxy. None of these sources is extended on the scale of the cluster, so we do not include this emission in the measurement of the diffuse cluster radio emission. To search for diffuse radio emission, we used the survey radio image to determine the total radio flux from a circle of radius 30' (1.55 Mpc at the distance of Abell 2199). We then subtracted from this measured flux the sum of the integrated fluxes of all sources in the WENSS catalog within this region. This residual flux was found to be $3.25 \pm 0.21$ Jy.

However, the cD galaxy in Abell 2199 is the very strong radio source 3C 338, with a peak-to-rms brightness ratio of 3190 in WENSS. Slight instrumental variations between receivers in a radio interferometer cause the region immediately around a bright source with such a large peak-to-rms ratio to have both an increased rms noise level and a systematic positive flux from uncleaned sidelobes in the absence of real diffuse emission (Condon et al. 1998). This systematic excess flux varies from source
to source in WENSS. We did an inspection of several other bright sources in the surveys and found that the effect is consistently between about 8 and 12% of the peak intensity of the source. The residual flux in Abell 2199 is approximately 12% of the peak flux of the cD, so we must treat this residual as an upper limit on the diffuse synchrotron flux from the cluster rather than as a detection of diffuse emission. If we subtract our best estimate of this systematic effect from the measured flux, the upper limit on the flux would be reduced by at least a factor of five. However, due to the uncertainty in the magnitude of this baseline offset, we use the more conservative value without attempting to remove the effect of the offset baseline. Thus, our upper limit to the diffuse radio flux of Abell 2199 at 92 cm is 3.25 Jy.

The dynamic range of the NVSS is more sensitive, and the cD is better resolved than in the WENSS observations, so the peak-to-rms of the cD is not as great. There is still some noticeable uncleaned sidelobe structure in the image, but it is relatively minor. Since the NVSS resolves out structures larger than 15′, we used the same procedure as with WENSS, but restricted to a 15′ circle. We measure a residual flux of $-97 \pm 56$ mJy. The small negative flux appears to be caused by the uncleaned sidelobes and is consistent with zero diffuse emission. From this we can rule out the existence of a radio halo within the central 750 kpc of the cluster. The 3-$\sigma$ upper limit of the diffuse flux in the NVSS survey is $<168$ mJy. The WENSS limit is more conservative since, unlike the NVSS, no flux is resolved out in the region containing the HXR emission observed by BeppoSAX.

3.3 IC X-ray Emission and the Cluster B Field

If the relativistic electrons in the cluster have a power-law energy distribution, then both the radio synchrotron and the IC hard X-ray spectra are expected to be power
laws in frequency with the same spectral index (e.g., Rephaeli 1979). Kaasra et al. (1998, 1999) fit the X-ray spectra from *BeppoSAX* with a power-law spectrum excess to the thermal emission from the ICM. In Kaasra et al. (1999), a single power-law excess was fit across the entire X-ray band, roughly from 0.1–100 keV. The total luminosity in this band was \((1.30 \pm 0.32) \times 10^{44}\) ergs s\(^{-1}\). The cluster Abell 2199 shows both a hard X-ray excess and and extreme ultraviolet (EUV) or soft X-ray excess (Lieu, Bonamente, & Mittaz 1999). In Kaasra et al. (1999), the authors argue that both the EUV and HXR excesses are nonthermal IC emission. The best-fit power-law photon spectral index was \(\Gamma = 1.81 \pm 0.25\) for the entire spectral band 0.1–100 keV. This implies a flux of \(S\_{HXR} = (1.6 \pm 0.4) \times 10^{-11}\) ergs cm\(^{-2}\) s\(^{-1}\) in the HXR band, 10–100 keV.

If this hard X-ray emission is due to IC scattering of the CMB photons, then the predicted radio synchrotron flux is

\[
S_{\nu} = 234 \left( \frac{S\_{HXR}}{10^{-11}\ \text{ergs cm}^{-2}\ \text{s}^{-1}} \right) \left( \frac{B}{1\ \mu\text{G}} \right)^{1.81} \left( \frac{\nu}{327\ \text{MHz}} \right)^{-0.81}\ \text{Jy},
\]

if the photon spectral index of the HXR emission is \(\Gamma = 1.81\). Here, \(S\_{HXR}\) is the HXR flux in the 10–100 keV band, \(B\) is the cluster magnetic field, and \(\nu\) is the observed frequency.

If we use the observed HXR flux of Abell 2199 and our conservative upper limit on the radio flux at 327 MHz \((S_{\nu} < 3.25\ \text{Jy})\), this implies a strong upper limit on the magnetic field of \(B < 0.073\ \mu\text{G}\). If we correct for the aforementioned instrumental excess radio emission near strong sources, we reduce the observed radio flux by a factor of \(\sim 8\) and consequently reduce the maximum magnetic field by a factor of 2 to 3. Similarly, if the NVSS limit on a smaller radio halo at higher frequencies is used, the limit on the magnetic field is \(B \lesssim 0.02\ \mu\text{G}\). Thus, we have a conservative upper
limit of 0.073 μG, with the strong suggestion that the field must be even weaker. If we instead assume a more typical magnetic field of 1 μG, the upper limit on the radio flux implies an upper limit to the inverse Compton HXR flux which is more than 100 times fainter than was observed with BeppoSAX.

3.4 Nonthermal Bremsstrahlung

Alternatively, the HXR excess observed in Abell 2199 might result from some other emission process. Perhaps the most likely possibility is nonthermal bremsstrahlung (NTB) from suprathermal electrons in the ICM (Kaastra et al. 1998; Enßlin, Lieu, & Biermann 1999; Sarazin & Kempner 2000). These might be electrons with energies ≳ 10 keV which are currently being accelerated up to much higher energies, either by shocks or by turbulent acceleration. Detailed models for NTB emission in clusters are given in Sarazin & Kempner (2000).

One feature of such models is that the excess emission spectrum should flatten at low energies, because the suprathermal population only contains electrons with energies which are higher than typical thermal energies (see Figure 3.1 below). Thus, one does not expect nonthermal bremsstrahlung to produce any EUV excess emission directly. It is also inappropriate to fit a single power-law spectrum to the NTB emission across the entire X-ray band 0.1–100 keV. On the other hand, Sarazin & Kempner (2000) show that a power-law does provide a reasonable fit to the spectrum of the HXR emission, 10–100 keV. In Kaastra et al. (1998), the HXR excess emission in Abell 2199 as seen in the BeppoSAX PDS was fit independently of any softer excess. This gave a flux of $S_{HXR} = (1.4 \pm 0.4) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the 10–100 keV band. The best-fit power-law photon spectral index was $\Gamma = 2.5^{+1.1}_{-0.8}$. This is steeper than the spectral index found by fitting a power-law excess to the entire X-ray band (Kaastra
et al. 1999), although the error bars overlap.

Let \( N(p)dp \) be the total number of nonthermal electrons with normalized momenta in the range \( p \) to \( p + dp \), where \( p \) is the momentum normalized to \( m_e c \). The simplest models for the nonthermal electrons in clusters have a power-law momentum distribution (Sarazin & Kempner 2000), with

\[
N(p) = N_0 p^{-\mu} \quad p \geq p_t. 
\]

We will assume that the suprathermal population consists only of particles with momenta \( p > p_t \), such that their kinetic energies exceed \( 3kT \) where \( T \) is the temperature of the thermal ICM. If the cooling flow at the center of Abell 2199 is excluded, the mean ICM temperature is \( kT = 4.8 \pm 0.2 \) keV (Markevitch et al. 1999b). This implies that \( p_t = 0.24 \).

For steep power-law momentum distributions (\( \mu \gtrsim 3.5 \)), the nonthermal bremsstrahlung HXR emission is nearly a power-law with \( \Gamma \approx 1 + \mu / 2 \) (Sarazin & Kempner 2000). For flatter momentum distributions, the NTB spectra are still approximately fit by power-laws, but the exponent is flatter than given by this expression. The observed spectral index of \( \Gamma = 2.5 \) between 10 and 100 keV is produced by a model with \( \mu = 3.33 \). The predicted nonthermal bremsstrahlung spectrum of this models is shown in Figure 3.1. The observed flux in the 10-100 keV band is reproduced by a model with \( N_o = 3.88 \times 10^{68} \), which implies that the total number of nonthermal electrons is \( 4.6 \times 10^{69} \) if the electron spectrum extends to high energies. This represents about 5% of the total number of thermal electrons in the intracluster medium in Abell 2199 (Mohr, Mathiesen, & Evrard 1999).

If the nonthermal electron distribution extends to much higher energies, HXR would be produced through IC by these higher energy electrons. In fact, if the
Fig. 3.1.— The nonthermal bremsstrahlung hard X-ray emission of our model with a power-law momentum distribution with $\mu = 3.33$. The emitted spectrum is given as a function photon energy. The flattening of the spectrum at low energies is due to the cut-off in the suprathermal electron population at an energy of $3kT$. 
electron spectrum is flatter than $\mu \lesssim 2.7$, more HXR emission is produced by IC than by NTB. However, for the steep electron spectrum in our NTB model, IC by high energy electrons only contributes about 0.6% of the flux in the 10–100 keV HXR band. The small number of high energy electrons in this steep spectrum model also reduces the radio synchrotron emission. For a magnetic field of 1 $\mu$G, the predicted radio flux is 0.73 Jy at 327 MHz. Thus, the predicted radio emission is consistent with our limit as long as $B \lesssim 2 \mu$G.

On the other hand, with this steep electron spectrum, the model cannot reproduce the EUV or soft X-ray excess which has been observed in Abell 2199 (Kaastra et al. 1999; Lieu et al. 1999), either by NTB or IC emission. Apparently, a distinct population is needed to produce the observed EUV emission. Since the electrons which generate EUV by IC have long lifetimes comparable to cluster ages (Sarazin & Lieu 1998), it is possible that the EUV emission is produced by an older population of electrons, while the NTB HXR emission is due to electrons currently being accelerated.

### 3.5 Conclusions

We have used the WENSS and NVSS radio surveys to search for any diffuse radio emission (a radio halo or relic) associated with the cluster of galaxies Abell 2199. We do not detect any such emission. The best limit on any cluster-wide emission comes from the WENSS survey, which gives a limit of 3.25 Jy at 327 MHz. The limit would be considerably tighter were it not for the confusing effects of uncleaned sidelobes from the central radio source 3C 338. The NVSS survey gives a much tighter limit of 168 mJy at 1.4 GHz, but only applies to a centrally condensed radio halo with a size of less than about 750 kpc.
The absence of diffuse radio emission in Abell 2199 is not surprising when this cluster is compared to other clusters with and without radio halos. Abell 2199 is an extremely regular cluster with a strong central cooling flow (e.g., Markevitch et al. 1999b). Radio halos and relics are relatively rare objects which are generally associated with irregular clusters which are undergoing mergers (e.g., Giovannini, Tordi, & Feretti 1999). It has generally been argued that the presence of diffuse radio emission in these irregular clusters is the result of the acceleration or transport of relativistic particles by shocks or turbulence associated with the merger. The presence of a strong cooling flow in Abell 2199 is also an indication that this cluster has not had a recent strong merger, as cooling flows and irregular cluster structures tend to be anticorrelated (Buote & Tsai 1996). Clusters with radio halos also tend to be rather hot clusters (Giovannini et al. 1999), whereas Abell 2199 is fairly cool ($kT = 4.8 \pm 0.2$ keV; Markevitch et al. 1999b), even when the temperature is corrected for the cooling flow.

On the other hand, extended nonthermal hard X-ray emission was detected from Abell 2199 with BeppoSAX (Kaastra et al. 1998, 1999). HXR tails in the spectra of clusters with radio halos are expected as a result of IC scattering by high energy ($\gtrsim 1$ GeV) relativistic electrons (Rephaeli 1979), and this is an explanation which has been proposed for the HXR emission in Abell 2199 (Kaastra et al. 1999). Unless the ICM magnetic field is very weak, the same electrons would produce diffuse radio synchrotron emission. The absence of such diffuse radio emission in Abell 2199 is a significant problem for the IC model for the HXR emission.

If we accept inverse Compton radiation as the explanation of the observed hard X-ray tail, then the cluster magnetic field implied by the limit on the radio flux is very weak. If we adapt our most conservative limit on the total diffuse radio flux of
the cluster, it implies that the ICM magnetic field is $B < 0.073 \ \mu$G. If we correct the
decoating limit for the uncleaned sidelobes of the central radio source 3C 338, or if we
use the stronger limit on a centrally condensed radio halo ($\lesssim 750$ kpc in diameter)
from the NVSS, then the limit on the magnetic field is smaller by a factor of about
3. These field limits are at least an order of magnitude smaller than the magnetic
fields derived from Faraday rotation measurement towards individual radio galaxies
(e.g., Feretti et al. 1995) or statistical samples of radio sources (Clarke, Kronberg, &
Bohringer 1999) in other clusters. Very strong Faraday rotation is detected toward
the central radio source 3C 338 in Abell 2199 (Ge & Owen 1994), which implies the
presence of a magnetic field which is about two orders of magnitude stronger than
the limit we find for the diffuse field if the HXR emission is due to IC scattering.
However, the field around 3C 338 might have been enhanced by compression or shear
associated with the cooling flow at the center of the cluster (Soker & Sarazin 1990).

One possibility is that the magnetic field in Abell 2199 (and, presumably, other
clusters) is very inhomogeneous, and the magnetic field and relativistic electrons
are anticorrelated (Enßlin et al. 1999). This might occur because electrons in high
magnetic field regions lose energy rapidly by synchrotron emission, and the remaining
high energy electrons might be found preferentially in weak magnetic field regions.
This model was proposed for the Coma cluster (Enßlin et al. 1999), where the observed
IC HXR emission implies a lower value of the magnetic field than has been determined
from Faraday rotation measurements (Fusco-Femiano et al. 1999).

If the intraduster magnetic field and relativistic electrons are not anticorrelated,
it is difficult to believe that the ICM magnetic field is as weak as required by the
HXR flux. Of course, it is possible that the nonthermal HXR flux is in error, because
of calibration uncertainties with BeppoSAX, or because of another hard X-ray source
in the field of view, or because of a complex thermal structure in the ICM which produces a thermal HXR tail.

Alternatively, the HXR emission may be real, but not due to IC scattering of CMB photons. The most attractive alternative emission mechanism may be the nonthermal bremsstrahlung emission by a population of mildly subrelativistic nonthermal electrons with energies of 10-1000 keV (Kaastra et al. 1998; Enßlin et al. 1999; Sarazin & Kempner 2000). We constructed a NTB model for the HXR emission in Abell 2199, based on a power-law momentum distribution for the nonthermal electrons starting at an energy of $3kT$. A model with a power-law exponent of $\mu = 3.33$ containing about 5% of the thermal electron population of the cluster fits the BeppoSAX observations acceptably. With a power-law exponent this steep, the electron population can be extended to arbitrarily high electron energies without producing too much HXR IC emission or radio synchrotron emission. Assuming the same electron spectrum extrapolates to very high energies, our limit on the diffuse radio emission is consistent with any magnetic field with an average value of $\lesssim 2 \mu G$.

