JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
**37**: 433 ∼ 438, 2004

# MERGERS, COSMIC RAYS, AND NONTHERMAL PROCESSES IN CLUSTERS OF GALAXIES

CRAIG L. SARAZIN
Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903-0818, USA
*E-mail: sarazin@virginia.edu*

## ABSTRACT

Clusters of galaxies generally form by the gravitational merger of smaller clusters and groups. Major cluster mergers are the most energetic events in the Universe since the Big Bang. The basic properties of cluster mergers and their effects are discussed. Mergers drive shocks into the intracluster gas, and these shocks heat the intracluster gas. As a result of the impulsive heating and compression associated with mergers, there is a large transient increase in the X-ray luminosities and temperatures of merging clusters. These merger boost can affect X-ray surveys of clusters and their cosmological interpretation. Similar boosts occur in the strong lensing cross-sections and Sunyaev-Zeldovich effect in merging clusters. Merger shock and turbulence associated with mergers should also (re)accelerate nonthermal relativistic particles. As a result of particle acceleration in shocks and turbulent acceleration following mergers, clusters of galaxies should contain very large populations of relativistic electrons and ions. Observations and models for the radio, extreme ultraviolet, hard X-ray, and gamma-ray emission from nonthermal particles accelerated in these shocks will also be described. Gamma-ray observations with GLAST seem particularly promising.

*Key words :* clusters of galaxies – cosmic rays – nonthermal processes

## I. INTRODUCTION

Clusters of galaxies form hierarchically by the merger of smaller groups and clusters. Major cluster mergers are the most energetic events in the Universe since the Big Bang. In these mergers, the subclusters collide at velocities of ∼2000 km/s, releasing gravitational binding energies of as much as $\gtrsim 10^{64}$ ergs (e.g., Sarazin 2002). Figure 1 shows the Chandra image of the merging cluster Abell 85, which has two subclusters merging with the main cluster (Kempner, Sarazin, & Ricker 2002). The relative motions in mergers are modestly supersonic, and shocks are driven into the intracluster medium. Figure 2 shows a numerical hydrodynamical simulation of the cluster merger, showing the hot shocks propagating through the merging clusters (Ricker & Sarazin 2001). In major mergers, these hydrodynamical shocks dissipate energies of $\sim 3 \times 10^{63}$ ergs; such shocks are the major heating source for the X-ray emitting intracluster medium. Merger shocks heat and compress the X-ray emitting intracluster gas, and increase its entropy. We also expect that particle acceleration by these shocks will produce nonthermal electrons and ions, and these can produce synchrotron radio, inverse Compton (IC) EUV and hard X-ray, and gamma-ray emission.

## II. THERMAL EFFECTS OF MERGERS

Mergers heat and compress the intracluster medium. Shocks associated with mergers also increase the entropy of the gas. Mergers can help to mix the intracluster gas, possibly removing abundance gradients. Mergers appear to disrupt the cooling cores found in many clusters; there is an anticorrelation between cooling core clusters and clusters with evidence for strong ongoing mergers (e.g., Buote & Tsai 1996). The specific mechanism by which cooling cores are disrupted is not completely understood at this time (e.g., Ricker & Sarazin 2001).

The heating and compression associated with mergers can produce a large, temporary increase in the X-ray luminosity (up to a factor of ∼10) and the X-ray temperature (up to a factor of ∼3) of the merging clusters (Figure 3; Ricker & Sarazin 2001; Randall, Sarazin, & Ricker 2002). Very luminous hot clusters are very rare objects in the Universe. Although major mergers are also rare events, merger boosts can cause mergers to strongly affect the statistics of the most luminous, hottest clusters. Simulations predict that many of the most luminous, hottest clusters are actually merging systems, with lower total masses than would be inferred from their X-ray luminosities and temperatures (Randall et al. 2002). Since the most massive clusters give the greatest leverage in determining the cosmological parameters $\Omega_M$ and $\sigma_8$, these values can be biased by merger boosts. Recent weak lensing studies appear to have confirmed these large merger boosts (e.g., Smith et al. 2003).

