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# THERMAL CONDUCTION IN SIMULATED GALAXY CLUSTERS

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## ABSTRACT

We study the formation of clusters of galaxies using high-resolution hydrodynamic cosmological simulations that include the effect of thermal conduction with an effective isotropic conductivity of $\frac{1}{3}$ the classical Spitzer value. We find that, for both a hot ($T_{L_x} \simeq 12$ keV) and several cold ($T_{L_x} \simeq 2$ keV) galaxy clusters, the baryonic fraction converted into stars does not change significantly when thermal conduction is included. However, the temperature profiles are modified, particularly in our simulated hot system, where an extended isothermal core is readily formed. As a consequence of heat flowing from the inner regions of the cluster both to its outer parts and into its innermost resolved regions, the entropy profile is altered as well. This effect is almost negligible for the cold cluster, as expected based on the strong temperature dependence of the conductivity. Our results demonstrate that while thermal conduction can have a significant influence on the properties of the intracluster medium (ICM) of rich clusters, it appears unlikely to provide by itself a solution for the overcooling problem in clusters or to explain the current discrepancies between the observed and simulated properties of the ICM.

*Subject headings:* conduction — cosmology: theory — galaxies: clusters: general — methods: numerical

*On-line material:* color figure

## 1. INTRODUCTION

Over the last few years, spatially resolved spectroscopic observations with the *XMM-Newton* and *Chandra* satellites have provided invaluable information about the structure of cooling gas in central cluster regions. Contrary to expectations based on the standard cooling flow model (Fabian 1994), these observations have ruled out the presence of significant amounts of star formation and cold gas at temperatures below one-fourth of the cluster virial temperature (e.g., Peterson et al. 2001; Molendi & Pizzolato 2001; Böhringer et al. 2002). The spectroscopically measured mass-deposition rates are ~10 times smaller than those inferred from the spikes of X-ray emissivity seen in relaxed clusters (e.g., McNamara et al. 2001; David et al. 2001). These results consistently indicate that some heating mechanism operates in cluster cores, supplying sufficient energy to the gas to prevent it from cooling to low ($\lesssim 1$ keV) temperatures. Furthermore, measurements of temperature profiles for relaxed clusters with $T \gtrsim 3$ keV show that they follow an approximately universal profile: gas is almost isothermal on scales below one-fourth of the virial radius (De Grandi & Molendi 2002, hereafter DM02; Pratt & Arnaud 2002), with a smooth decline of temperature toward the innermost regions (e.g., Allen, Schmidt, & Fabian 2001; Johnstone et al. 2002; Ettori et al. 2002).

Direct hydrodynamical simulations of cluster formation have so far failed to reproduce these features. In particular, simulations that include cooling and star formation find an increase of the gas temperature in the central regions (e.g., Katz & White 1993); here central gas *does* cool out of the intracluster medium (ICM) and loses its pressure support, so that gas flows toward the center, undergoing compressional heating. This leads to the counterintuitive result that cooling generates a steepening of the central temperature profiles, unlike observed.

Narayan & Medvedev (2001, hereafter NM01) have suggested thermal conduction as a possible heating mechanism for the cores of clusters. This process could transport thermal energy from the outer cluster regions to the (slightly cooler) central gas, thereby largely offsetting its cooling losses and stabilizing the ICM (cf. Soker 2003). However, conduction can have a significant effect only if the conductivity $\kappa$ of the ICM is a sizable fraction of the Spitzer (1962) value, $\kappa_{Sp}$, appropriate for an unmagnetized plasma. In the presence of a magnetic field, conduction is heavily suppressed orthogonal to the field lines, so that for a tangled magnetic field, one usually expects a relatively low, effectively isotropic conductivity, with the amount of suppression depending on the field topology. However, NM01 have shown that for a chaotically tangled magnetic field, conductivities in the range $\kappa \sim (0.2–0.5)\kappa_{Sp}$ can be recovered. Such field configurations may quite plausibly arise in clusters of galaxies as a result of turbulence, so that high conductivities in some parts of the ICM may be viable despite the presence of magnetic fields. Using simple analytic models based on the assumption of a local balance between radiative cooling and thermal conduction, Zakamska & Narayan (2003) and Voigt & Fabian (2004) were able to reproduce the observational data for several clusters, including their detailed temperature profiles. They treated the effective isotropic conductivity $\kappa$ as a fit parameter and found good fits for several clusters with sub-Spitzer values, while some implied unphysically large super-Spitzer conductivities. These results interestingly suggest that conduction may play an important role, while also hinting that yet another heating mechanism may be present, for example, the energy feedback from a central active galactic nucleus (AGN; e.g., Ruszkowski & Begelman 2002; Brighenti & Mathews 2003). Note, however, that a number of other estimates of $\kappa$, based on the complex temperature structure of clusters, suggest a strong suppression of the conductivity, with $\kappa \approx (0.1–0.001)\kappa_{Sp}$ (Ettori & Fabian 2000; Vikhlinin et al. 2001; Markevitch et al. 2003).