This steep nonthermal electron population could not produce the observed EUV and soft X-ray excess observed from Abell 2199 (Kaastra et al. 1999; Lieu et al. 1999) either by NTB or IC emission. A distinct electron population is needed to produce this emission. The electrons which would emit EUV by IC have lifetimes which are nearly comparable to cluster ages (Sarazin & Lieu 1998). Thus, it is possible that the EUV is generated by an older population of electrons, while the NTB HXR emission is due to electrons currently being accelerated out of the thermal population.

The most likely source of the nonthermal subrelativistic electrons would be acceleration of electrons out of the thermal distribution. The acceleration might be due to shocks or turbulence (e.g., plasma waves). The required electron spectrum is about
one power steeper ($\mu \approx 3.3$) than is normally associated with particle acceleration in strong shocks ($\mu \approx 2$). However, in simple shock models, the exponent of the power-law depends on the shock compression $r$ as $\mu = (r + 2)/(r - 1)$ (e.g., Bell 1978). In shocks in the intracluster gas, the preshock gas is quite hot, and the Mach numbers are expected to be several, rather than being very large. The NTB model electron exponent of $\mu \approx 3.3$ corresponds to a shock compression of $r \approx 2.3$ and a Mach number $M \approx 2$. These values are similar to those derived from the thermal and density structures in several merging clusters (Markevitch, Sarazin, & Vikhlinin 1999a). Alternatively, the electron acceleration might be due to turbulence. This could give a steep power-law spectrum if the acceleration were relatively inefficient.

One concern with the NTB model is that Abell 2199 is very regular, and shows no real evidence for any hydrodynamical activity which might generate shocks or turbulence. On the other hand, the required particle spectrum is fairly steep, and might be produced by relatively weak shock or turbulent acceleration, which might persist for long periods after any major dynamical event. Such weak shocks and turbulence might even be continually generated by the infall of small galaxy groups into the clusters or possibly by the motions of galaxies. If so, then one would expect to find comparable nonthermal HXR tails in most clusters of galaxies.

The work presented in this chapter was supported in part by NASA Astrophysical Theory Program grant NAG 5-3057.
Chapter 4

Chandra Observations of Abell 85:
Merger of the South Subcluster
Abstract

We present an analysis of a highly asymmetric cluster merger from a *Chandra* observation of Abell 85. The merger shows significant disruption of the less massive subcluster from ram pressure effects. Nevertheless, a cold core, coincident with the cD galaxy, is observed to persist in the subcluster. We derive dynamical information from the motion of the cold core through the main cluster’s ICM. Multiple derivations of the velocity of the core suggest a Mach number of $M \approx 1.4$, or $v \sim 2150$ km s$^{-1}$. We construct a consistent kinematic model for the merger based on this dynamical analysis. As has been found for other such “cold fronts,” conduction appears to be suppressed across the front. We analyze the role of hydrodynamic instability in determining the shape and extent of the front. Both thermal conduction and hydrodynamic instability may be suppressed by a magnetic field with a significant component perpendicular to the subcluster’s direction of motion. The effect of the merger interaction in creating and shaping the observed radio sources is also discussed. It appears most likely that the radio source is due to distorted and detached lobes from the subcluster cD galaxy, rather than being a radio halo.
4.1 Introduction

Mergers of clusters of galaxies are highly energetic events, releasing a total kinetic energy of $\sim 10^{63}$ ergs into the intradcluster medium (ICM). When clusters merge, shocks are driven into the ICM, dissipating the kinetic energy of the merger and heating the gas. These shocks also have nonthermal effects, including the generation of turbulence in the ICM and acceleration of charged particles to relativistic, or cosmic ray, energies. Observations with Chandra of merging clusters have provided new insights into the cluster merger process, including the unpredicted discovery of the persistence of cold cores from pre-merger cooling flows well into the lifetime of a merger ("cold fronts:" Markevitch et al. 2000; Vikhlinin et al. 2001a).

Abell 85 is in the early stages of merging with two subclusters, each much less massive than the main cluster. One subcluster is merging from the southwest while the other subcluster is merging from the south. The south subcluster will be the focus of our discussion here, while the other subcluster and its associated radio relic will be discussed in a later paper. Abell 85 is unusual in being one of the few clusters known to be in the process of a merger while maintaining a moderate (107 $M_\odot$ yr$^{-1}$; Peres et al. 1998) cooling flow. Presumably, this implies that the merging subclusters have not yet penetrated the inner few hundred kiloparsecs of the cluster and have therefore not yet been able to disrupt the cooling flow.

The south subcluster is more massive than the southwest subcluster. There has been some uncertainty in the past as to whether or not this subcluster is in fact merging with the main cluster or is merely seen against the main cluster in projection. Using data from ASCA, Markevitch et al. (1998) determined that the temperature in the region of the subcluster is the same as or slightly greater than that of the rest of the main cluster at the same radius. If the subcluster were not merging and were
only seen it projection, its smaller mass would give it a lower temperature than that of the main cluster. Thus, the higher temperature indicates that the subcluster is almost certainly interacting.

The redshifts of the galaxies in the southern subcluster are slightly larger than those of the main cluster (Beers et al. 1991; Durret et al. 1998). This suggests that the southern subcluster is either a background cluster or that it is slightly in front of the main cluster and its excess redshift comes from its peculiar motion as it falls into the main cluster. Based on the analysis of Markevitch et al. (1998) and the observations presented in the present paper, we believe that it is merging with the main cluster. Thus, we will assume that the southern subcluster is at essentially the same distance as the main cluster, and that any difference in their observed redshifts is caused by their relative motion along the line of sight as they merge.

The *Chandra* observation and basic data reduction are discussed in § 4.2. The X-ray image is presented in § 4.3.1. In § 4.3.2, we analyze the spectra of interesting regions associated with the southern subcluster. The profiles of the X-ray surface brightness and temperature within the subcluster and in the region ahead of the subcluster are extracted in § 4.3.3. We discuss the evidence for a merger and X-ray determinations of the merger Mach number in § 4.4. The pressure increase at the cold front and properties of the bowshock are used to derive the merger velocity in § 4.4.1 and 4.4.2. We construct a consistent kinematic model for the merger in § 4.5. The suppression of conduction across the cold front is discussed briefly in § 4.6.1. In § 4.6.2, we examine the possible role of hydrodynamic instabilities in determining the shape of the cold front. There have been claims of a possible radio relic in this cluster as well (Bagchi et al. 1998), which we discuss in § 4.7. Our results are summarized in § 4.8. We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout this paper. At the
cluster redshift of \( z = 0.0538 \), 1\( '' \) corresponds to 1.43 kpc. All of the errors quoted are at the 90\% confidence level.

### 4.2 Observation and Data Reduction

Abell 85 was observed with ACIS-I detector on Chandra in a single 39 ksec observation. Using the count rate in the S3 chip, we excluded data during two small background flares using the \texttt{lc\_clean}\(^1\) routine written by Maxim Markevitch. This left 36,587 s of useful exposure time. Although the observation included the four ACIS-I chips and the S3 and S4 chips, the analysis presented here will be based on the ACIS-I data only. The focal plane temperature during the observation was \(-120\) C. A raw image of the entire ACIS-I detector in the spectral band 0.3–10 keV is presented in Figure 4.1.

The ACIS-I suffers from enhanced charge transfer inefficiency (CTI) caused by radiation damage early in the mission. We corrected for the quantum efficiency non-uniformity and gain variations caused by this damage, but the degradation in spectral response was not corrected for due to the lack of availability of appropriate response matrices. We used version 1 of the January 29, 2001 gainfile and response files. Because of uncertainties in the spectral response at low energy, we limit our spectral analyses to the range 0.7–10.0 keV, excluding the 1.8–2.2 keV band around the mirror iridium edge. We constructed blank sky backgrounds from the March 23, 2001 versions of Maxim Markevitch’s ACIS-I background photon lists using the routine \texttt{make\_acisbg}\(^1\).

\(^1\)see http://hea-www.harvard.edu/~maxim/axaf/acisbg/
Fig. 4.1.— Raw X-ray image of Abell 85 in the 0.3–10 keV band, uncorrected for background or exposure. All four ACIS-I chips are shown; the regions of reduced exposure are the interchip gaps. The center of the main cluster and cooling flow are located on the upper left chip, the center of the southwest subcluster is located just above the lower edge of the upper right chip, and the south subcluster is near the bottom and overlaps the two lower chips.
4.3  X-ray Properties of the Southern Subcluster

4.3.1  X-ray Image

Figure 4.2 shows an adaptively smoothed image of an approximately 6'4"×6'4" region around the southern subcluster. The image was smoothed to a signal-to-noise ratio of three for each smoothing beam. The same set of smoothing kernels were used to smooth the blank-sky background image and the exposure map. The smoothed background image was subtracted from the smoothed subcluster image, and the result was divided by the smoothed exposure map.

The subcluster is roughly cone-shaped (Figure 4.2), with a high surface brightness knot at the northwest corner. This bright region is spatially extended, with a diameter of about 26", and is centered on the cD galaxy which is the brightest galaxy in the southern subcluster (see Figure 4.8 below). The northern edge of this knot shows an abrupt surface brightness edge. This suggests that it is either a merger shock or a "cold front," the leading edge of a cold core. There is a curved tail of brighter X-ray emission extending to the southeast of the bright knot.

The overall geometry indicates that the ICM in the subcluster has been affected by ram pressure from the gas in the main cluster. The morphology suggests that the south subcluster is in the early stages of merging with the main cluster, and that it is falling into the main cluster for the first time from the south. The sharp edge at the top of the bright knot is symmetrical about a position angle of −15° (15° west of north). The bulk of the subcluster forms a conic distribution centered about a position angle of 123° (58° east of south). This difference between 123° and 165° = (180° − 15°) may indicate that the cD galaxy is moving relative to the center of mass of the subcluster, or that the shape has been affected by the density structure.
Fig. 4.2.— Adaptively smoothed image of the south subcluster, corrected for background and exposure. The cold core is at the NW corner of the subcluster.
in the subcluster and main cluster gas. In any case, it appears that the transverse component of the velocity of the subcluster relative to the main cluster lies at a position angle between $-60^\circ$ and $-10^\circ$. The position angle of the center of the main cluster from the subcluster is about $+13^\circ$. This implies that this is an offset merger; the collision is occurring with a nonzero impact parameter and angular momentum.

Several point X-ray sources are also seen in the region of the subcluster (Figure 4.2). Only two of these have an optical counter part: the source at R.A. = $00^{h}41^{m}50^{s}.4$, Dec. = $-9^\circ 25'48''$ is coincident with the nucleus of the galaxy PGC 93226, which is a cluster member and a radio source (radio source B in Figure 4.8 below); and the source at R.A. = $00^{h}41^{m}59^{s}0$, Dec. = $-9^\circ 24'49''$ is coincident with a very faint galaxy of unknown redshift (source 1-2117; Slezak et al. 1998).

### 4.3.2 X-ray Spectra

We extracted the X-ray spectra of the bright knot coincident with the cD galaxy at the top of the subcluster (“cold core”), of the remainder of the subcluster, and of the main cluster gas at a similar projected distance from the center of the main cluster. The spectrum of the bright knot was extracted from the elliptical region at the center in Figure 4.3. The spectrum from the remainder of the subcluster was extracted from a polygonal region encompassing most of the rest of the subcluster, minus the point sources within that region. The main cluster spectrum came from an annular pie wedge to the east of the subcluster and which encompassed the same radii from the cluster center as the subcluster. The spectral fits in these regions are presented in Table 4.1. The spectra were grouped to have a minimum of 20 counts per channel. As described in § 4.2, we restricted our spectral analysis to the range 0.7–10.0 keV, minus the band from 1.8–2.2 keV. In the fit to the spectrum of the main cluster,
we cut the spectrum off at 9.0 keV because the spectrum of this diffuse emission is dominated by background above this energy. The spectra were fit within xspec using the mekal model for the thermal emission. The absorption column was fixed at the Galactic value of 2.85 \times 10^{20} \text{ cm}^{-2} (Dickey & Lockman 1990). Since the observed emission from the cold core and subcluster presumably contain emission from the main cluster seen in projection in front of and behind these regions, we also fit the spectrum of the cold core and subcluster with two mekal thermal components, with the shape of the hotter component fixed at the values found for the main cluster, and the normalization determined by the relative areas of the regions.

We find that the temperature of the bright knot at the top of the subcluster (2.1^{+0.5}_{-0.4} \text{ keV}) is much lower than the temperature of the remainder of the subcluster or of the surrounding gas from the main cluster. This shows that this X-ray bright and dense region is a cooling core associated with the central region and central cD galaxy in the subcluster. The sharp surface brightness discontinuity at the northern edge of this knot must be a cold front, rather than a merger shock, since the compressed gas has a lower temperature and specific entropy than the less dense gas (Markevitch et al. 2000; Vikhlinin et al. 2001a).

We also fit the cold core with a cooling flow model, with and without an additional

<table>
<thead>
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<th>Region</th>
<th>model</th>
<th>$k_B T$ (keV)</th>
<th>$Z (Z_\odot)$</th>
<th>$\chi^2$</th>
<th>d.o.f.</th>
<th>net counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold core</td>
<td>mekal</td>
<td>2.3^{+0.6}_{-0.4}</td>
<td>0.48^{+0.97}_{-0.27}</td>
<td>16.7</td>
<td>16</td>
<td>416</td>
</tr>
<tr>
<td>cold core</td>
<td>mekal + main cluster</td>
<td>2.1^{+0.5}_{-0.4}</td>
<td>0.53^{+0.86}_{-0.34}</td>
<td>15.9</td>
<td>16</td>
<td>416</td>
</tr>
<tr>
<td>subcluster - cold core</td>
<td>mekal</td>
<td>6.3^{+0.6}_{-0.5}</td>
<td>0.34^{+0.15}_{-0.15}</td>
<td>254.0</td>
<td>196</td>
<td>8486</td>
</tr>
<tr>
<td>subcluster - cold core</td>
<td>mekal + main cluster</td>
<td>5.5^{+0.7}_{-0.6}</td>
<td>0.36^{+0.30}_{-0.10}</td>
<td>254.6</td>
<td>196</td>
<td>8486</td>
</tr>
<tr>
<td>main cluster</td>
<td>mekal</td>
<td>9.0^{+2.2}_{-1.7}</td>
<td>0.52^{+0.67}_{-0.50}</td>
<td>186.8</td>
<td>168</td>
<td>4527</td>
</tr>
</tbody>
</table>
foreground and background contribution from the main cluster. In both cases, the
gas was allowed to cool to the minimum allowable temperature, essentially zero. For
the fit without the additional component for the main cluster, we fixed the maximum
temperature and abundance to those from the third fit in Table 4.1. We found a
cooling rate of $7.3_{-0.8}^{+0.7} M_\odot$ yr$^{-1}$. With an additional mekal model component set to
the main cluster parameters, and with the maximum temperature and abundance
set to the parameters from fit number 4 in Table 4.1, we derived a cooling rate of
$6.8 \pm 0.6 M_\odot$ yr$^{-1}$. Both fits are consistent with a low present cooling rate. Both
fits also had a significantly worse reduced $\chi^2$ than did either of the first two models
presented in Table 4.1.