---

Proceedings of The 3rd Korean Astrophysics Workshop on
*Cosmic Rays and Magnetic Fields in Large Scale Structure*

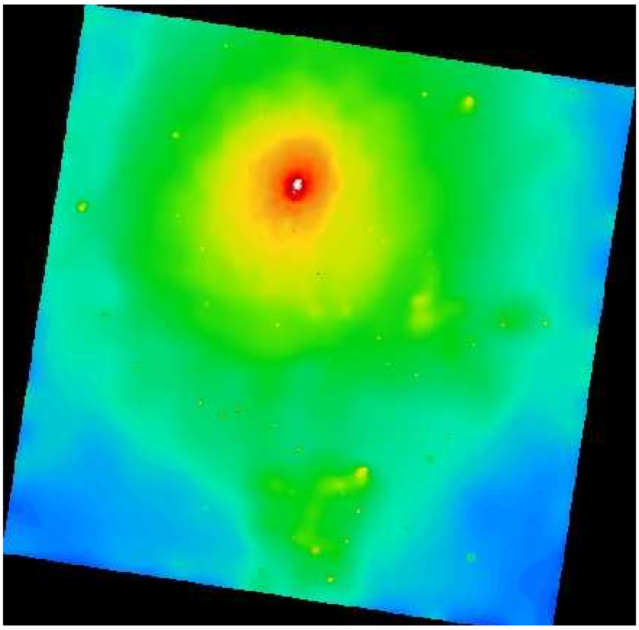

**Fig. 1.**— The Chandra X-ray image of the merging cluster Abell 85 (Kempner, Sarazin, & Ricker 2002). Two subclusters to the south and southwest are merging with the main cluster.

Cluster mergers can also boost the Sunyaev-Zeldovich effect and particularly the cross-section for a cluster to have strong lensing (Randall, Sarazin, & Ricker 2004; Torri et al. 2004).

## III. NONTHERMAL EFFECTS OF MERGERS

High speed astrophysical shocks in diffuse gas generally lead to significant acceleration of relativistic electrons. For example, typical supernova remnants have blast wave shock velocities of a few thousand km/s, which are comparable to the speeds in merger shocks. (However, the Mach numbers in merger shocks are much lower.) The ubiquity of radio emission from Galactic supernova remnants implies that at least a few percent of the shock energy goes into accelerating relativistic electrons, with more probably going into ions. If these numbers are applied to strong merger shocks in clusters, one would expect that relativistic electrons with a total energy of $E_{\rm rel,e} \sim 10^{62}$ erg would be accelerated, with even more energy in the relativistic ions. Thus, merging clusters should have huge populations of relativistic particles.

### (a) Models for Relativistic Particles

Clusters may contain both primary and secondary relativistic electrons. Primary electrons are accelerated directly in mergers. Secondary electron are produced by the interactions of relativistic ions with thermal ions in the intracluster medium. Collisions between relativistic ions (mainly protons) and thermal ions (also mainly protons) can produce pions (and other mesons):

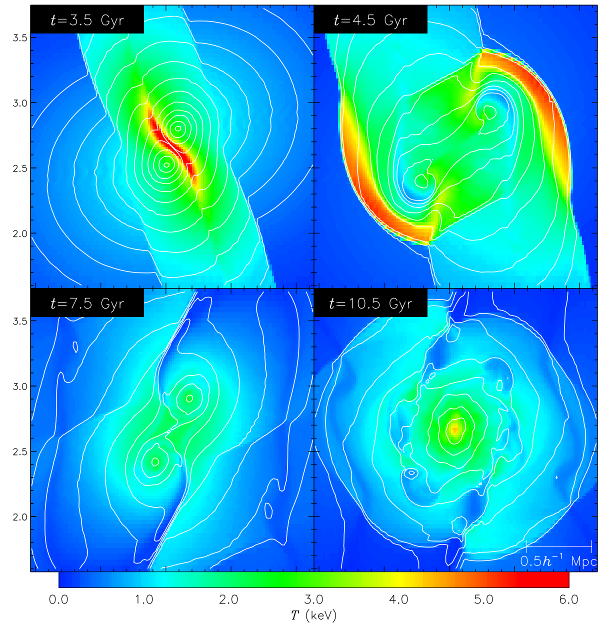

**Fig. 2.**— A hydrodynamical simulation of a cluster merger from Ricker & Sarazin (2001). The hot (red) regions are merger shocks.