In this Letter, we present the first cosmological hydrodynamical simulations of cluster formation that account self-consistently for thermal conduction, as well as radiative cooling and supernova feedback. Such simulations are essential to understand the highly nonlinear interplay between conduction and

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| Simulated Clusters (1) | $M_{\rm vir}$ ($10^{14}\ h^{-1}\ M_\odot$) (2) | $f_{\rm cold}$ (3) | $T_M$ (keV) (4) | $T_{L_{\rm X}}$ (keV) (5) | $L_{\rm X}$ ($10^{44}$ ergs s$^{-1}$) (6) |
|---|---|---|---|---|---|
| $\langle$Cl1$\rangle$ .............. | $1.13 \pm 0.05$ | $0.27 \pm 0.01$ | $1.32 \pm 0.04$ | $2.28 \pm 0.07$ | $0.47 \pm 0.04$ |
| $\langle$Cl1$\rangle_{+\rm cond.}$ ......... | $1.08 \pm 0.06$ | $0.26 \pm 0.01$ | $1.30 \pm 0.05$ | $2.15 \pm 0.04$ | $0.43 \pm 0.05$ |
| Cl2 ................ | 22.6 | 0.23 | 9.3 | 11.9 | 38.0 |
| Cl2$_{+\rm cond.}$ ........... | 22.6 | 0.23 | 9.8 | 12.3 | 54.6 |

NOTES.—Properties of clusters without and with conduction ("+cond"). Col. (2): Virial mass. Col. (3): Fraction of stars + gas below $3 \times 10^4$ K within $R_{\rm vir}$. Col. (4): Mass-weighted temperature. Col. (5): Emission-weighted temperature. Col. (6): Bolometric X-ray luminosity.

cooling during the formation of clusters. In this study, we focus on the effect of conduction on the temperature and entropy structures of clusters with rather different temperatures of $T_{L_{\rm X}} \simeq 2$ and 12 keV.
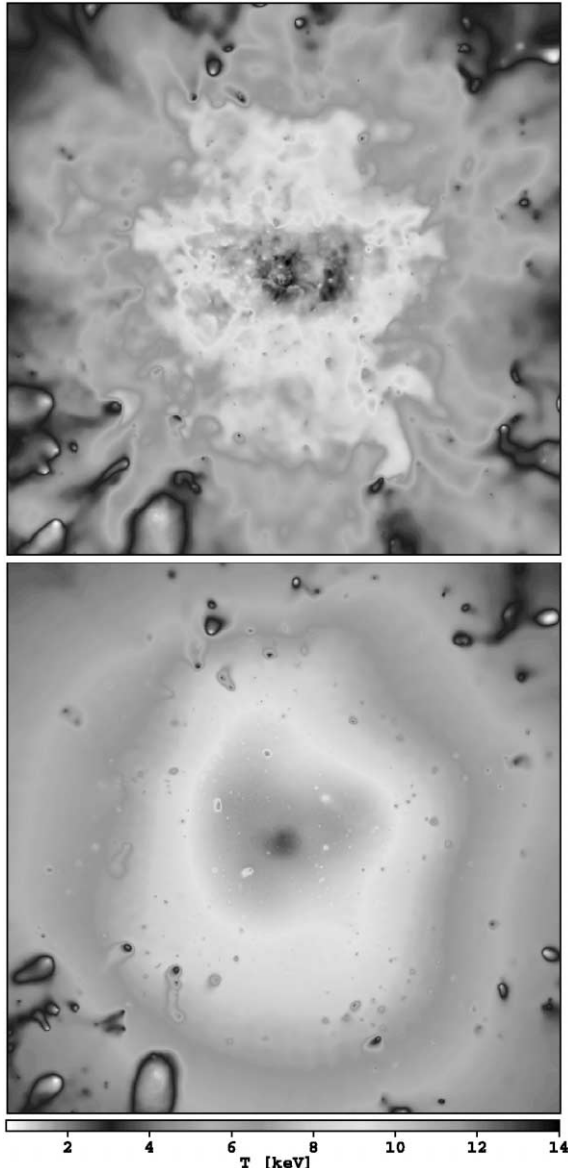