We fit a single temperature model to the spectrum of the subcluster minus the
cold core and found a temperature of $6.3_{-0.5}^{+0.6}$ keV. If we add a model component for
the emission from the main cluster, we find a subcluster temperature of $5.5_{-0.6}^{+0.7}$ keV.
The former temperature is slightly lower than the value given by Markevitch et al.
(1998), but is consistent to within the errors. Our extraction region is smaller than
that used by Markevitch et al. (1998) due to the much poorer angular resolution of
ASCA. Thus, the ASCA spectrum may have included more emission from the main
cluster, which is hotter. In any case, the bulk of the subcluster is hotter than might
be expected for a cluster of this mass and X-ray luminosity, which may indicate
that much of the subcluster gas has been heated by shocks or adiabatic compression
associated with the merger.

4.3.3 Temperature and X-ray Surface Brightness Profiles

We measured the temperature and surface brightness gradients inside the subcluster
and in front of the cold front (Figures 4.4 and 4.5). The temperature measurements
Fig. 4.3.— Elliptical annular wedge regions used for determining temperatures are shown superposed on a gaussian smoothed image of the south subcluster.
in front of the cold front were made by extracting spectra in a wedge of elliptical annuli whose curvature matched that of the cold front. The measurements within the subcluster were made from spectra also accumulated from annular wedges using ellipses self-similar to those in front of the cold front. The size and orientation of the wedges inside the subcluster were determined by the edges of the subcluster, and therefore were not oriented 180° from the wedge in front of the subcluster. While the annular wedges in front of the subcluster were centered along a line 15° west of north, the wedges inside the subcluster were centered on a line \( \sim 58° \) east of south. The regions used to extract the spectra are shown in Figure 4.3.

We fit single-temperature models to these spectra, with the absorption column set to the Galactic value. The resulting temperatures from fits to these spectra are shown in Figure 4.4. The gas in front of the cool core is hot, and the temperatures are consistent (within the large errors) with the temperature in the main cluster at this radius. The temperature in the cool core of the subcluster is quite low. Behind the cool core, the temperatures in the subcluster rise up to moderately high values.

X-ray surface brightness measurements were made in elliptical annular wedges with the same shape as those used to extract the spectra, but with smaller widths. The resulting surface brightness profile in the 0.3–10 keV band is shown in Figure 4.5a. As is clear from the image (Figure 4.2), the highest surface brightness is associated with the cool core. There is a very sharp surface brightness discontinuity (a factor \( \gtrsim 5 \)) at the northern edge of the cool core. The combination of the surface brightness discontinuity with the low temperature in the bright region shows that this is a cold front. The subcluster south of the cool core is much brighter than the gas ahead of the cold front.

If one assumes that the subcluster is merging for the first time, that the motion is
Fig. 4.4.— Temperature profile in the regions shown in 4.3. The dotted line indicates the position of the cold front, with positive radii in the direction of motion of the subcluster (i.e., ahead of the cold front). The dashed lines indicate the temperatures from the single-temperature fits given in Table 4.1. The fit to the subcluster is shown for the radii over which it was determined.
Fig. 4.5.—(a) X-ray surface brightness from 0.3-10 keV in a set of elliptical annular wedges with the same shape and orientation as those in 4.3, but more closely spaced. (b) X-ray surface brightness values from (a), after correction for the foreground and background emission from the main cluster. The dashed curve in (a) is the projected surface brightness contribution from the main cluster, which is used to correct the values in (b).
transonic, and that the mass of the subcluster is much smaller than that of the main cluster, one would expect the gas far ahead of the cold front would be undisturbed main cluster ICM. Also, main cluster emission may be projected in the foreground and background of the subcluster. To determine the contribution of undisturbed main cluster emission, we measured the surface brightness profile of the main cluster in a wedge to the southeast; this region is essentially the same region as that occupied by the subcluster, but reflected across the north-south axis of symmetry of the main cluster. We fit a $\beta$-model to the surface brightness at projected radii from 380 to 680 arcsec, which covers the range of radii containing the subcluster.

The main cluster surface brightness determined from this fit is shown as a dashed curve in Figure 4.5a. More than $\sim$40 kpc ahead of the cold front, the X-ray surface brightness is consistent with the undisturbed main cluster emission within the errors. However, there is some evidence for a rise in the surface brightness just ahead of the cold front; the four values at $\sim$0–40 kpc are all slightly higher than expected. This may indicate that the main cluster gas is compressed ahead of the subcluster and cold front, by a bow shock and/or by adiabatic compression.

To show more clearly the excess X-ray emission associated with the subcluster and any compression of main cluster gas ahead of the cold front, in Figure 4.5b we subtract the fit to the undisturbed main cluster emission from the surface brightness values in Figure 4.5a. In most of the region in front of the subcluster, there are only upper limits on the excess emission. There may be some excess emission just ahead of the cold front, but in the residual surface brightness profile only the point from $\sim$1–10 kpc appears to be significantly increased. In the residual profile, the surface brightness of the subcluster is relatively uniform except for the brighter cool core. Thus, the apparent fall-off in the surface brightness of the subcluster with increasing
distance from the cold front in Figure 4.5a may actually be due to projected main cluster emission.

We determined the gas densities in the regions around the cold front and subcluster by deprojection. We assumed different geometries for the subcluster and for the gas ahead of the cold front. For the densities inside the subcluster, we assumed the subcluster to be a cone opening up behind the cold front, with an opening angle determined from the image. We further assumed that this cone’s axis of symmetry lies in the plane of the sky. We determined the gas density well ahead of the cold front from the $\beta$-model fit to the surface brightness of the main cluster discussed above. We also assumed a spherically symmetric main cluster to do the deprojection. We used the deprojected gas densities and the temperatures from spectral fits to determine the pressures across the cold front.

4.4 Hydrodynamical Analysis of Merger

We now use the gas temperatures, densities, and pressures derived in § 4.3.3 to analyze the kinematics and hydrodynamics of the subcluster merger. Our treatment closely follows that in Vikhlinin et al. (2001a). A schematic view of the geometry of the flow of main cluster gas near the cold front is shown in Figure 4.6), which is adapted from Vikhlinin et al. (2001a). A bowshock will be present ahead of the cold front if the merger velocity of the cold front relative to undisturbed main cluster gas is supersonic. (There is also a shock in the cold front, but the shocked region will be very narrow if the cool core is much denser than the main cluster gas.) If the motion is subsonic, the flow around the cold front is continuous. For any blunt cold front, there will be a point in front of the cold front where the velocity of the main cluster gas is zero. This stagnation point is labeled “st” in Figure 4.6).
Fig. 4.6.— Schematic diagram of the flow of hot main cluster gas around a blunt cold front. A bowshock will be present ahead of the cold front if the merger is supersonic. The stagnation point is labeled “st”. Region 1 is unshocked gas of the main cluster; region 2 is gas which has passed through the bowshock (if present).
4.4.1 Stagnation Pressure at Cold Front

The ratio of the pressures in the main cluster gas far ahead of the cold front to that at the stagnation point, combined with temperature measurements of the gas, can be used to determine the velocity of the cold front (Vikhlinin et al. 2001a). Ideally, we would measure the pressure at the stagnation point in the hot gas. However, since the surface brightness of the hot gas at the stagnation point is actually quite low, we instead measure the pressure in the cool core just behind the stagnation point where the surface brightness is much higher. Because the cold front is a contact discontinuity and the gas is moving subsonically near the stagnation point, the pressure across the cold front is expected to be continuous. The pressure difference between the stagnation point and a point far upstream (region 1 in Figure 4.6) must be caused by compression of the gas in region 2 by a bow shock and/or adiabatic compression.

The ratio of the pressure at the stagnation point to the pressure in the far upstream region 1 is given by (e.g. Landau & Lifshitz 1959, §114)

$$\frac{P_{\text{st}}}{P_1} = \begin{cases} \frac{(1 + \frac{2-1}{2} \mathcal{M}^2)^{\frac{2}{2+1}}}{\mathcal{M}^2 \left( \frac{2+1}{2} \right)^{\frac{2}{2+1}} \left( \gamma - \frac{2-1}{2\mathcal{M}^2} \right)^{\frac{-2+1}{2+1}}} , & \mathcal{M} \leq 1, \\ \frac{1}{\mathcal{M}^2 \left( \frac{2+1}{2} \right)^{\frac{2}{2+1}} \left( \gamma - \frac{2-1}{2\mathcal{M}^2} \right)^{\frac{-2+1}{2+1}}} , & \mathcal{M} > 1. \end{cases}$$ (4.1)

Here $P_{\text{st}}$ and $P_1$ are the pressures at the stagnation point and in region 1, respectively and $\gamma = 5/3$ is the adiabatic index for a fully ionized plasma. $\mathcal{M} \equiv v_1/c_{s1}$ is the Mach number of the cold core, $v_1$ is the cold core’s velocity relative to the upstream gas, and $c_{s1}$ is the sound speed in that gas.

We do indeed measure a higher pressure inside the cold core as compared to the undisturbed gas in front of the core. The best fit measurement is $P_{\text{st}}/P_1 = 3.4$ which implies a Mach number of 1.4. The formal errors yield a wide range in allowable Mach numbers, from 0 to 3.3, but since not all the sources of error are independent, the
actual error is probably somewhat smaller. While a Mach number of zero is allowed, the morphology of the system makes such a value highly unlikely. In any case, the best fit value of the pressure ratio requires that the merger motions be slightly supersonic.

4.4.2 Possible Bowshock

For a supersonic cold core, a bow shock should also form in front of the cold core. Assuming that the density and temperature of the gas in region 1 is constant, the bowshock should have a predictable “stand-off” distance, $d_s$, which is the shortest distance from the stagnation point to the bow shock (Vikhlinin et al. 2001a). This distance can be calculated using the approximate method given by Moekel (1949), and depends only on the value of $\mathcal{M}$ and on the shape of the cold front. A useful plot of the stand-off distance versus Mach number is given in Sarazin (2002, Figure 4). For $\mathcal{M} \gtrsim 2$, the stand-off distance of the shock is not very sensitive to the value of $\mathcal{M}$, while for smaller Mach numbers the distance increases rapidly. For the best fit value of $\mathcal{M} = 1.4$, the expected stand-off distance is $d_s \sim 18$ kpc if we treat the cold front as a spherical surface with a radius of curvature of 19 kpc. Such a bowshock would compress the gas in region 2, and should produce a measurable increase in the X-ray surface brightness, $I_X$, in that region. A possible surface brightness excess is seen in the $\sim 20$ kpc immediately upstream from the cold front, but it is significant at only slightly greater than the $1.7\sigma$ level. While this surface brightness excess is not visible in the image of the cluster, we might expect such a feature to be more visible in profile given the significant azimuthal averaging done to create the profile.

Given enough source photons, the spatial resolution of Chandra would be sufficient to measure the expected stand-off distance of the bowshock, which corresponds to $\sim 5-15''$. However, the surface brightness in the hot gas ahead of the cold front is too low
to allow $d_s$ to be accurately determined from the available data. Thus, all we can
c conclude is that the expected values of the stand-off distance are consistent with the
(marginal) evidence for an increase in the X-ray surface brightness within $\sim 20$ kpc
of the cold front.

We can also use the Rankine-Hugoniot shock jump conditions at the putative
bowshock to independently determine the Mach number (e.g. Landau & Lifshitz 1959,
§85). The shock jump conditions yield

$$\frac{1}{C} = \frac{2}{\gamma + 1} \frac{1}{\mathcal{M}^2} + \frac{\gamma - 1}{\gamma + 1},$$

(4.2)

where $C \equiv \rho_2/\rho_1$ is the shock compression. Because we do not have spectra or
temperatures determined on the scale of the bowshock, we estimate the shock com-
pression from the small increase in the surface brightness as $C \approx (I_{X2}/I_{X1})^{1/2}$. The
observed surface brightness increase in the first 10 kpc is a factor of $\sim 1.7$, which im-
plies that $C \sim 1.3$. This implies $\mathcal{M} \sim 1.2$. It is likely that the finite resolution with
which the surface brightness contrast was determined and projection effects cause the
shock compression to be underestimated. Thus, this value for the Mach number is
consistent with that determined from the pressure increase at the stagnation point,
If we assume the Mach number determined by the stagnation condition $\mathcal{M} \sim 1.4$,
the expected shock compression is $C \sim 1.6$. Projection effects (if the cluster is not
moving in the plane of the sky) would cause us to overestimate the stand-off distance
and underestimate the Mach number. Projection could also cause us to inaccurately
determine the true shape of the cold front.
4.5 Merger Kinematics

Since it provides a consistent fit to the stagnation pressure, the bowshock compression, and the bowshock stand-off distance, we will adopt the merger Mach number of $\mathcal{M} \approx 1.4$. The sound speed in the upstream gas is $\approx 1540$ km s$^{-1}$, so a Mach number of 1.4 implies a merger velocity of $v \approx 2150$ km s$^{-1}$.

4.5.1 Kinematic Model

We now construct a kinematic model for the merger which is consistent with the X-ray and optical observations of the main cluster and subcluster. Because the errors on our determination of the Mach number are large, the parameters of this model are not well constrained. We therefore do not suggest that this model is the only possible interpretation of the data, but that it is merely a “toy model” that is adequate to explain the data given the best-fit values from the various hydrodynamic tests. The model, then, is presented as illustrative rather than interpretive, using the best-fit parameters from the hydrodynamic analyses as the primary constraints of the model. We also discuss the implications of this model for the merger.

The parameters of the model are shown in Figure 4.7. We will approximate the subcluster as a point mass with a single velocity relative to the main cluster. We will also assume that the mass of the subcluster is small relative to that of the main cluster, so we can treat the subcluster as a test particle falling into the extended mass distribution of the main cluster. We put the center of the main cluster at the center of our coordinate grid, and using polar coordinates, we define the $x$-axis to be parallel to North and the $z$-axis to be the line of sight, with the positive $z$-axis extending away from the observer. Let the vector $\vec{d}$ be the position the subcluster relative to the main cluster (direction from the main cluster to the subcluster). The components of $\vec{d}$ are
defined by its magnitude \(d\), the angle to the line of sight \(\theta_d\) (from the positive \(z\)-axis), and the position angle on the plane of the sky \(\phi_d\) measured counterclockwise from the north. Similarly, let \(\vec{v}\) be the velocity of the subcluster relative to the main cluster, with magnitude \(v\), and direction given by the angles \(\theta_v\) and \(\phi_v\). We also define \(\psi\) to be \(180^\circ\) minus the angle between \(\vec{d}\) and \(\vec{v}\).