$$p + p \rightarrow p + p + n\pi \, . \tag{1}$$

The charged pions decay to produce electrons and positrons:

$$\begin{aligned} \pi^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \\ \mu^{\pm} &\rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e}) \, . \end{aligned} \tag{2}$$

In mergers, primary relativistic particles may be produced through shock acceleration or by turbulent acceleration, where the turbulence may have been generated by a merger shock passage. Often, it is argued that cluster radio relics are due to shock acceleration, while cluster radio halos are produced by turbulent acceleration. Although the seed particles for acceleration could come from the thermal intracluster gas, it is easier to re-accelerate a relic population of low energy relativistic particles.

In the simple kinetic theory for diffusive shock acceleration, a power-law momentum is produced. Let $f(p)dp$ be the number of particles with momenta in the range $p \rightarrow p + dp$. For highly relativistic particles, $p = E/c$, so the same distribution applies to the particle energy. The predicted momentum distribution for shock acceleration is

$$f(p) \propto p^{-m} \, , \tag{3}$$

where

$$m = \frac{r+2}{r-1} = 2 \, \frac{\mathcal{M}^2 + 1}{\mathcal{M}^2 - 1} \, . \tag{4}$$

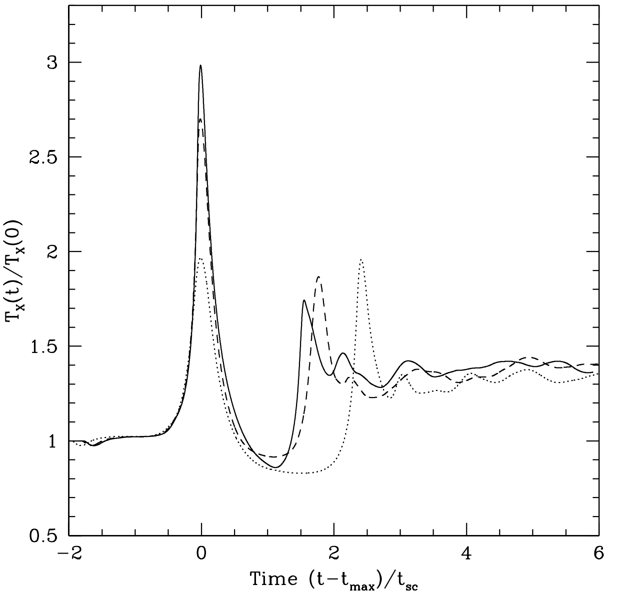

**Fig. 3.**— The X-ray emission-averaged temperature in a pair of equal mass clusters undergoing a merger (Ricker & Sarazin 2001; Randall et al. 2002). During a merger, the temperature can undergo a transient boost by up to a factor of three and the X-ray luminosity by up to a factor of ten.

Here, $r$ is the shock compression, and $\mathcal{M}$ is the shock Mach number. This is the accelerated source distribution. If the particle distribution is in steady-state between acceleration and IC and/or synchrotron losses, the particle distribution steepens by one. For very strong shocks ($\mathcal{M} \rightarrow \infty$), the compression is $r = 4$ and the exponent is $m = 2$. However, most merger shocks in the interiors of clusters are relatively weak with $\mathcal{M} \sim 1.5$. Thus, these merger shocks should produce rather steep particle distributions. Flatter particle spectra might be expected for accretion shocks at the outer edges of clusters.

Turbulent acceleration is often involved to explain radio halos in clusters, which are probably too extended to be due to electrons which have diffused or been advected from shocks (see the paper by Brunetti in this volume). These models require that clusters with radio halos have a highly turbulent intracluster medium, with $E_{\rm turb} \sim 0.2 E_{\rm therm}$ is the post merger shock regions of clusters (Fujita, Takizawa, & Sarazin 2003). This is consistent with hydrodynamical simulations of merging clusters (e.g., Ricker & Sarazin 2001). The upcoming Astro-E2 X-ray mission should be able to easily detect these turbulent motions by measuring the X-ray line profiles in radio halo clusters.