FIG. 1.—Projected maps of mass-weighted gas temperature for our hot cluster (Cl2), simulated both without and with thermal conduction (*top and bottom panels, respectively*). Each panel shows the gas within a box of physical side-length of 8 Mpc ($R_{\rm vir} \approx 3.9$ Mpc), centered on the cluster center. [*See the electronic edition of the Journal for a color version of this figure.*]

## 2. NUMERICAL SIMULATIONS

Our simulations were carried out with GADGET-2, a new version of the parallel TreeSPH simulation code GADGET (Springel et al. 2001). It uses an entropy-conserving formulation (Springel & Hernquist 2002) of smoothed particle hydrodynamics (SPH) and includes radiative cooling, heating by a UV background, and a treatment of star formation and feedback processes. The latter is based on a subresolution model for the multiphase structure of the interstellar medium (Springel & Hernquist 2003). We have augmented the code with a new method for treating conduction in SPH, which both is stable and manifestly conserves thermal energy even when individual and adaptive timesteps are used. In our cosmological simulations, we assume an effective isotropic conductivity parameterized as a fixed fraction of $\kappa_{\rm Sp}$. We also account for saturation, which can become relevant in low-density gas. A full discussion of our numerical implementation of conduction is given in Jubelgas, Springel, & Dolag (2004). We simulated galaxy clusters having two widely differing virial masses, referred to as "Cl1" and "Cl2" (see Table 1). The clusters have been extracted from a dark matter–only simulation with box size 479 $h^{-1}$ Mpc of a flat $\Lambda$ cold dark matter model with $\Omega_0 = 0.3$, $h = 0.7$, $\sigma_8 = 0.9$, and $\Omega_b = 0.04$. Using the "zoomed initial conditions" technique (Tormen, Bouchet, & White 1997), we resimulated the clusters with higher mass and force resolution by populating their Lagrangian regions in the initial conditions with more particles, adding additional small-scale power appropriately. Gas was introduced in the high-resolution region by splitting each parent particle into a gas and a dark matter particle with $m_{\rm gas} = 1.7 \times 10^8\ h^{-1}\ M_\odot$ and $m_{\rm DM} = 1.13 \times 10^9\ h^{-1}\ M_\odot$, respectively. The clusters were hence resolved with about $4 \times 10^6$ and $2 \times 10^5$ particles, respectively. The lower computational cost of Cl1 systems allowed us to simulate five clusters within a very narrow mass range, all yielding consistent results. The gravitational softening length was $\epsilon = 5.0\ h^{-1}$ kpc (Plummer equivalent), kept fixed in comoving units. For each cluster, we ran simulations both with and without thermal conduction, but we always included radiative cooling with a primordial metallicity and star formation. For the conduction runs, we assume a conductivity of $\kappa = (1/3)\,\kappa_{\rm Sp}$, where $\kappa_{\rm Sp} \propto T^{5/2}$ is the temperature-dependent Spitzer rate for a fully ionized unmagnetized plasma. Our choice for $\kappa$ is appropriate in the presence of magnetized domains with randomly oriented $B$ fields (e.g., Sarazin 1988) or for a chaotically tangled magnetic field (NM01).