On the X-ray image (Figure 4.1), the subcluster center is located at a position angle of \(\phi_d = 194^\circ\) from the main cluster. The position angle of the direction of motion, \(\phi_v\), is less certain, since the curvature of the cold front suggests \(\phi_v \sim -15^\circ\) whereas the body of the subcluster is more consistent with \(\phi_v \sim -58^\circ\). We will adopt the average value of \(\phi_v \approx -36^\circ\).

We can estimate the radial component of the relative velocity of the subcluster from the optical redshifts of the main cluster and subcluster. We will adopt the velocity of the subcluster cD galaxy as representative of the subcluster; in any case, it is most closely related to the cold front, which was used to derive the merger velocity. Beers et al. (1991) give the redshift of the subcluster cD galaxy as \(z = 0.05633 \pm 0.00012\), while the galaxies within 5′25 of the center of the cluster have a mean redshift of \(0.0538 \pm 0.0050\) (Durrett et al. 1998). Combining the line-of-sight velocity determined from the optical redshifts with the velocity merger velocity determined in § 4.4 from the X-ray data, we find that the direction of motion of the subcluster relative to the main cluster is between \(\theta_v = 63^\circ\) and \(76^\circ\) from the line of sight, or 14° to 27° from the plane of the sky. We adopt the average value of \(\theta_v \approx 71^\circ\).

It is difficult to determine the angle between the separation of the main cluster and subcluster, \(\vec{d}\), and the line-of-sight. Initially, we will assume that the main cluster and subcluster are separated in the plane of the sky (\(\theta_d = 90^\circ\)), so that the separation between the main cluster and cluster is equal to the projected separation, \(d = 730\) kpc.
Fig. 4.7.— Schematic diagram of the kinematic model. The position of the subcluster relative to the main cluster is given by the vector $\vec{d}$, and $\vec{v}$ is the velocity of the subcluster relative to the center of the main cluster. The $z$-axis is along the line-of-sight. The dashed lines are projections of the direction and velocity vectors onto the plane of the sky. The dotted line is parallel to the $N$-axis. The small inset shows the projection of the direction and velocity vectors onto the $N$-$z$ plane, with the dotted line parallel to the $z$-axis.
The angle between $\mathbf{d}$ and $\mathbf{v}$ is then $\psi = 53^\circ$, and the impact parameter of the merger is $b \approx 580$ kpc.

### 4.5.2 Infall Velocity

We now compare the merger velocity inferred from the hydrodynamics of the cold front and subcluster with the infall velocity expected for the subcluster and main cluster. Reiprich & Böringer (2002) derive a virial mass for the main cluster of $M_{200} = 1.080 \times 10^{15} M_\odot$ for a virial radius $r_{200} = 2.66$ Mpc. We will assume that the main cluster mass is much larger than that of the south subcluster. We will assume that the subcluster has fallen into the main cluster from its turn-around distance of 5.5 Mpc, which is the value if the age of the Universe is 13 Gyr. As noted above, we initially assume that the main cluster and subcluster are separated in the plane of the sky.

We will consider two models for the mass distribution and potential of the main cluster. We first consider a singular isothermal sphere out to the virial radius, which has a potential given by

$$\Phi(r) = -2\sigma^2 \times \begin{cases} 1 + \ln(r_{200}/r), & r \leq r_{200}, \\ r_{200}/r, & r \geq r_{200}. \end{cases}$$

Here, $\sigma = (GM_{200}/2r_{200})^{1/2} \approx 934$ km s$^{-1}$ is the velocity dispersion. The infall velocity at the subcluster’s current projected distance of 730 kpc is 2520 km s$^{-1}$. We also consider a model in which the density within the virial radius is given by the
Navarro, Frenk, & White model (1997, hereafter NFW), for which the potential is

$$\Phi(r) = \frac{-GM_{200}}{r_s} \times \begin{cases} \frac{\ln(1+x)}{x} - \frac{1}{x} - \frac{1}{r_s^c}, & r \leq r_{200}, \\ \frac{1}{x}, & r \geq r_{200}. \end{cases}$$

(4.4)

Here, $r_s$ is the scale radius, and $x \equiv r/r_s$. We adopt a concentration parameter $c \equiv r_{200}/r_s = 10$, which is consistent with NFW’s simulations for cluster-mass halos. For this potential, the predicted infall velocity at the projected distance is 2740 km s$^{-1}$.

For either potential, the infall velocity at the projected separation is somewhat larger than the velocity we determined from the X-ray observations of the merger hydrodynamics. Given the large errors in the determinations of the velocities, this difference may not be significant. As first noted by Markevitch et al. (1999a), the degree of agreement between the merger velocity determined by hydrodynamical measurements and that expected from infall can be used to test the hypothesis that the intracluster medium is predominantly a non-relativistic, thermal plasma. That is, the calculation of the merger velocity from shock conditions (equation 4.2) assumes that the merger shock energy is thermalized, and is not converted into relativistic particles, or magnetic fields, or turbulence. All of the hydrodynamic diagnostics require that the intracluster medium act as a $\gamma = 5/3$ gas. Thus, the difference between our hydrodynamical estimate of the merger velocity and the predicted infall velocity (assuming the main cluster and subcluster are separated in the plane of the sky) could suggest that the kinetic energy of the merger is not thermalized particularly efficiently, but instead goes partially into turbulence, magnetic fields, or relativistic particles. As noted by Markevitch et al. (1999a), this argument is somewhat circular, as the mass of the cluster was also determined from hydrostatic equilibrium assuming purely thermal pressure support. Given the uncertainties in the determination of
merger velocity and infall velocity, we will instead take the crude agreement between the two speeds as an indication that at least a significant fraction of the merger energy ($\gtrsim 50\%$) is thermalized.

Our initial estimate of the infall velocity was based on the assumption that the main cluster and the subcluster both lay in the plane of the sky ($\theta_d = 90^\circ$). If this is not true, the actual separation $d$ will be larger than the projected separation of 730 kpc, and the predicted infall velocity will be lowered. To illustrate this effect, we construct a consistent model for the merger geometry and kinematics in which the merger velocity equals the predicted infall velocity. As we move the subcluster farther out in the main cluster potential, the density and hence the pressure in the ambient medium drops, thereby increasing the pressure ratio used to determine the Mach number. This in turn increases the Mach number we would measure, lessening the need to place the subcluster significantly in front of or behind the main cluster.

Given the large errors in the two numbers, our model is certainly not a unique solution, but is consistent with the current best-fit values of the parameters. For the isothermal potential (equation 4.3), this consistent solution requires that $d \approx 820$ kpc, while for the NFW potential (equation 4.4) we find $d \approx 860$ kpc. The Mach numbers we derive are $\mathcal{M} = 1.6$ for the isothermal potential and $\mathcal{M} = 1.7$ for the NFW potential. The corresponding velocities are $v \approx 2460$ km s$^{-1}$ and $v \approx 2610$ km s$^{-1}$ respectively. For both solutions, we assume that the sound speed does not vary over the range of radii in question. If we were to allow the sound speed to vary, it would decrease slightly at larger radii, increasing the physical separation that we determine. To be specific, we will adopt the isothermal result. This distance implies that the angle between the separation and the line of sight is either $\theta_d \approx 64^\circ$ or $\theta_d \approx 116^\circ$. The former value implies that the $\psi \approx 66^\circ$, which means that the subcluster is moving
nearly perpendicular to the radius from the center of the main cluster, and about
to start exiting the cluster. The observed morphology of the X-ray image of the
subcluster seems inconsistent with this interpretation. Furthermore, the fact that the
cD galaxy in the subcluster is coincident with the center of the cold core and not
ahead of it implies that the ram pressure effects from the merger have not slowed
the cold core considerably. This further strengthens the argument that the merger
is still in a quite early stage, and is therefore probably falling into the main cluster
rather than exiting it. Thus, we adopt the solution with $\theta_d \approx 144^\circ$ and $\psi \approx 46^\circ$, in
which the subcluster is moving into the main cluster, probably for the first time. In
summary, our consistent kinematic model has $v \approx 2460$ km s$^{-1}$, $\theta_v \approx 71^\circ$, $\phi_v \approx -36^\circ$,
$d \approx 820$ kpc, $\theta_d \approx 116^\circ$, $\phi_d \approx 194^\circ$, and $\psi \approx 46^\circ$. The subcluster is closer to us than
the main cluster, and is falling into the main cluster.

4.5.3 Angular Momentum and Impact Parameter

As noted above in § 4.3.1, the direction of the merger velocity is not parallel to
the separation of the centers of the main cluster and subcluster. The transverse
component of the merger velocity lies at an angle of $\sim 50^\circ$ with respect to the projected
separation of the two clusters. This implies that this is an offset merger; the collision
is occurring with a nonzero impact parameter and angular momentum. If we adopt
the consistent model for the merger kinematics which we have just discussed, the angle
between the velocity and the separation is $\psi \approx 46^\circ$, and the impact parameter for
the collision is $b = d \sin \psi \approx 750$ kpc. This is 3.7 times the core radius we determine
from a $\beta$-model fit to the cluster.

A useful dimensionless form for the angular momentum is given by the $\lambda$ param-
eter, defined as (Peebles 1969)
\[ \lambda \equiv \frac{J|E|^{1/2}}{GM^{3/2}}. \] (4.5)

Here \( J \) is the total angular momentum of the merged cluster, \( E \) is its total energy, and \( M \) is its mass. We estimated the value of \( \lambda \) implied by the merger velocity and impact parameter of the subcluster by differentiating equation (4.5), assuming the mass of the subcluster is much smaller than that of the main cluster. We assumed that the orbital angular momentum of the subcluster was parallel to the initial angular momentum of the main cluster, and ignored the initial internal angular momentum of the subcluster. Using the kinematic parameters for our consistent model for the merger, we find \( \lambda \approx 0.21 \). Fixing \( v, \theta_v \), and the projected angles \( \phi_d \) and \( \phi_v \) at the values from the consistent model, and allowing the value of \( \theta_d \) to vary, we find a minimum value of \( \lambda \) of about 0.16. If the initial spin of the main cluster is not aligned with the orbital angular momentum of the subcluster, the value of \( \lambda \) would be an upper limit. These values are both somewhat larger than the median values of 0.05–0.1 expected from tidal effects in large scale structure. This may reflect the large uncertainties in the kinematic parameters. If this large angular momentum is correct, it might be the result of tidal effects associated with the triple merger occurring in Abell 85 (i.e., the fact that there are two merging subclusters). Alternatively, it may be that mergers with small subcluster have a larger range of values of \( \lambda \), which average out when many small subclusters merge to form a larger halo.
4.6 Thermal Conduction and Kelvin-Helmholtz Instabilities at the Cold Front

4.6.1 Suppression of Conduction Across the Cold Front

As discussed in § 4.3.1, the cold front is seen as a sharp surface brightness discontinuity, with a dramatic increase in surface brightness in the cold gas over only a few kiloparsecs. From the surface brightness profile in Figure 4.5, the change in surface brightness occurs over at most 20 kpc—half the width of the elliptical region on the cold core or the width of about 2 bins ahead of the cold front. The raw image suggests that it is actually quite a bit narrower than this, but we are limited by photon statistics to the aforementioned resolution. Unfortunately, the same photon statistics prevent us from measuring the temperature gradient on this size scale. However, because the pressure is continuous across the cold front, the observed density gradient should be accompanied by a temperature gradient of the opposite sign and with the same length scale. Therefore, while the width of the gradient is determined from the surface brightness, we can assume that the same width applies to the temperature gradient. Thermal conduction should smear out any such sharp edges to a length a few times the electron mean free path in a relatively short time. However, conduction appears to be suppressed in the case of Abell 85, as it does in other clusters with observed cold fronts (e.g. Abell 2142, Abell 3667; Ettori & Fabian 2000; Vikhlinin et al. 2001a).

Ettori & Fabian (2000) showed that thermal conduction should smear out the temperature gradient to a width $\delta r$ on a characteristic timescale

$$
\delta \tau = \frac{\delta r}{\bar{v}},
$$

(4.6)
where
\[
\bar{v} = \frac{2 \kappa}{3 n_e k_B T_e} \frac{d(k_B T_e)}{dr}
\] (4.7)
is the characteristic velocity of the diffusion. Here,

\[
\kappa = 8.2 \times 10^{20} \left( \frac{k_B T_e}{10 \text{ keV}} \right)^{5/2} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ keV}^{-1}
\] (4.8)
is the thermal conductivity, and \( n_e \) and \( T_e \) are the electron number density and temperature, respectively. For the upper limit on the width of the cold front of 20 kpc, the diffusion timescale is \( 2.0 \times 10^6 \) yr.

At the subcluster’s current velocity and distance from the cluster center, the relevant timescale for interaction is roughly \( d/v \approx 5.6 \times 10^8 \) yr. This means that in order for thermal conduction to have failed to erase the sharp edge of the cold front, conduction must be suppressed by at least a factor of 280. In fact, since the rate of conduction is independent of density, the time over which conduction has had a chance to act is probably somewhat longer, meaning that the degree of suppression is probably even higher.

One mechanism that has been suggested for this suppression is the existence of a magnetic field perpendicular to the direction of diffusion, i.e. parallel to the surface of the discontinuity (Vikhlinin et al. 2001a). A tangled magnetic field would serve the same purpose, with a maximum loop size equal to the width of the front. The former type of field would also serve to suppress hydrodynamic instabilities, as discussed in the following section.
4.6.2 Kelvin-Helmholtz Instability

Unlike the cold fronts observed in Abell 2142, Abell 3667, and RX J1720.1+2638 (Markevitch et al. 2000; Vikhlinin et al. 2001a; Mazzotta et al. 2001), the cold front in Abell 85 does not have a long, continuous, smooth leading edge (Figure 4.2). Rather, the cold core protrudes slightly from the surrounding subcluster gas, and the trailing edges to the sides of the cold front are not well defined. This might be due to differences between the size of the subcluster in Abell 85 and those in the other clusters. However, the X-ray image suggests that the edges of the subcluster in Abell 85 are both more diffuse and have smaller scale structure than in some of the other cases. This suggests the presence of an instability in the gas. The structure of the subcluster is swept back, indicating that ram pressure plays an important role in the shape of the subcluster. Then, one might expect that Kelvin-Helmholtz (KH) instabilities could occur. We will consider the stability of the cool core and surrounding subcluster separately; the X-ray image (Figure 4.2) suggests that the leading edge of the subcluster is irregular and unstable, but that the cold core may be more regular.

We first consider the cold core. Following the analysis of Fujita et al. (2002), in the presence of a gravitational field the cold front will be KH unstable to perturbations of wavenumber $k \sim 2\pi/r_c$ if the velocity of the front, $U$, satisfies the relation (e.g. Fujita et al. 2002, and references therein)

$$ U \gtrsim \sqrt{\frac{k_B T_c D^2 - 1}{\pi \mu m_H D}}, $$

(4.9)

where $r_c$ is the radius of curvature of the cold front, $T_c$ is the temperature of the cold core, $\mu = 0.61$ is the mean molecular weight, and $D = \rho_c/\rho_h$ is the ratio of the...
density in the cold core to that in the surrounding hot medium. For $D = 19$ (see Figure 4.5) and $T_2 = 2.1$ keV, the maximum velocity to avoid being affected by KH instabilities is $\sim 1400$ km s$^{-1}$. As this value is well below the inferred velocity of 2150 km s$^{-1}$, the front itself should be KH unstable in the absence of some other stabilizing mechanism.