However they are produced, clusters should retain some of these relativistic particles for very long times. The cosmic rays gyrate around magnetic field lines, which are frozen-in to the gas, which is held in by the strong gravitational fields of clusters. Because clusters are large, the timescales for diffusion are generally longer than the Hubble time. The low gas and radiation densities in the intracluster medium imply that losses by relativistic ions are very slow, and those by relativistic electrons are fairly slow.

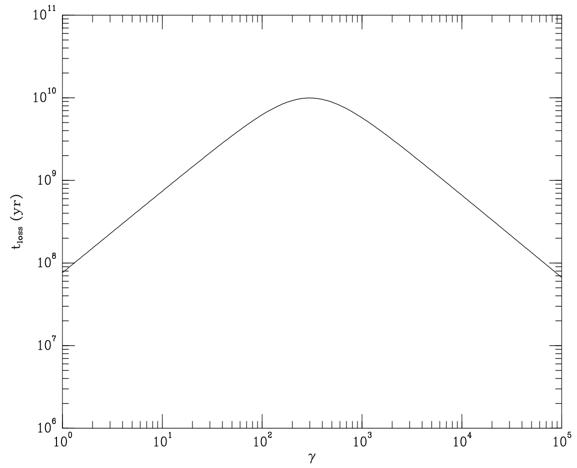

**Fig. 4.**— The lifetimes of relativistic electrons in a typical cluster as a function of their Lorentz factor $\gamma$ (Sarazin 1999a). The lifetime is maximum for $\gamma \sim 300$.

Figure 4 shows the loss timescale for electrons under typical cluster conditions; electrons with Lorentz factors $\gamma \approx 300$ and energies of ≈150 MeV have lifetimes which approach the Hubble time, as long as cluster magnetic fields are not too large ($B \lesssim 3\ \mu$G). On the other hand, the higher energy particles which produce radio synchrotron emission and could produce hard X-ray emission have relatively short lifetimes, comparable to the durations of cluster mergers. As a result, clusters should contain two populations of primary relativistic electrons accelerated in mergers: those at $\gamma \sim 300$ which have been produced by mergers over the lifetime of the clusters; and a tail to higher energies produced by any current merger.

## (b) Nonthermal Emission

Figure 5 shows the energy spectrum of primary electrons in an example of a model for a cluster undergoing a merger (Sarazin 1999a). There is a large population of low energy electrons ($\gamma \sim 300$, $E \sim 150$ MeV), which were accelerated in earlier mergers in the same cluster. There is also an approximately power-law tail of higher particles in the electron distribution; these electrons are being accelerated in the current merger.

The IC emission spectrum from the electrons in this model is shown in Figure 6. The lower energy electrons ($\gamma \sim 300$) will mainly be visible in the EUV/soft X-ray range (e.g., Sarazin & Lieu 1998). Because these low energy electrons have very long lifetimes, they should be present in most clusters. Such EUV/soft X-ray emission may have been seen in several clusters (e.g., Nevalainen et al. 2003; Bowyer et al. 2004), although

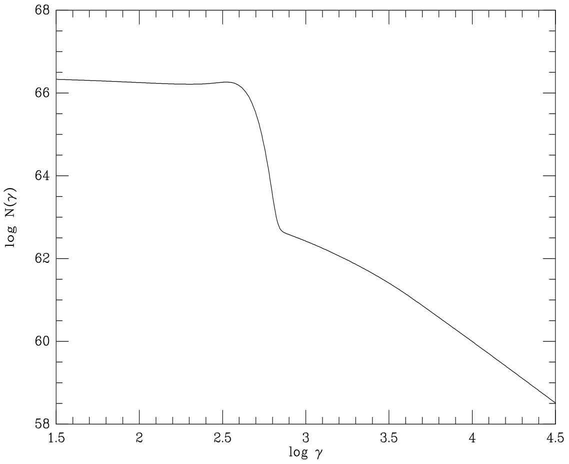

**Fig. 5.**— The energy spectrum of relativistic electrons in a model for a merging cluster (Sarazin 1999a). The large population at $\gamma \sim 300$ are due to many previous mergers, while the tail to high energies is due to the current merger.