## 3. RESULTS

An expected general effect of thermal conduction is to make the gas more isothermal by smoothing out temperature substructure in the ICM. This effect is clearly visible in Figure 1, where we compare projected temperature maps of Cl2, with
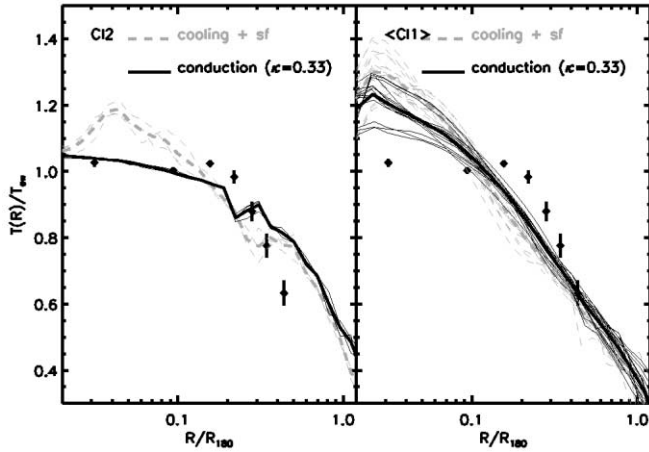
Fig. 2.—Comparison of projected temperature profiles for our hot (Cl2, *left panel*) and cold clusters (Cl1, *right panel*) when conduction is, or is not, included. For each run, thick lines give the average profiles for three orthogonal projection directions, which are also shown individually as thin lines. The bundle of lines in the bottom panel illustrates the dispersion among our five simulated clusters of this mass. For reference, symbols with error bars give observational data (DM02).
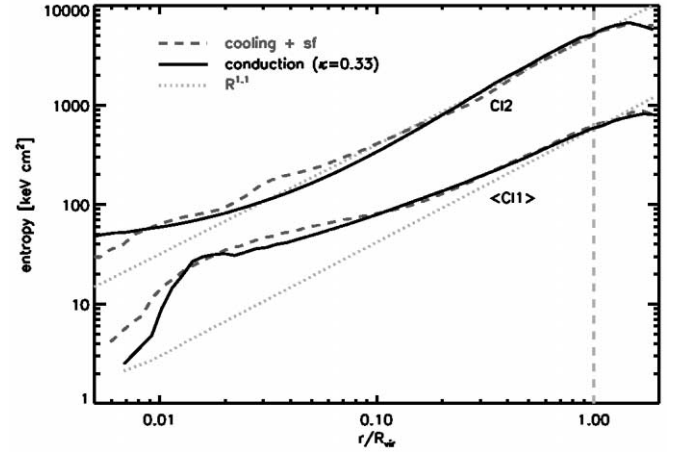


Fig. 3.—Entropy profiles for the Cl2 cluster (*top curves*) and for the average of the Cl1 clusters (*bottom curves*). The different lines distinguish runs with and without thermal conduction and for pure gravitational heating.

and without conduction. Without conduction (*top*) a rich small-scale pattern of temperature variations is formed, stemming from the continuous stirring of the ICM by infalling galaxies. These fluctuations are largely wiped out when conduction is included (*bottom*). Gas in large infalling galaxies can stay cooler than the surrounding ICM (prior to ram pressure stripping) in the simulation without conduction, but this same gas is conductively heated as soon as it enters the hot cluster atmosphere in the other simulation, leading to much more rapid thermalization. We also note that the cluster with conduction shows a larger near-isothermal region near the center and appears somewhat hotter in its outer parts. In Figure 2, we show the projected temperature profiles for the simulated clusters, compared with observational results (DM02) for a set of 22 clusters with $T > 3$ keV observed with *BeppoSAX*. For the runs that include only cooling and star formation, we find rising temperature profiles toward the cluster center, consistent with recent simulation work (e.g., Lewis et al. 2000; Kay et al. 2002; Tornatore et al. 2003; Borgani et al. 2004). This behavior disagrees with observational evidence for the presence of an isothermal regime at $R \lesssim 0.2R_{180}$ (here $R_{180}$ is the radius encompassing an average density $180\rho_{crit}$) and a smooth decline in the innermost regions (Allen, Schmidt, & Fabian 2001; DM02). However, thermal conduction significantly flattens the temperature profiles, and for the hot cluster, an isothermal core is created, making it more similar to what is observed. For the colder system, the profile is almost unaffected, consistent with expectations based on the strong dependence of the conductivity on electron temperature ($\kappa_{Sp} \propto T^{5/2}$). This also implies that thermal conduction cannot easily account for the observed self-similarity of the temperature profiles of fairly relaxed clusters.