The growth rate of such an instability of wavenumber $k$ is given by (e.g. Fujita et al. 2002, and references therein)

$$\omega = k \frac{D^{1/2}U}{1 + D}. \quad (4.10)$$

The timescale for this instability, $t_{KH} = 2\pi/\omega$, is a mere $4.0 \times 10^7$ yr for the large relative velocity of the subcluster through the ICM. As noted in §4.6.1, it is likely that the merger has been going on for roughly $5.6 \times 10^8$ yr. The fact that such an instability has not developed on the scale of the cold core thus requires that it be suppressed by some other mechanism. It should be noted that equation 4.10 gives the timescale in the absence of gravity. The expression including gravity reduces to this form when the perturbations become large, that is, when gravity becomes unimportant. In this case, where the instability timescale is an order of magnitude less than the interaction timescale, gravity would indeed be unimportant in the absence of a mechanism for suppressing the growth of instabilities.

One possible mechanism for suppressing the KH instability is surface tension from a magnetic field parallel to the interface between the hot and cold gasses. (For a detailed discussion and derivation, see Vikhlinin et al. 2001b.) The front is particularly sharp over an angle of $2\varphi \approx 80^\circ$. To determine the flow velocity along the surface of the cold front as a function of the angle $\varphi$, we extend an argument given by Vikhlinin et al. (2001b). They noted that the velocity for incompressible flow around a sphere
varied as \( v_c \propto \sin \varphi \), and proposed that this relation be extended to transonic compressible flows to give \( \mathcal{M}_c(\varphi) \propto \sin \varphi \). Here, \( v_c \) and \( \mathcal{M}_c \) are the velocity and Mach number of the flow along the cold front. For a Mach number of \( \mathcal{M} = 1.05 \), they found that \( \mathcal{M}_c(\varphi) \approx 1.1 \sin \varphi \) gave a reasonable fit to a numerical simulations of the flow. To extend this to other values of \( \mathcal{M} \), we note that the location of the sonic point on the surface of a smooth object is approximately the point where the tangent to the surface is at the maximum deflection angle for a supersonic flow, \( \chi_{\text{max}}(\mathcal{M}) \) (Moekel 1949; Landau & Lifshitz 1959, Fig. 51). For a spherical cold front, this suggests that the flow around the cold front should be roughly \( \mathcal{M}_c(\varphi) \approx \sin \varphi / \cos \chi_{\text{max}} \).

Using this approximation to scale from the fit in Vikhlinin et al. (2001b), we find \( \mathcal{M}_c(\varphi) \approx 1.2 \sin \varphi \) for \( \mathcal{M} \approx 1.4 \). Thus, at the end of the regular region (\( \varphi \approx 40^\circ \)), the Mach number of the flow around the cold front is about \( \mathcal{M}_c \approx 0.77 \).

If the magnetic pressure is much less than the gas pressure or if it is a constant fraction of the gas pressure on both sides of the interface, Vikhlinin et al. (2001b) show that the interface will be stable if

\[
\frac{B_h^2}{8\pi} + \frac{B_c^2}{8\pi} > \frac{\gamma \mathcal{M}_c^2}{2(1 + T_c/T_h)} p, \tag{4.11}
\]

where \( B_h \) and \( B_c \) are the magnetic field strengths in the hot and cold regions respectively, \( T_h \) and \( T_c \) are the hot and cold temperatures, and \( p \) is the gas pressure. For \( T_c \) equal to the temperature of the cold core and \( T_h \) set to the mean cluster temperature at the radius of the subcluster, the sum of the magnetic pressures must be

\[
(B_h^2 + B_c^2)/8\pi > 0.4 p. \tag{4.12}
\]
For the stagnation point pressure derived above,

\[
\frac{(B_h^2 + B_c^2)}{8\pi} > 5 \times 10^{-11} \text{ dyn cm}^{-2}. \tag{4.13}
\]

The larger of the two fields must be responsible for at least half of the total magnetic pressure, so the greater of the two magnetic field strengths must be, at minimum, \( B > 8 \mu \text{ G} \) in order for KH instability to be suppressed.

A magnetic field of this magnitude might not be surprising at this location, as it is in the center of a cooling flow where there is likely to have been recent AGN activity (see § 4.7). One concern is that this field will make a contribution of \( \gtrsim 20\% \) to the gas pressure in the region, and this could contradict our previous assumption that the magnetic pressure is small compared to the gas pressure.

Calculating the instability criteria for the subcluster as a whole, we find similar results. The temperature is more than a factor of two higher, but the density contrast is a factor of four lower \((D = 5.5)\), so the maximum speed to avoid KH instability drops to 1200 km s\(^{-1}\), well below the subcluster's velocity. Because of the larger size scale, the instability timescale grows to \( 2 \times 10^8 \text{ yr} \), which is probably just short enough for the instability to have developed. Unlike at the leading edge of the cold core, however, the KH instability does not appear to be suppressed over the rest of the subcluster. As with the cold core, the suppression of the KH instability by a magnetic field would require a nontrivial magnetic pressure in the cluster or subcluster gas. The fact that the KH instability appears to have acted on the main body of the subcluster may indicate that the strong magnetic fields are concentrated in the cold core, rather than the surrounding subcluster or main cluster gas. As noted above, the strong magnetic fields in the cold core could be the result of a cooling flow or the action of the AGN in the cD galaxy.
4.7 Subcluster/Radio Source Interaction

The possible existence of a large scale radio halo or relic in the southern subcluster in Abell 85 was raised by Bagchi et al. (1998). As shown in Figure 4.8, the diffuse emission was later resolved by Giovannini & Feretti (2000) into what may be a tailed source associated with a dead or dying AGN in the dominant galaxy of the subcluster, where the nuclear emission is very faint compared to the radio lobes. If this is in fact its origin, the shape of the tail is well explained by the merger interaction. Figure 4.8 shows that the source associated with the cD galaxy in the subcluster (Source D) has possible weak nuclear emission, and a lumpy C-shaped extended source to the southeast of the cD galaxy. The radio emission has no significant extent north of the subcluster’s leading edge, and the bulk of the radio emission follows the bright X-ray arc through the subcluster. If it is indeed a tailed galaxy, this shape implies that the same ram pressure forces which have shaped the subcluster have also bent the lobes of the AGN into their current shape.

An alternative explanation for the diffuse radio emission is that this is a small, merger-induced halo in the subcluster. The fact that its surface brightness correlates roughly with that of the X-ray gas is consistent with findings for other halos, as is its steep spectral index ($\alpha_{0.3}^{1.4} \sim 2-2.5$; Giovannini & Feretti 2000). On the other hand, the radio source is quite overluminous compared to the expected radio power derived from the empirical relation between X-ray temperature or luminosity and radio halo power (Liang et al. 2000; Feretti 2000). For the observed X-ray luminosity of the subcluster of $5 \times 10^{43}$ erg s$^{-1}$ (rest frame 0.1–2.4 keV), the empirical relation would require a monochromatic radio power of only $4 \times 10^{21}$ W Hz$^{-1}$ at 1400 MHz in the cluster rest frame, compared to the observed value of $1.8 \times 10^{24}$ W Hz$^{-1}$ (Feretti, private communication) Furthermore, halos have previously only been observed in
Fig. 4.8.— Radio contour map at 90 cm of the “B” and “D” sources (from Giovannini & Feretti 2000) in the region of the southern subcluster, overlaid on the adaptively-smoothed Chandra image of the subcluster (color, from Figure 4.2). The D source appears to be associated with the cD galaxy in the south subcluster, while the B source is associated with another cluster galaxy.
the hottest and most massive clusters, never in a cluster as small and cool as this subcluster. While previous observations may have been biased towards finding halos in hot clusters (Kempner & Sarazin 2001), it would nonetheless be surprising to find a halo in such a cool, low luminosity cluster. Our observations are therefore more consistent with the interpretation of the source being a tailed radio galaxy (Giovannini & Feretti 2000) than with it being a radio halo or relic.

Source “B” in Figure 4.8 is a narrow angle tail (NAT) source studied in detail by Odea & Owen (1985). It has a redshift of $z = 0.0579$ (Wegner et al. 1999), which is within the dispersion of the main cluster. Since the line of sight component of the subcluster’s infall velocity is so small, however, it is not possible to determine whether or not this galaxy is a member of the subcluster or of the main cluster based solely on radial velocity information. The direction of the tail, plus the fact that the radio tail does not appear to be interacting with the flow around the subcluster, suggest that it is seen in projection in front of or behind the subcluster, and that it is a member of the main cluster.

4.8 Summary

Our analysis of the south subcluster in Abell 85 from $\sim 37$ ksec of Chandra data has revealed several interesting features. The most obvious is a confirmation that the subcluster is indeed merging with the the main cluster. The subcluster contains a remnant cold core which has survived the early stages of the merger. It is smaller and more discrete than similar structures found in other clusters such as Abell 2142 (Markevitch et al. 2000), Abell 3667 (Vikhlinin, Markevitch, & Murray 2001a), and RX J1720.1+2638 (Mazzotta et al. 2001), and is perhaps more akin to the “bullet” in 1E0657-56 (Markevitch et al. 2002) or the “tongue” seen in Abell 133 (Fujita et al.
2002).

Based on the ratio of the pressure at the stagnation point of the cold front to that far upstream, on the standoff distance of a possible bow shock, and on the shock compression from the bow shock, we find a consistent Mach number and velocity for the merger of $\mathcal{M} \approx 1.4$ and $v \approx 2150 \text{ km s}^{-1}$. By comparing this velocity to the radial velocity of the subcluster relative to that of the main cluster, we have determined that the merger velocity is about $19^\circ$ from the plane of the sky. We find a consistent kinematic model for the merger in which the subcluster is in front of and falling into the main cluster. This model is consistent with the expected merger velocity if the subcluster and main cluster have fallen towards one another due to gravity from their turn-around distance in the Hubble flow.

The X-ray observations indicate that this is an offset merger with a finite impact parameter and a significant angular momentum. A crude estimate based on our consistent kinematic model suggests an angular momentum parameter of $\lambda \sim 0.2$, which is somewhat larger than the median values expected due to tidal torques.

We have also examined the possibility of hydrodynamic instability on the leading edges of the subcluster and found that the observed nonlinearities on the leading edges are consistent with the expected development of Kelvin-Helmholtz instability. The smoothness of the leading edge of the cold core is likely due to suppression of this instability by magnetic fields. The magnetic fields in the cold core may be high as a result of a cooling flow or the AGN located in the central cD galaxy.

Magnetic fields may also be responsible for suppressing thermal conduction across the cold front. This would explain the sharpness of the front, which should be smeared out by conduction in the absence of a magnetic field.

We confirm the assertion that the diffuse radio structure in the subcluster is not
a cluster radio halo or relic, but is more likely to be a tailed galaxy with a weak or
dead nucleus. We also show that its morphology has been shaped by ram pressure in
the merger interaction.

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Chapter 5

Abell 2034
Abstract

We present an analysis of a Chandra observation of Abell 2034. The cluster has multiple signatures of an ongoing merger, including a cold front and probable significant heating of the intracluster medium above its equilibrium temperature. We find no evidence for the large cooling rate previously determined for the cluster, and in fact find it to be roughly isothermal out to a radius of \( \sim 700 \) kpc. The hydrodynamics of the cold front provides several diagnostics for determining the Mach number of the merger, which we measure to be \( \mathcal{M} = 1.5 \pm 0.5 \), or \( 2200 \pm 700 \) km s\(^{-1}\). We also find that conduction across the cold front must be suppressed by a factor of at least 250. We suggest that emission to the south of the cluster, which was previously thought to be a merging subcluster, is actually a moderate redshift \( (z \approx 0.7) \) background cluster in projection against Abell 2034.
5.1 Introduction

Clusters of galaxies are bright X-ray sources, with typical bolometric luminosities of clusters range from $10^{43}$ to $10^{45}$ erg s$^{-1}$. In the standard hierarchical model of cluster formation, larger clusters are formed by hierarchical accretion of smaller clusters. Occasionally, two clusters of roughly equal mass will merge. These major mergers are expected to have significant effects on the intracluster medium (ICM). Effects include low Mach number shocks, which significantly heat the ICM. While strong, centrally condensed cooling flows are anticorrelated with major mergers, merger shocks are too weak to completely disrupt cooling flows at the centers of clusters. Consequently, cold cores of gas which are the remnants of cooling flows have been observed to be moving supersonically through the ICM of several clusters (e.g. Abell 2142, Abell 3667; Markevitch et al. 2000; Vikhlinin et al. 2001a). In principle, these thermal effects should all be visible in X-rays: the shocks as abrupt increases in the entropy of the X-ray emitting gas, and cold cores as regions of high density, cold gas.

The survival of these cold cores during the merger process has been one of the most significant discoveries in the area of cluster research made by Chandra. Prior observations did not have the spatial resolution to resolve these cold cores of gas from the surrounding hotter gas. The leading edges of these cold cores, dubbed “cold fronts,” are contact discontinuities, where the pressure gradient from the hot gas to the cold gas is continuous. The abruptness of the temperature change over the small distance of these fronts means that transport processes (diffusion) across the fronts must be suppressed (Vikhlinin et al. 2001b; Ettori & Fabian 2000).

Abell 2034 is a moderate redshift cluster at $z = 0.113$ (Struble & Rood 1999). Previous observations of the cluster with ASCA and ROSAT have found, respectively, a cooling flow-corrected temperature of 9.6 keV (White 2000) and a bolometric lumi-
nosity of $2.2 \times 10^{45}$ erg s$^{-1}$ (David, Forman, & Jones 1999). Optically, it is quite rich (ACO richness class 2; Abell, Corwin, & Olowin 1989). It has a cD galaxy which is offset $\sim 1'$ from the X-ray centroid and $2.5'$ from the optical centroid of the cluster. The relative displacements of the cD galaxy, average galaxy position, and center of the X-ray gas distribution suggest that the cluster is out of equilibrium. Indeed, non-equilibrium features were seen in the cluster in a pointed ROSAT observation; the unpublished ROSAT PSPC image is presented below (Figure 5.3). It showed an excess of emission to the south of the cluster center which was suspected to be a merger shock. Also visible in the ROSAT image was a surface brightness discontinuity to the northeast of the cluster center, opposite the suspected merger shock. The detection of a radio relic near the position of the northeast discontinuity (Kempner & Sarazin 2001) strengthens the case for the cluster being out of equilibrium due to a recent or ongoing merger.