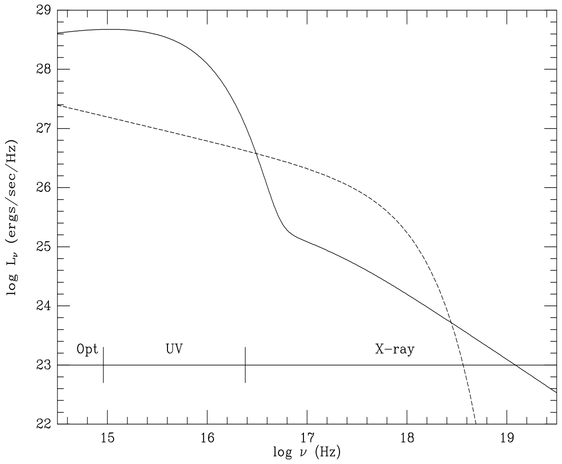

**Fig. 6.**— The IC spectrum produced by the electrons in the model for a merging cluster in Figure 5. For reference, the dashed line is thermal bremsstrahlung at a typical cluster luminosity.

its general existence and origin is uncertain. The observed EUV/soft X-ray emission from clusters might also be thermal (e.g., Kaastra et al. 2003).

More energetic electrons, with energies of many GeV, produce hard X-ray IC emission and radio synchrotron emission. Diffuse radio sources, not associated with radio galaxies, have been observed for many years in merging clusters (see the reviews by Feretti and by Giovannini in this volume). Centrally located, unpolarized, regular sources are called "radio halos", while peripheral, irregular, polarized sources are called "radio relics". Radio halos and relics are only found in clusters which are undergoing mergers. Recent Chandra observations seem to show a direct connection between radio halos and merger shocks in clusters (Markevitch & Vikhlinin 2001; Govoni et al. 2004; see also the papers by Feretti and by Markevitch in this volume).

In a few cases, radio sources resembling cluster radio relics have been found in projection near the central regions of cooling core clusters; examples include the relics in Abell 13, Abell 85, Abell 133, and Abell 4038 (Slee et al. 2001). Figure 7 shows the Chandra X-ray image of the central region ($2\times1\overset{\prime}{.}7$) of Abell 133 (red), with the radio image of the cluster superposed in green (Fujita et al. 2002). A tongue of cool X-ray emitting gas extends from the center of the cD galaxy (which is a radio source), to the northern "relic" source, suggesting that the radio plasma originated in the AGN in the central cD. It may be that these inner "relics" are really detached radio lobes from the central galaxies.

The radio power in cluster radio halos correlates very strongly with the X-ray luminosity and X-ray temperature of clusters (e.g., Bacchi et al. 2003; Liang et al. 2000). The correlation is much stronger than expected based on a simple scaling of cluster properties (e.g., Kempner & Sarazin 2001). This strong correlation might be explained if the radio-emitting electrons are due to merger shock or turbulent acceleration, and if the high X-ray luminosities and temperatures are due to the transient boosts which occur during mergers (Figure 3; Randall et al. 2002; Randall & Sarazin 2004).

The same higher energy electrons responsible for the radio emission will produce hard X-ray IC emission. Recently, such emission appears to have been detected with BeppoSAX and RXTE in at least Coma (Fusco-Femiano et al. 1999; Rephaeli, Gruber, & Blanco 1999), Abell 2256 (Fusco-Femiano et al. 2000; Rephaeli & Gruber 2003), and Abell 754 (Fusco-Femiano et al. 2003). However, the detections are relatively weak and controversial (Fusco-Femiano et al. 2004; Rossetti & Molendi 2004). Observations with INTEGRAL may help to resolve the nature of the hard excesses in clusters by providing higher spatial resolution hard X-ray images.

One of the difficulties in detecting nonthermal hard X-ray excesses in clusters of galaxies is the very strong thermal emission from clusters. As noted above, clusters with radio halos tend to be particularly hot (Liang et al. 2000), which only adds to this difficulty. One possible way around this difficulty would be to find cooler groups with radio halos; then, the contrast of the hard X-ray IC emission with the group thermal emission would be more favorable. A survey for radio halos in groups and follow-up hard X-ray observations might be useful. It is possible that such emission may have been detected already (Fukazawa et al. 2001; Hudson

& Henriksen 2003).