We find that the mass-weighted as well as emission-weighted temperatures of the two simulated clusters change by less than 10% when conduction is included. Conduction thus mainly appears to redistribute the overall thermal energy content within the cluster, while not causing a significant heat loss to the outer intergalactic medium as proposed by Loeb (2002). We do however find that the temperature of the outer parts of clusters is raised by conduction, as seen in the temperature profiles of Figure 2. On the basis of our simulations, it is not clear whether conductive heating of the innermost parts of clusters occurs in

any significant way. Instead, the dominant effect seems to be heat transport from inner to outer parts, which can be understood as a consequence of the falling temperature gradient obtained in simulations that include only radiative cooling and star formation. While conduction appears to be effective in establishing an isothermal temperature in the core, the innermost regions subsequently do not become still cooler, which would be required to turn around the direction of conductive heat flow and tap the thermal reservoir at larger radii in the way proposed by Zakamska & Narayan (2003). We thus do not find that conduction can really prevent the central cooling flow; it apparently only transports the energy gained by compressional heating of inflowing gas to outer regions of the cluster. In fact, the inclusion of conduction may even make the central cooling flow stronger, depending on the resulting density and temperature structure of the inner parts in dynamical equilibrium. For our hot cluster, this actually seems to be the case, judging from the bolometric X-ray luminosity, which is increased by about 40% at $z = 0$ when conduction is included. The colder clusters, on the other hand, show an essentially unchanged X-ray luminosity, consistent with our previously found trends.

The fraction of collapsed baryons (cold gas and stars) in the clusters is essentially independent of conduction (see Table 1 for a summary of the main cluster characteristics). This result is not really surprising because at high $z$, when most of the star formation in the cluster galaxies takes place, the gas temperature in the progenitor systems is much lower than the virial temperature reached eventually at $z = 0$. Therefore, the effect of thermal conduction is expected to be weak. The amount of collapsed gas thus remains at $f_{cold} \simeq 0.20$–$0.25$, about a factor of 2 larger than indicated by observations (e.g., Balogh et al. 2001; Lin, Mohr, & Stanford 2003), suggesting that stronger feedback processes than included in our simulations are at work in the real universe. Conduction therefore appears unable to resolve this overcooling problem on its own.

Further information about the thermodynamical properties of the ICM is provided by its entropy ($S = Tn_e^{-2/3}$) profile, shown in Figure 3 for our simulations, also compared to results for pure gravitational heating. Cooling selectively removes low entropy gas from the hot diffuse phase in central cluster regions, such that a net entropy increase of X-ray–emitting gas compared to pure gravitational heating simulations is seen. This has been predicted by analytic models of the ICM (e.g., Voit et al. 2002) and has also been confirmed in direct hydrody-

namical simulations. The inclusion of heat conduction appears to reverse part of this change in the entropy profile. The entropy decreases on scales $\sim(0.01–0.1)R_{\mathrm{vir}}$ because of conductive losses both to the outer and to the innermost parts. For the colder systems, only a very weak modification in the region of central mass drop-out is seen. Hotter systems hence tend to become more isentropic in central regions, which is just the opposite of what one would observe if, instead, preheating is responsible for breaking the ICM self-similarity (Borgani et al. 2001), but the trend is consistent with a recent analysis of entropy profiles obtained from *ASCA* data of groups and clusters (Ponman et al. 2003).

## 4. CONCLUSIONS

We have presented self-consistent cosmological hydrodynamical simulations of the formation of clusters that for the first time included the effect of thermal conduction. We performed simulations of five moderately poor clusters with $T_{L_X} \simeq 2.0$ keV and one rich system with $T_{L_X} \simeq 12$ keV. For all clusters, we compared simulations following radiative cooling, star formation, and feedback, with the corresponding ones that also included thermal conduction with an effective isotropic conductivity of $\kappa = \kappa_{\mathrm{Sp}}/3$, finding:

1. Thermal conduction creates an isothermal core in the center of our hot cluster, thus producing a temperature profile similar to that observed. However, this effect is much less pronounced for our poorer systems, owing to the sensitive temperature dependence of conduction. As a result, the presence of conduction together with cooling does not lead to self-similar temperature profiles, unlike observed for real clusters.

2. Compared to simulations with cooling only, conduction leads to a small decrease of the entropy in most of the inner regions of the hot cluster, except perhaps for the innermost part at $R \lesssim 0.01R_{\mathrm{vir}}$. This can be understood as a result of heat flowing from these regions both to outer parts of the cluster and at some level also to the innermost regions. Again, this effect is largely absent in the colder simulated clusters.