Despite these pieces of evidence for a merger, Abell 2034 has also been reported to have a large cooling flow with a cooling rate of $\sim 90$–580 $M_\odot$ yr$^{-1}$ (White 2000). Usually, large cooling flows are strongly anti-correlated with major cluster mergers (Buote & Tsai 1996). Thus, ASCA and ROSAT observations did not lead to a consistent picture of the dynamical state of this cluster. Higher spatial resolution observations with spatially resolved spectra and a broad X-ray band (given the high temperature) were needed.

This makes Abell 2034 an interesting target for a Chandra observation, particularly since it is located at a sufficiently large redshift that most of the center of the cluster can be imaged with the ACIS-I camera. In this paper, we present the results of such an observation. All errors are quoted at 90% confidence unless otherwise stated. We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout this paper. Abell 2034 has
a redshift $z = 0.113$, so $1' \approx 160$ kpc.

## 5.2 Observation and Data Reduction

Abell 2034 was observed on 2001 May 5 in a single 54 ksec exposure. The data were taken in Very Faint (VF) mode using the four ACIS-I chips and the S-3 chip. The focal plane temperature was $-120$ C, the frame time was 3.2 s, and only events with ASCA grades of 0,2,3,4, and 6 were analyzed. The S-3 chip was used to check the background during the observation; no background flares were observed. A binned image, uncorrected for background or exposure, is shown in Figure 5.1.

Although the data were taken in VF mode, we did not apply the additional correction to the quiescent background that is made possible by the added event island information inherent in VF mode\(^1\). Our reason for this was the lack of availability of good background data in VF mode. The cluster extends over most of the detector, so we were unable to use the local background for either our spectral analysis or our surface brightness analysis, both of which require accurate background subtraction. Thus, we determined the background using the blank sky background files included in the Chandra Calibration Database\(^2\). These blank sky background files do not include data from very faint mode with the extra quiescent background reduction applied. For the data analysis, we used the original data without the additional background reduction.

\(^1\)http://cxc.harvard.edu/cal/Links/Acis/acis/Calprods/vfbkgnd/index.html

\(^2\)http://asc.harvard.edu/caldb/
Fig. 5.1.— Raw X-ray image of Abell 2034 in the 0.3–10 keV band, uncorrected for background or exposure. All four ACIS-I chips are shown; the regions of reduced exposure are the interchip gaps. This image was binned by a factor of 4, so the pixels in the binned image are each approximately $2'' \times 2''$. 
5.3 X-ray Image

The raw *Chandra* image, binned by a factor of 4 and uncorrected for background or exposure, is shown in Figure 5.1. At its moderate redshift, Abell 2034 fills much of the ACIS-I detector on *Chandra*. The cluster was positioned on the detector so that the aimpoint would be about halfway between the cD galaxy and the centroid of the X-ray emission as determined from the *ROSAT* image. The image shows several interesting features in the cluster itself, and a number of point sources.

A smoothed image of the diffuse emission is shown in Figure 5.2. Point sources were removed from the raw image using the *dmfilth* tool from the CIAO software package\(^3\). The image was then smoothed using a Gaussian with $\sigma = 2$ binned pixels. Blank sky background and exposure images were smoothed using the same kernel, and were then used to correct the smoothed raw image.

As can be seen in Figures 5.1 and 5.2, the cluster has significant emission out to a distance of $5'-6'$ in all directions. There is a sharp discontinuity in the surface brightness $\sim 3'$ to the northeast of the cluster center. We will refer to this feature as the “northeast cold front.” It is discussed in detail below (§5.5). This feature was seen in the earlier *ROSAT* image (Figure 5.3; the image was corrected for background and exposure using the *ROSAT* extended object analysis tools by S. Snowden\(^4\)). This feature was one of the motivations for observing this cluster with *Chandra*. Based on the *ROSAT* observations, which provided no useful information on the X-ray spectra near this feature, we had interpreted this feature as a possible merger shock.

Also visible in the raw and smoothed X-ray images is an excess of emission to the south of the cluster center. We will refer to this region as the “south excess;” it is discussed in more detail below (§ 5.4). This feature was also seen in the earlier

\(^3\)http://asc.harvard.edu/ciao/
\(^4\)ftp://legacy.gsfc.nasa.gov/rosat/software/fortran/sxrb/
Fig. 5.2.— X-ray image of Abell 2034 in the 0.3–10 keV band with point sources removed, smoothed with a Gaussian having $\sigma \approx 4''$. It has been corrected for exposure and for background. The region shown is the same as Fig. 5.1.
Fig. 5.3.— ROSAT image of Abell 2034 in the 0.5–2.4 keV band, corrected for background and exposure. The contours show levels of constant surface brightness, with square-root spacing.
\textit{ROSAT} image (Figure 5.3), where it appeared as a rather distinctive arc of emission running from the southeast to the northwest. We believe that this feature may be a merger shock cutting across the cluster. The extensions of this arc in the \textit{ROSAT} image are due, at least partially, to unresolved point sources seen in the \textit{Chandra} image. Because \textit{Chandra} is able to better resolve these distinct regions of emission and separate out point sources, the south excess appears as a fairly regular region of diffuse emission rather than as the arc which we believed to see in the \textit{ROSAT} image (Figure 5.3).

The cluster does not have a particularly sharply peaked core, suggesting that it does not contain a strong cooling flow. The core of the cluster has a somewhat irregular structure. The central arcminute or so is shaped like a curved teardrop, with the brightness peak centered on the broad end of the teardrop, to the north of center. Outside of 1', the cluster becomes more regular and circular. This structure is clearly visible in the contours in Figure 5.4.

An optical image of the Digital Sky Survey (DSS) is shown in Figure 5.4. Note that the cD galaxy which is the brightest cluster member is not located at the peak in the X-ray surface brightness, but is \sim 77'' south of the peak. There is a smaller peak in the X-ray surface brightness which does coincide with the central cD galaxy.

A very bright cluster galaxy, also classified as a cD, is located NNW of the X-ray peak near the location of the northeast cold front. There are several other bright elliptical galaxies in this neighborhood, and numerous fainter galaxies. In fact, the number of moderately bright to faint galaxies in this region significantly outnumbers that in the region of the more central cD galaxy. The majority of these galaxies are north, or ahead, of the cold front, perhaps suggesting that the collisionless galaxies have moved ahead of the collisional gas, which has been slowed during the merger.
Fig. 5.4.— Digital Sky Survey II (DSS2) R-band optical image of the same region as shown in Figures 5.1 and 5.2. Contours of the Chandra X-ray image are superposed. The surface brightness contours are linearly spaced, ranging from $1.6 \times 10^{-5}$ to $1.8 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$, and are smoothed on a scale of 16 pixels.
There is a significant excess of X-ray emission just inside the cold front, as discussed later in §5.3.1.

There are no bright galaxies and no obvious excess in the galaxy density evident in the DSS image of the region covered by the south excess. A several faint galaxies (R~17) are visible on the western edge of the south excess, two of which are associated with the wide angle tail radio galaxy FIRST J150957.2+332716 and the narrow angle tail radio galaxy FIRST J150959.5+332746. The latter is also visible as an X-ray source in the Chandra image.

The bright X-ray source to the NE of the cluster is 1RXS J151040.8+333515, a BL Lac at the redshift of Abell 2034 (Schwope et al. 2000), which is also a radio source (Bauer et al. 2000). The faint source at R.A. = 15h09m40s, Dec. = +33 deg 30'34") is identified with a moderately bright galaxy and is also an infrared source (2MASXJ1509401+333040). Several of the other X-ray point sources appear to be associated with faint optical sources, some of which have been identified as USNO-A2 sources, and most of which do not appear in any catalog. A total of 53 point sources were identified in the Chandra image.

### 5.3.1 Radial Gas Distribution

The X-ray image of Abell 2034 shows a number of strong features which suggest that the cluster may not be relaxed. These include the northeast cold front, the south excess, the lumpy structure near the center, and the displacement of the central cD galaxy from the X-ray peak. Despite these local irregularities, the radial surface brightness profile of the cluster is fairly consistent over most azimuthal angles.

We determined the radial surface brightness profile in 5 sectors where the cluster is approximately circularly symmetric within each sector. The sectors and annuli
Fig. 5.5.— Gaussian smoothed X-ray image of Abell 2034 overlaid with the sectors used for fitting radial surface brightness and temperature profiles. All point sources have been removed.

used to extract the surface brightness profile are shown in Figure 5.5. The annuli were selected to have between 1000 and 2000 source counts per annulus in order to produce reasonable spectral fits. This meant that for the purposes of the surface brightness analysis presented here they had a much higher flux than was necessary. In Figure 5.6, we show the radial surface brightness profiles in these five sectors. The sectors’ common origin is the approximate centroid of the cluster emission. A \( \beta \)-model fit to the sum of these profiles yields the best-fit core radius of \( r_c = 280 \pm 10 \) kpc and
slope of $\beta = 0.67 \pm 0.01$ (1-σ errors). We could not find any previously published values for these parameters for comparison. This model provides a reasonably good fit to all of the inner regions of the sectors except for the one encompassing the northeast edge, plotted in red in Figure 5.6. This particular sector shows an excess of emission immediately inside the edge and a smaller deficit outside, but at smaller and larger radii is reasonably consistent with the profiles in the other sectors.

The two sectors in the south half of the cluster have a noticeably flatter profile with brighter emission at large radii due to the south excess region. It is particularly
noticeable in the southwest quadrant where most of the excess emission lies. The south excess may in fact be a separate, possibly more distant cluster seen in projection against Abell 2034, as we discuss in detail in §5.4.

5.3.2 Spectral Properties

To test the previous report using data from ASCA of a large cooling flow in Abell 2034, we extracted a spectrum from a circular region with radius equal to the core radius determined in §5.3.1. We fit it with a single temperature MEKAL model (Kaastra 1992; Liedahl, Osterheld, & Goldstein 1995), and then with a single temperature plus a cooling flow. In both cases we fixed the absorption to the Galactic value of $1.58 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The single temperature fit determined a temperature of $10.71 \pm 0.70$ keV, and an abundance of $0.27 \pm 0.10$ times solar, with $\chi^2/d.o.f. = 1.4$. The addition of a cooling flow component, with the minimum temperature set to essentially zero and the maximum temperature and abundance tied to the values of the single-temperature component, did not improve the fit significantly. The resultant cooling rate was determined to be $\leq 2.4 M_\odot$ yr$^{-1}$, consistent with no cooling at all. In short, we find no evidence for a centrally condensed cooling flow. It is likely that the large cooling rate measured by White (2000) was due to the presence of cooler gas in the cold front (see §5.5) and in the south excess (see §5.4) rather than in a classical cooling flow in the cluster core.

We extracted spectra in the same sectors as were used in §5.3.1, and fit them with a single temperature MEKAL model. For the initial spectral fits, we fixed the absorption at the Galactic value. We first allowed only the temperature and normalization to vary, with the abundance fixed at the mean value of $0.17$ times solar determined by ASCA (White 2000). We then allowed the abundance to vary and
re-fit the spectra. The results of these fits are shown in Figure 5.7.

With the exception of the southwest quadrant, where contamination from the south excess is significant at large radii, we find no evidence for a large scale temperature gradient like that seen in some clusters (Markevitch et al. 1998). The temperature gradients reported by Markevitch et al. (1998), however, were generally at radii $\lesssim 1$ Mpc, whereas our temperature profiles are only significant out to $\sim 700$ kpc.

### 5.3.3 Mass Distribution

Combining the surface brightness and temperature profiles from above, we produce two mass profiles of the cluster in each of the five sectors: a profile of the gas mass, and a profile of the total gravitational mass. The gas mass is determined primarily by the surface brightness profile, which is deprojected under the assumption that the cluster is spherically symmetric. The temperatures from the variable-abundance fits were used to derive the emissivity. The gravitational mass is calculated by deriving the pressure in each concentric annulus and applying the condition of hydrostatic equilibrium to derive the necessary mass interior to the given shell. The gravitational and gas masses are plotted in Figure 5.8.

As can be seen from the figure, the gas masses determined from the different sectors are quite consistent. This should not be surprising given the similarities between the surface brightness profiles. The gravitational mass profiles are not as well determined as those of the gas mass, for several reasons. The first is the scatter in the temperature measurements, which contribute directly to the pressure calculations. Furthermore, the calculation of the gravitational mass assumes that the cluster is in hydrostatic equilibrium. Since it is undergoing a merger and shows evidence of relative motion between the gas in different parts of the cluster, such as the cold front
Fig. 5.7.— Parameters of single temperature fits to concentric annular wedges. The top panel is the temperature profile with abundance fixed at $0.17\ Z_\odot$. The middle and bottom panel are, respectively, temperatures and abundances for the fits where both were free parameters. The colors of the data points correspond to the same sectors as in Figure 5.6. There were not enough source counts to do the spectral analysis in the outer most annulus in either the north or northwest sectors. The $y$-axis error bars have been shifted slightly from the bin centers so as not to obscure each other; the black points are unshifted.
Fig. 5.8.— Gravitational mass (top panel) and gas mass (bottom panel) interior to the radius at which the mass is plotted. The colors correspond to the same sectors as in the previous figures. Where the pressure in a given annulus was found to be greater than the pressure in the annulus immediately interior to it, no data are plotted. The $y$-axis error bars have been shifted slightly from the bin centers so as not to obscure each other; the black points are unshifted. The mass profiles derived from the $\beta$-model are overplotted as solid curves.
in sector 2 (the red points in Figure 5.8), it is almost certainly not in hydrostatic equilibrium. Not only is the gas unlikely to be at rest relative to the gravitational potential, it has also probably been heated by the merger beyond the temperature one would derive simply by applying the hydrostatic condition to a cluster with the combined mass of the original subclusters (Randall, Sarazin, & Ricker 2002). Indeed, if we calculate the bolometric luminosity of the cluster from the single-temperature spectral model discussed in §5.3.2 and extrapolate it out to 2 Mpc, we find that it is quite underluminous for the measured temperature of 10.7 keV. That is, the observed luminosity implies a temperature of $\sim$5.2 keV using the $L_X-T$ relation from Markevitch (1998), so the temperature has probably been boosted by about a factor of 2 by the merger. This is consistent with the temperature boost expected for a head-on, equal mass merger which is at or near core passage.

Also shown in Figure 5.8 is a mass profile derived from the $\beta$-model fit produced in §5.3.1, under the assumption that the cluster is isothermal. Here we used the mean temperature from the spectral models in §5.3.2 with variable abundance. This model fits the data remarkably well, both for the gas mass and total mass profiles, particularly at large radii. At radii less than the core radius of the $\beta$-model, ($r < 280$ kpc), the fit to the gravitational mass is worse. In this region, however, the pressure gradient should be small, and since our method for determining the gravitational mass from the data involves computing pressure differences between points, the accuracy of mass at these radii is suspect.