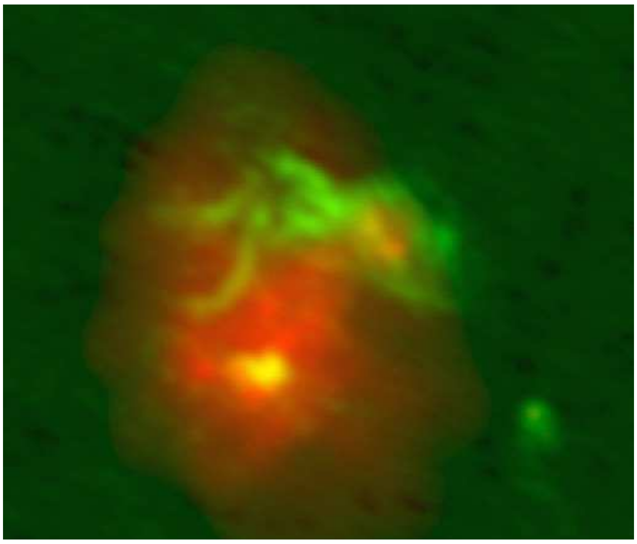

**Fig. 7.**— The Chandra X-ray image of the central region of the cooling core cluster Abell 133 is shown in red, with the radio image of the cluster superposed in green (Fujita et al. 2002). A tongue of cool X-ray emitting gas extends from the center of the cD galaxy (which is a radio source), to the northern "relic" source, suggesting that the radio plasma is a detached radio lobe from the central galaxy.

## IV. GAMMA-RAY EMISSION

I believe one of the most exciting possibilities for the future is the detection of clusters in hard gamma-ray radiation (Figure 8). Essentially, all models for the nonthermal populations in clusters predict that they should be very luminous gamma-ray sources, particularly at photon energies of ∼100 MeV (Sarazin 1999b; Gabici & Blasi 2004). The emission at these energies is partly due to electrons with energies of ∼150 MeV, which should be ubiquitous in clusters. One nice feature of this spectral region is that emission is produced both by relativistic electrons (through bremsstrahlung and IC emission) and relativistic ions. The ions (mainly protons) produce gamma-rays by $\pi^o$ decay; the process is similar to the secondary electron production process in Eq. (1) & (2):

$$\begin{aligned} p + p &\rightarrow p + p + n\pi \\ \pi^o &\rightarrow 2\gamma\,. \end{aligned} \tag{5}$$

Both the emissivity of bremsstrahlung by relativistic electrons and that of gamma-ray emission by $\pi^o$ decay involve collisions with the ions in the thermal intracluster gas; thus, the ratio of the two emission mechanisms depends mainly on the ratio of relativistic electrons to relativistic ions. Since the two emission mechanisms have different spectral shapes and are expected to be of comparable importance, one can determine separately both population is clusters. Models suggest that GLAST and AGILE will detect $\gtrsim$40 nearby clusters (e.g., Gabici & Blasi 2004).

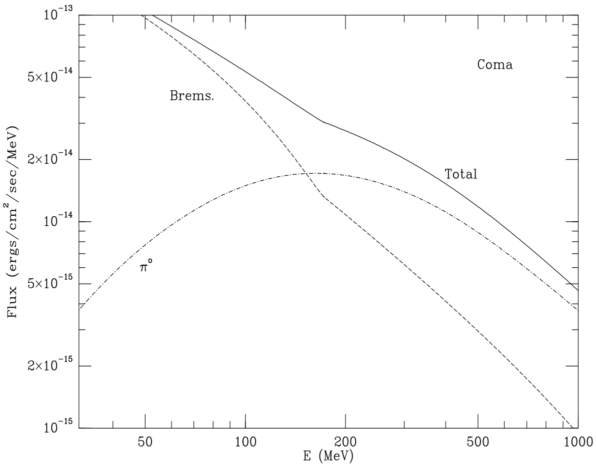

**Fig. 8.**— The gamma-ray emission spectrum from a model for relativistic particles in the Coma cluster (Sarazin 1999b). The emission from electrons (mainly bremsstrahlung in this model) and ions (due to $\pi^o$ decays) are shown separately.