Extrapolating the $\beta$-model mass profile out beyond the limit of the data, we find that $M_{200} = 2.91 \times 10^{15} M_\odot$ at a radius $r_{200} = 3.69$ Mpc, where $r_{200}$ is the radius at which the average density of the ICM is equal to 200 times the critical density, and $M_{200}$ is the total mass enclosed within that radius. Randall et al. (2002) show
that the temperature boost from an equal mass, head-on merger can be up to a factor of \( \sim 2 \) larger than the temperature of the resultant cluster once it has relaxed. Since the gravitational mass is proportional to temperature, this could cause us to overestimate the gravitational mass by as much as a factor of two, and would in turn reduce \( r_{200} \) to 2.60 Mpc. This is, however, a fairly strong upper limit to the merger-induced temperature boost, since a non-zero impact parameter for the merger or a mass ratio of the subclusters that deviates from unity would decrease the magnitude of the temperature boost.

Using the outermost bin for which we have estimates of both the gas mass and the gravitational mass, the gas mass fraction is \( \sim 8\% \). The \( \beta \)-model mass profile gives a similar fraction. This fraction is slightly small compared to a more typical value of 10–20\% (David et al. 1995; Allen et al. 2002). However, the effect of the merger-induced temperature boost mentioned above could raise the actual gas fraction to as much as \( \sim 16\% \).

### 5.4 South Excess

As mentioned above, there is a faint, large scale excess of emission to the south and southwest on the cluster periphery. In the \( ROSAT \) image of the cluster (Figure 5.3, this excess appeared to be linear, leading us to believe that it was likely to be a merger shock. As mentioned in §5.3, the \( Chandra \) image of the cluster shows this region to be much more diffuse, and not a sharp feature at all. It appears much more round, and may extend off the south edge of the detector. However, the \( ROSAT \) image with a larger field-of-view shows that most of the south excess image is in the region covered by the ACIS-I detector.

We extracted a spectrum from a circular region containing the south excess and
excluding point sources, and another spectrum from a region of similar size at roughly the same distance from the cluster center and to the northeast of the excess. We fix this second region with a single temperature MEKAL model. We then fit a model which was the sum of two component MEKAL models to the region of the excess, with one component’s parameters fixed to those from the other fit, normalized appropriately to account for the different region sizes. With the redshift of the second component fixed at the redshift of Abell 2034 and the temperature, abundance, and normalization allowed to vary, the second component was found to have a temperature of $4.7^{+1.2}_{-0.9}$ keV and an abundance of $< 0.34 Z_\odot$. Thus, the south excess is much cooler than the gas in the main body of the Abell 2034 cluster. The excess in this region therefore cannot be due to shock compression of this hotter gas.

One possible interpretation is that the south excess is a smaller cluster which is merging with Abell 2034, but which has not yet been shock heated by the interaction. This would explain the low temperature of the south excess. However, the flux from the south excess is much too low for a $\sim 4.7$ keV cluster at $z = 0.113$, if it follows the standard $L_X-T$ relation for clusters (e.g. Markevitch 1998). The bolometric flux from the south excess, determined from the best-fit spectrum, is $f_{\text{bol}} = (6.2 \pm 0.4) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The south excess appears to extend off the edge of the detector, so this flux needs to be corrected for the fraction of the presumed cluster which does not fall into our spectrum. Under the assumption that the excess is emission from a roughly spherical cluster, we subtracted our best-fit $\beta$-model from the smoothed image shown in Figure 5.2 and fit a circle, centered at R.A. = $15^h10^m05^s$, Dec. = $+33\text{deg} 24\text{'}07\text{''}$, to the residual emission. We then corrected the above flux for the fraction of this circle which fell off the detector. At a redshift of $z = 0.113$, the corresponding bolometric luminosity is $L_{\text{bol}} = 4.3 \times 10^{43}$ erg s$^{-1}$. On the other hand, the bolometric
X-ray luminosity-temperature relation derived by Markevitch (1998) would imply a luminosity of $L_{\text{bol}} = 6.5 \times 10^{44}$ erg s$^{-1}$ for a cluster with $kT = 4.7$ keV. Including the uncertainties in the measured temperature and the dispersion in the $L_{\text{bol}}-T$ relation, the expected flux would then be $f_{\text{bol}} = 1.1^{+0.8}_{-0.6} \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is much higher than the observed value. If the south excess were a smaller foreground cluster seen in projection against Abell 2034, its expected flux from the $L_{\text{bol}}-T$ relation would be even larger and more discrepant with the measured flux.

One possible explanation of the south excess is that it was originally a relatively small, cool, and X-ray faint subcluster which has been shock heated to $kT = 4.7$ keV as a result of a merger with Abell 2034. There are two possible concerns with this explanation. First, there is no evidence for a strong interaction between the south excess and the main cluster in Abell 2034. Second, the observed temperature of the south excess is lower than might be expected for gas shocked while merging with the main cluster, given the very high temperature of Abell 2034. However, it is possible that the merger shock was a weak oblique shock resulting from an offset merger (a merger with a large impact parameter), or that the south excess region originated as substructure within Abell 2034 and did not fall through the full potential well of the cluster.

Alternatively, we consider the possibility that the south excess is a cluster at a considerably larger redshift than that of Abell 2034. However, moving this cluster to a higher redshift would also increase its temperature roughly as

$$T(z) = T_0 \frac{1 + z}{1 + z_0},$$

(5.1)

where $T_0 \approx 4.7$ keV and $z_0 = 0.113$ are the temperature and redshift if the south excess is located at the distance of Abell 2034. The increase in temperature would also
increase the cluster’s X-ray luminosity according to the $L_X-T$ relation. However, the increase in luminosity as a result of the increased temperature grows more slowly with redshift than does the luminosity required to produce the observed flux. Since the luminosity required by the flux is about an order of magnitude smaller at $z = 0.113$ than the luminosity implied by the $L_X-T$ relation, the two functions should intersect at some redshift $z > 0.113$.

We estimated the required redshift to make the observed temperature and flux consistent with the $L_X-T$ relation. We used the observed bolometric flux $f_{\text{bol}}$ given above. Note that if the spectrum of the south excess contained strong line emission, the spectrum would change in a non-trivial way with redshift, and the derived values of $T_0$ and $f_{\text{bol}}$ might vary with redshift. However, the bulk of the observed X-ray spectrum is continuum, and the observed spectrum gives only an upper limit on the abundance of heavy elements which would give line emission. We use the $L_{\text{bol}}-T$ relation derived by Markevitch (1998), which we parameterize as

$$L_{\text{bol}} = A_6 \left( \frac{kT}{6 \text{ keV}} \right)^{\alpha_{LT}},$$

where $A_6 = (3.11 \pm 0.27) \times 10^{44} h^{-2} \text{ erg s}^{-1}$ and $\alpha_{LT} = 2.64 \pm 0.27$ (Markevitch 1998). We ignore any evolution in the $L_X-T$ relation with redshift. The bolometric luminosity is also related to the bolometric flux by

$$L_{\text{bol}} = 4\pi d_L^2(z) f_{\text{bol}},$$

where $d_L(z)$ is the luminosity distance to the south excess cluster as a function of its redshift. Equations (5.1)–(5.3) can be solved to give the estimated redshift for the cluster of $z \approx 0.7$. To test the consistency of this solution, we used this redshift
to fit the spectrum of the south excess, and found a temperature of $7.4^{+1.9}_{-1.2}$ keV and an abundance of $< 0.28 Z_\odot$. A temperature of 7.2 keV was expected by blueshifting the best-fit temperature at $z_0 = 0.113$. The best-fit bolometric luminosity from this spectral fit was also reasonably consistent with that expected from the $L_X-T$ relation. Including the uncertainties in the spectral properties and flux, and the dispersion in the $L_X-T$ relation, the estimated redshift is roughly in the range $0.35 \lesssim z \lesssim 1.48$.

Unfortunately, there are no strong line features in the X-ray spectrum of the south excess region. Thus, it isn’t possible to determine the redshift associated with this emission directly from the spectrum. There are only a handful of faint galaxies visible in the Digital Sky Survey 2 (DSS-2) red image in the region of the south excess. This would be consistent with the south excess being associated with a moderately distant cluster. Assuming the brightest cluster galaxy had an absolute magnitude of $M_V = -22$, it would have an apparent R magnitude $m_R = 21.8$ at a redshift of $z = 0.7$, and would be fainter than the limit of the DSS-2. (We assume a rest frame color $(V - R) = 0.9$ and take $K$-corrections from Coleman, Wu, & Weedman 1980.) If the cluster were nearer to the lower limit of $z = 0.35$, the brightest cluster galaxies would be easily visible in the DSS-2. The fact that no galaxies significantly brighter than $m_R = 20$ are observed leads us to believe that the cluster is more likely to be at a higher redshift. We have obtained moderately deep optical images in V- and R-band using the 1.8-meter VATT observatory. These images show tentative evidence for a cluster of galaxies at about the brightness predicted above, but the data have not been thoroughly reduced and calibrated. We also have plans to obtain deep near-infrared images of the field using the Palomar 5-meter telescope in June and July 2002. Deep optical spectroscopy using a larger aperture telescope should also be done to verify the existence and proposed redshift of this background cluster.
We have calculated the probability of detecting a cluster in a random *Chandra* field at a redshift $z > 0.113$ with luminosity at least as large as that required to produce the observed flux in the south excess, by integrating the luminosity function for bolometric luminosities given by Ebeling et al. (1997) over this range of luminosities and redshifts. The probability of detecting a cluster with the required luminosity in a random *Chandra* field is about $8 \times 10^{-3}$. The probability of a chance superposition of a background cluster on any nearby rich cluster (e.g. on an arbitrary Abell cluster) is therefore high enough that a background cluster should occasionally be found in a *Chandra* observation of an Abell cluster.

5.5 Northeast Cold Front

The northeast end of the cluster contains a sharp surface brightness discontinuity which was visible in an earlier *ROSAT* image (Fig. 5.3). As with other such features seen prior to *Chandra*, it was assumed to be a merger shock. Also like some other features of its kind, it in fact has turned out to be a “cold front” of the type first discovered in Abell 2142 (Markevitch et al. 2000), although the temperature contrast is small relative to Abell 2142 or other, similar cases. The leading edge of the cold front is roughly circular within $\sim 55^\circ$ of its axis of symmetry, which we assume to be equivalent to its projected direction of motion. The projected direction of motion, then, is at a position angle of $\sim 20^\circ$ (counterclockwise from North). We extracted surface brightness and temperature measurements from a series of concentric circular annular wedges which were defined to match the curvature of the cold front as well as possible (see Figure 5.9). Figures 5.10, 5.11, and 5.12 show, respectively, the projected temperature, surface brightness, and gas pressure profiles in these annuli. The quantity $x$ is the projected perpendicular distance from the surface brightness
discontinuity; that is, \( x \equiv r - r_{cf} \), where \( r \) is the radius of the annular wedge, and \( r_{cf} = 172'' \) is the radius of the cold front. We modeled the surface brightness inside the discontinuity (placed at \( x = 0 \) in the figures) as a sphere with a power law density projected onto the sky. A detailed derivation of this model is given in the appendix of Vikhlinin, Markevitch, & Murray (2001a). The dotted line in Figure 5.10 shows the good agreement of this spatial model with the data. Outside the discontinuity, the surface brightness falls off until it encounters another discontinuity, this time a small change in slope, at about \( x = 160 \) kpc.

At large negative values of \( x \) (i.e. far into the cluster), the temperature is consistent with that of the bulk of the cluster. The temperature profile then shows a decrease in the temperature just inside the discontinuity and an increase in the temperature just outside, both of which are consistent with the interpretation of the discontinuity as a cold front with the gas ahead of it having been heated by a bow shock. The large positive errors on the temperatures in the bins outside the cold front result from the temperatures being hotter than or comparable to the upper energy of the \textit{Chandra} spectral band used in the fit (9 keV). This is particularly true for the first bin immediately ahead of the cold front. Outside the point at which the surface brightness profile changes slope, the temperature drops considerably, but again with a large error, this time due primarily to the small number of source counts.

We deprojected the surface brightness under the assumption of spherical symmetry. Due to the small number of counts in the regions at positive radii and the high temperature of the gas just ahead of the cold front, it was not possible to deproject the temperature profile without introducing unacceptably large uncertainties into the spectral fits. The deprojected surface brightnesses were then converted to electron densities, which, when combined with the measured temperatures, produced the
Fig. 5.9.— Gaussian smoothed X-ray image of Abell 2034, the same as Fig. 5.2. The wedge used for the analysis in §5.5 is indicated by the dashed lines. The “x” marks the location of the cD galaxy.
Fig. 5.10.— Temperature profile across the cold front. The point $x = 0$ corresponds to the cold front, while negative values are toward the cluster center and positive values extend out of the cluster.
Fig. 5.11.— Surface brightness profile across the cold front. The $x$-axis is the same as in Figure 5.10. The dotted line indicates the projected sphere model that best fits the data.
Fig. 5.12.— Pressure profile across the cold front. The $x$-axis is the same as in Figure 5.10.
pressure profile shown in Figure 5.12. The pressure is continuous across the surface brightness discontinuity at \( x = 0 \), while it appears to drop abruptly at \( x = 160 \) kpc. The sharp pressure increase at radii less than that of this second discontinuity suggests that this is the location of the bow shock formed by the cold front’s motion through the cluster. While no clear evidence for a bow shock is visible in the image, the increased signal-to-noise provided by azimuthally averaging the surface brightness makes such a bow shock visible in a radial profile.

5.5.1 Hydrodynamic Kinematics

For a blunt body such as the cold front moving through an ambient medium, one can determine the Mach number, \( \mathcal{M} \), from the ratio of the pressure at the stagnation point just ahead of the front \( (P_{st}) \) to that far upstream \( (P_1) \). This ratio is given by (e.g. Landau & Lifshitz 1959, §114)

\[
\frac{P_{st}}{P_1} = \begin{cases} 
(1 + \frac{\gamma - 1}{2} \mathcal{M}^2)^{\frac{\gamma - 1}{\gamma + 1}}, & \mathcal{M} \leq 1, \\
\mathcal{M}^2 \left( \frac{\gamma - 1}{2} \mathcal{M}^2 \right)^{\frac{\gamma - 1}{\gamma + 1}} (\gamma - \frac{\gamma - 1}{2\mathcal{M}^2})^{-\frac{1}{\gamma + 1}}, & \mathcal{M} > 1.
\end{cases}
\]

Here, \( \gamma = 5/3 \) is the ratio of specific heats in the gas. For the cold front in Abell 2034, \( P_{st}/P_1 = 3.9^{+2.9}_{-1.8} \), which implies \( \mathcal{M} = 1.5 \pm 0.5 \) (1-\( \sigma \) errors). The large error in the Mach number is due primary to the errors in the measured temperatures, which are discussed above.

If the front is in fact moving supersonically, that is, if \( \mathcal{M} > 1 \), a bow shock will form ahead of the front. Under the assumption that the pressure jump at \( x \approx 160 \) kpc is indicative of such a bow shock, we can apply the Rankine-Hugoniot shock jump conditions as an independent measure of the Mach number. The shock jump
conditions are
\[
\frac{1}{C} = \frac{2}{\gamma + 1} \frac{1}{\mathcal{M}^2} + \frac{\gamma - 1}{\gamma + 1},
\]
where \( C \equiv \rho_2/\rho_1 \) is the shock compression, and \( \rho_1 \) and \( \rho_2 \) are the pressure in front of and behind the shock, respectively. Because of the low count rate at this large radius, we do not have spectra or temperatures determined on the scale of the bow shock, so we estimate the shock compression from the small increase in the surface brightness as \( C \approx (I_{X2}/I_{X1})^{1/2} \). This yields a shock compression of \( \sim 1.2 \), which in turn implies a shock Mach number of \( \mathcal{M} = 1.1^{+0.2}_{-0.1} \).

A third independent measurement of the Mach number is provided by the “stand-off” distance of the bow shock, the distance between the cold front and the bow shock. For a constant density ambient medium and a spherical cold front, this distance can be calculated using the approximate method given by Moekel (1949). The stand-off distance, \( d_s \), depends only on the radius of curvature, \( R_{cf} \), of the cold front and on the Mach number, such that \( d_s/R_{cf} \) is a monotonically increasing function of \( 1/(\mathcal{M}^2 - 1) \). So, a measurement of the bow shock stand-off distance allows us to determine the Mach number of the shock. For a stand-off distance of \( d_s \approx 160 \) kpc and radius of curvature of the cold front \( R_{cf} \approx 470 \) kpc, the Mach number of the shock is \( \mathcal{M} \approx 2.1 \). Projection effects will cause \( d_s \) to be overestimated, thereby underestimating the Mach number. The potential for systematic error caused by our selection of the annular regions for this analysis is also significant. Given the excellent fit to the surface brightness profile interior to the cold front, however, these systematics are likely to introduce a relatively small systematic uncertainty.

The mean of the two values for the Mach number determined from the tentative detection of a bow shock is consistent with that determined from the stagnation point pressure. Despite the smaller errors on the measurements using the bow shock,
however, we are hesitant to view these as more precise since the detection of the bow shock itself is not secure. We therefore adopt $\mathcal{M} = 1.5 \pm 0.5$ as the more robust result. The sound speed outside of the putative bow shock is $c_s \approx 1500$ km s$^{-1}$, so we estimate the velocity of the cold front to be $2200 \pm 700$ km s$^{-1}$. This is consistent with the merger velocities seen in other similar systems (e.g. Abell 2142, Abell 3667; Markevitch et al. 2000; Vikhlinin et al. 2001a). Again, the large uncertainty stems from the high temperature of the gas and the resulting difficulty in constraining the spectral fits.

### 5.5.2 Transport Mechanisms

The surface brightness profile of the cold front shows that the distance across which the transition from high density to low density gas occurs is quite small. Because the pressure profile appears to be continuous, we will assume that this large density gradient is accompanied by a large temperature gradient of the opposite sign. Unfortunately, the spatial resolution of our temperature measurements is poor, so we cannot measure directly the temperature gradient on small scales. However, if the pressure were not continuous across the cold front, the higher pressure gas would expand on roughly the sound crossing time, which is comparable or shorter than the other timescale considered here. A sharp gradient in the temperature should be smeared out by thermal conduction. Thermal conduction appears to be suppressed here, as has been found for cold fronts in other clusters (e.g. Abell 2142, Abell 3667; Ettori & Fabian 2000; Vikhlinin et al. 2001a). Following the derivation of Ettori & Fabian (2000), we derive the timescale required to erase this temperature jump to be $\delta \tau = 1.7 \times 10^6$ yr. This latter assumption is probably safe, since any discrepancy between the scales of the gradients would cause a sharp pressure gradient, which would
be erased on a dynamical timescale much shorter than the conduction timescale. At the cold core’s current velocity and distance from the center of the cluster, the relevant timescale for the interaction is roughly $d/v \approx 4.2 \times 10^8$ yr. So, in order for the cold front to have its observed width of only $\sim 10$ kpc, conduction must be suppressed by a factor of at least 250.

5.6 Summary

Our analysis of the Chandra observation of the massive, moderate redshift cluster Abell 2034 has revealed a number of interesting features. We have determined that the temperature of the cluster is fairly constant out to a radius of at least about 800 kpc. This includes the central region of the cluster, which shows no evidence for the large cooling flow that had previously been claimed. In contrast, the cluster shows some strong signatures of an ongoing merger. We have shown that the surface brightness discontinuity on the NE edge of the cluster is a cold front, moving with a Mach number of $\sim 1.5$. There is some evidence for a bow shock 160 kpc ahead of the cold front. A large concentration of galaxies, including a cD galaxy, is visible just ahead of the cold front. We suggest that these galaxies, including a cD galaxy, were once centered on the potential well of a subcluster, and that the gas in the cold front was the cooling core of this subcluster. The collisionless galaxies have now moved ahead of the collisional gas, which has been slowed by ram pressure during the merger. As has been seen in other clusters, these observations are consistent with the idea that conduction across cold fronts must be suppressed significantly. In addition to the lack of a centrally condensed cooling flow, other major evidence for the cluster being out of equilibrium includes the significant offset of the central cD from the center of the X-ray emission.
There is a region of excess emission at a cooler temperature (4.7 keV) to the south of the main cluster. There is no clear evidence for any interaction between this gas and the main Abell 2034 cluster. The south excess is too faint to be an undisturbed cluster at the redshift of Abell 2034 or closer, if it follows the normal $L_X-T$ relation. Instead, we suggest that the south excess is a background cluster at an estimated redshift of $z \approx 0.7$. It may be at even higher redshift, given the absence of observed galaxies in that region with the brightness one would expect for that redshift. Much more work is needed to confirm both the existence of and distance to this new cluster, including deep optical imaging and spectroscopy.

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Chapter 6

Conclusions and Future Work
6.1 Summary

I have presented several studies of merging clusters of galaxies at radio and X-ray wavelengths. These studies all attempt to characterize the thermal and nonthermal processes produced by cluster mergers. In Chapter 2, I presented the discovery of seven new candidate radio halos and relics. The clusters hosting these sources were shown through a combination of optical and X-ray data to all show independent evidence of a recent or ongoing merger. Follow up observations of all these new sources will be needed to confirm their existence.

In Chapter 3, I applied a similar technique to search for diffuse radio emission from the cluster Abell 2199. The upper limit I was able to set on the flux of a radio halo produced very strong constraints on possible Inverse Compton emission from the cluster, the detection of which had been previously claimed (Kaastra et al. 1998, 1999). I also applied the nonthermal bremsstrahlung model from Sarazin & Kempner (2000) to attempt to explain the hard X-ray emission in the cluster. The model does a reasonable job of fitting the hard X-ray data, but fails to explain the extreme ultraviolet excess also observed (Lieu et al. 1999). In addition, it is difficult to understand how a cluster as relaxed as Abell 2199 would have a large enough population of suprathermal electrons to produce a significant nonthermal tail to the distribution.

 Chapters 4 and 5 demonstrated the use of X-ray observations of merging clusters in determining the merger dynamics. In the case of the south subcluster in Abell 85 and the northeast cold front in Abell 2034, I used the surface brightness and temperature information in the vicinities of the cold fronts to derive the velocities of those components of the mergers. I also showed that in both of these clusters, thermal conduction is suppressed across the cold fronts, perhaps by the local magnetic field
which gets stretched parallel to the cold front by the flow of gas around the cold core.

In Chapter 5, I also have presented measurements of the global properties of the cluster Abell 2034. I determined that the cluster does not in fact have a cooling flow, further strengthening the anti-correlation between mergers and cooling flows. I showed that previous measurements of a cooling flow were probably contaminated by the cooler gas to the south of the main cluster. I suggested that this emission is actually due to a background cluster at $z \approx 0.25$ which is seen in projection against the southern part of Abell 2034.

6.2 Future Directions

In addition to the X-ray observations presented here, I have an ongoing program of planned and proposed observations of merging clusters with both Chandra and XMM-Newton. Abell 2065 is scheduled to be observed in August 2002. It is a somewhat asymmetric, head-on merger wherein the cores of the two subclusters have just passed each other. ASCA observations of the cluster indicated that the ICM in the area of the two cores was significantly heated. Also scheduled for 2002, with the exact date yet to be determined, is an XMM-Newton observation of Abell 3395. This cluster is a symmetric merger with the plane of the merger roughly in the plane of the sky and a large impact parameter. ASCA images of the cluster look remarkably like simulations that have been performed of such mergers (Ricker & Sarazin 2001), so we hope this cluster will serve as a good test case for those simulations. I have also proposed to observe several other clusters which have radio relics or halos, including Abell 725, Abell 1240, Abell 1758, and Abell 2034 with XMM-Newton in Cycle 2, and Abell 725 and Abell 1240 with Chandra in Cycle 4. I have also proposed to observe with Chandra the group of galaxies centered on UGC 10853. This group has a large
velocity dispersion among its galaxies and is quite X-ray bright but is optically quite poor. It also hosts an unusual diffuse radio source which looks like a radio halo but which is a hundred times more luminous than one would expect given the $P_r-L_X$ relation presented in Chapter 2.

With regard to radio halos and relics, this thesis raises more questions than it answers. The 7 new sources discovered in Chapter 2 need to be confirmed by deeper, higher resolution imaging. I have begun this process with a series of observations of the sources in Abell 1240 and Abell 2034 using the VLA, and hope to observe the remaining 5 clusters at some point in the future. I have completed observations at 90 cm in the high resolution B array and medium resolution C array at the VLA. I have also completed C array observations of both clusters at 20 cm. I have proposed for observations with the lowest resolution VLA configuration, D array, but consideration of the proposal was delayed until 2003 because the sources were too close to the sun during the most recent configuration in the D array. As was expected, the high resolution of the B array resolved out any emission from the proposed relic sources in the two clusters, since the B array configuration is not sensitive to emission at large angular scales. The C array data are awaiting analysis.

The results from the VLA observations of Abell 2034 will then be compared to the X-ray data, although it is unlikely that the X-ray data contain enough photons to place a meaningful limit on IC emission from the region of the radio relic. A preliminary analysis of the B array data shows several tailed radio galaxies which may give further indications of the merger dynamics and may provide further useful comparison with the X-ray data.

The sources which are confirmed will then need to be mapped in greater detail, in both total intensity and polarization. The polarization maps will enable us to
determine the direction of the local magnetic field within the region of emission, and
to distinguish true radio relics from remnant lobes of extinct radio galaxies. It will also
be useful to observe these sources at multiple frequencies in order to generate spectral
index maps. Some well-studied radio relics have spectral index gradients, which may
be suggestive of a gradient in the ages of the electrons producing the emission, with
the steeper spectrum regions indicating electrons which were accelerated before those
in the flatter spectrum regions. If the relativistic electrons are accelerated in merger
shocks, one would expect to find flatter radio spectra at the shock, with the spectrum
steeping with distance from the shock. This provides an additional constraint on
the kinematics of mergers. However, variations in radio spectra could also be due to
a gradient in the magnetic field, since a higher magnetic field will also steepen the
electron momentum spectrum. Only a direct measurement of the magnetic field can
break this degeneracy.

If IC emission were to be resolved in the region of a radio relic, it could be used to
directly measure the magnetic field in the cluster \textit{in situ}, since the ratio of synchrotron
to IC emission depends only on the energy density in the magnetic field and the well
known energy density in the CMB. Whereas Faraday rotation measurements give a
measurement of the magnetic field integrated along the line-of-sight, IC would provide
a measurement of the field in the volume producing the emission. Knowledge about
the spatial structure of the magnetic field would allow us to break the degeneracy
mentioned earlier between age and magnetic field strength in spectral index maps.
This would then enable us to answer the question of whether or not spectral index
gradients in radio relics indicate the direction of the motion of the associated merger
shock. To do this, deeper, high resolution hard X-ray images will need to be made of
the regions of radio emission to detect or put strong limits on Inverse Compton (IC)
emission from the radio-emitting electrons. In our Chandra observations of Abell 85 and Abell 2034, we found that the radio relics occurred in regions of low X-ray surface brightness, and the spectra in these regions did not provide strong constraints on IC emission.

Future X-ray missions may be able to detect IC emission from radio relics. With high resolution spectral and moderate resolution imaging capabilities upwards of 15 keV, Integral should be able to resolve IC emission on scales of \( \sim 12' \). Integral is scheduled for launch in October 2002. The hard X-ray telescopes on Astro-E2 and Constellation-X will also provide important information on IC emission.

Future missions that will contribute to a greater understanding of merger dynamics include Astro-E2 and Constellation-X. Astro-E2, scheduled for launch in early 2005, is a replacement for the Astro-E mission which failed to achieve orbit in 2000. Its primary instrument will be a quantum calorimeter which will have very high spectral resolution in a small number of resolution elements. This mission will enable us to measure the relative velocities of the gas from the merger components at a resolution of hundreds of kilometers per second by accurately determining the observed wavelengths of spectral lines, primarily the iron K\( \alpha \) line. We were successful in proposing to observe Abell 85 and the Cygnus A cluster with the original mission and hope to continue this success with its replacement. Constellation-X, planned for the end of the decade, will feature quantum calorimeters with several times the spectral resolution of Astro-E2, many more resolution elements, and a vast collecting area. These advanced detectors with their extremely high sensitivity will be able to determine the detailed velocity structure of cold fronts and other merger features, with high spatial resolution.

In the radio regime, planned observatories at long wavelengths will dramatically
enhance our ability to find and study radio halos and relics. As demonstrated in Chapter 2, current low frequency radio surveys have not gone deep enough to detect radio halos in low- to moderate-luminosity clusters, if these halos exist. Several promising new observatories will make this possible. The Giant Metre-Wave Radio Telescope (GMRT) in Pune, India should be capable of detecting several hundred radio relics of the entire sky at a frequency of 100 MHz in one hour per observation (Enßlin et al. 2001). The capabilities of this new observatory are still being explored. In the United States, increasing computing power has recently enabled the new 74 MHz (4-meter) antennas on the VLA to be useful for imaging the sky at a wide range in declination. While the planned Four Meter All Sky Survey (4MASS) being done with the VLA will be only sensitive enough to detect new halos with spectral indices steeper than \( \sim -2 \), the Expanded VLA (EVLA) will increase the sensitivity and the resolution of the array at long wavelengths. This will enable future surveys to go much deeper than 4MASS without a very large increase in the required observing time. Further on the horizon is the Low Frequency Array (LOFAR), a planned array with receivers covering the range 10–240 MHz, collecting area of a square kilometer at 15 MHz, and arcsecond resolution with sensitivity at large scales as well. While the GMRT is expected to detect hundreds of relics at 100 MHz, LOFAR will be able to detect several thousand at slightly lower frequencies. Since halos and relics have such short lifetimes as short wavelength emitters, there may be a large population of them visible only with this new generation of long wavelength observatories.

With this large number of new X-ray and low-frequency radio observatories coming online in the next decade, our level of understanding of merging clusters of galaxies should expand dramatically in the next decade.
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