## ACKNOWLEDGEMENTS

I would like to thank my collaborators, who have included Liz Blanton, Tracy Clarke, Yutaka Fujita, Josh Kempner, Scott Randall, Paul Ricker, and Motokazu Takizawa. This work was supported by the National Aeronautics and Space Administration through Chandra Award Numbers GO3-4155X, GO3-4160X, GO4-5132X, GO4-5133X, GO4-5137X, GO4-5149X, and GO4-5150X, and XMM/Newton Award Numbers NAG5-13088, NAG5-13089, NAG5-13737, NNG04GO34G, NNG04GO80G, and NNG04GP46G.

## REFERENCES

Bacchi, M., Feretti, L., Giovannini, G., & Govoni, F. 2003, A&A, 400, 465

Bowyer, S., Korpela, E. J., Lampton, M., Jones, T. W. 2004, ApJ, 605, 168

Buote, D. A., & Tsai, J. C. 1996, ApJ, 458, 27

Fukazawa, Y., et al., 2001, ApJ, 546, L87

Fujita, Y., Sarazin, C. L., Kempner, J. C., Rudnick, L., Slee, O. B., Roy, A. L., Andernach, H., & Ehle, M. 2002, ApJ, 575, 764

Fujita, Y., Takizawa, M., & Sarazin, C. L. 2003, ApJ, 584, 190

Fusco-Femiano, R., et al., 1999, ApJ, 513, L21

Fusco-Femiano, R., et al., 2000, ApJ, 534, L7

Fusco-Femiano, R., et al., 2003, A&A, 398, 441

Fusco-Femiano, R., Orlandini, M., Brunetti, G., Feretti, L., Giovannini, G., Grandi, P., & Setti, G. 2004, ApJ, 602, L73

Gabici, S., & Blasi, P. 2004, APh, 20, 579

Govoni, F., Markevitch, M., Vikhlinin, A., VanSpeybroeck, L., Feretti, L., & Giovannini, G. 2004, ApJ, 605, 695

Hudson, D. S., & Henriksen, M. J. 2003, ApJ, 595, L1

Kaastra, J. S., Lieu, R., Tamura, T., Paerels, F. B. S., & den Herder, J. W. 2003, A&A, 397, 445

Kempner, J., & Sarazin, C. L. 2001, ApJ, 548, 639

Kempner, J., Sarazin, C. L., & Ricker, P. R. 2002, ApJ, 579, 236

Liang, H., Hunstead, R. W., Birkinshaw, M., & Andreani, P. 2000, ApJ, 544, 686

Markevitch, M., & Vikhlinin, A. 2001, ApJ, 563, 95

Nevalainen, J., Lieu, R., Bonamente, M., & Lumb, D. 2003, ApJ, 584, 716

Randall, S. W., & Sarazin, C. L. 2004, preprint

Randall, S. W., Sarazin, C. L., & Ricker, P. M. 2002, ApJ, 577, 579

Randall, S. W., Sarazin, C. L., & Ricker, P. M. 2004, preprint

Rephaeli, Y., & Gruber, D. 2003, ApJ, 579, 587

Rephaeli, Y., Gruber, D., & Blanco, P. 1999, ApJ, 511, L21

Ricker, P. M., & Sarazin, C. L. 2001, ApJ, 561, 621

Rossetti, M., & Molendi, S. 2004, A&A, 414, L41

Sarazin, C. L. 1999a, ApJ, 520, 529

Sarazin, C. L. 1999b, in Diffuse Thermal and Relativistic Plasma in Galaxy Clusters, ed. H. Böhringer, L. Feretti, & P. Schuecker (Garching: MPE Rep. 271), 185

Sarazin, C. L. 2002, in Merging Processes in Clusters of Galaxies, ed. L. Feretti, I. M. Gioia, & G. Giovannini (Dordrecht: Kluwer), 1

Sarazin, C. L., & Lieu, R. 1998, ApJ, 494, L177

Slee, O. B., Roy, A. L., Murgia, M., Andernach, H., & Ehle, M. 2001, AJ, 122, 1172

Smith, G. P., Edge, A. C., Eke, V. R., Nichol, R. C., Smail, I., & Kneib, J.-P. 2003, ApJ, 590, L79

Torri, E., Meneghetti, M., Bartelmann, M., Moscardini, L., Rasia, E., & Tormen, G. 2004, MNRAS, 349, 476