3. Conduction does not avoid the "overcooling problem." Even for our hot cluster, where conduction is quite efficient, we find an essentially unchanged baryon fraction of $f_{\mathrm{cold}} \gtrsim 0.2$ in cold gas and stars, which is larger than what is observed. This is

because most of the cooling and star formation takes place at high $z$ when the temperature of the diffuse gas in halos is low enough that conduction is inefficient. Stronger feedback processes than considered here, e.g., energetic galactic winds, are required to solve this problem. We note that even for the hot cluster at $z = 0$, we do not find a temperature structure that would allow central cooling losses to be offset by heat conduction, making it questionable whether a detailed local balance between radiative losses and heat conduction can arise naturally in hierarchical cluster formation.

While larger samples of simulated clusters will be required for a more detailed assessment of the role of thermal conduction, our results already demonstrate that conduction can have a sizable effect on the observational characteristics of rich clusters. However, its inclusion appears unlikely to overcome the current discrepancies between simulated and observed properties of the ICM. For instance, conduction tends to produce different temperature profiles for cold and hot clusters, invoking a conflict with the observed self-similarity. Furthermore, since conduction does not prevent overcooling, the presence of some other heating source, perhaps AGNs, appears to be still required. Admittedly, our present simulations still lack a realistic self-consistent description of the magnetic field structure, which can make conduction less important. Spatial variations in the conductivity, its interplay with gas turbulence, as well as potential effects of anisotropic conduction due to ordered field components can thus not be properly taken into account. This represents a major uncertainty in assessing the relevance of conduction for real clusters. It is a highly interesting task for future work to reduce this uncertainty by a better theoretical and observational understanding of the magnetic properties of the ICM.

## REFERENCES

Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2001, MNRAS, 328, L37
Balogh, M. L., Pearce, F. R., Bower, R. G., & Kay, S. T. 2001, MNRAS, 326, 1228
Böhringer, H., Matsushita, K., Churazov, E., Ikebe, Y., & Chen, Y. 2002, A&A, 382, 804
Borgani, S., Governato, F., Wadsley, J., Menci, N., Tozzi, P., Lake, G., Quinn, T., & Stadel, J. 2001, ApJ, 559, L71
———. 2004, MNRAS, 348, 1078
Brighenti, F., & Mathews, W. G. 2003, ApJ, 587, 580
David, L. P., et al. 2001, ApJ, 557, 546
De Grandi, S., & Molendi, S. 2002, ApJ, 567, 163 (DM02)
Ettori, S., & Fabian, A. C. 2000, MNRAS, 317, L57
Ettori, S., Fabian, A. C., Allen, S. W., & Johnstone, R. M. 2002, MNRAS, 331, 635
Fabian, A. C. 1994, ARA&A, 32, 277
Johnstone, R. M., Allen, S. W., Fabian, A. C., & Sanders, J. S. 2002, MNRAS, 336, 299
Jubelgas, M., Springel, V., & Dolag, K. 2004, MNRAS, in press (astro-ph/0401456)
Katz, N., & White, S. D. M. 1993, ApJ, 412, 455
Kay, S. T., Pearce, F. R., Frenk, C. S., & Jenkins, A. 2002, MNRAS, 330, 113
Lewis, G. F., et al. 2000, ApJ, 536, 623
Lin, Y.-T., Mohr, J. J., & Stanford, S. A. 2003, ApJ, 591, 749

Loeb, A. 2002, NewA, 7, 279
Markevitch, M., et al. 2003, ApJ, 586, L19
McNamara, B. R., et al. 2001, ApJ, 562, L149
Molendi, S., & Pizzolato, F. 2001, ApJ, 560, 194
Narayan, R., & Medvedev, M. V. 2001, ApJ, 562, L129 (NM01)
Peterson, J. R., et al. 2001, A&A, 365, L104
Ponman, T. J., Sanderson, A. J. R., & Finoguenov, A. 2003, MNRAS, 343, 331
Pratt, G. W., & Arnaud, M. 2002, A&A, 394, 375
Ruszkowski, M., & Begelman, M. C. 2002, ApJ, 581, 223
Sarazin, C. 1988, X-Ray Emission from Clusters of Galaxies (Cambridge: Cambridge Univ. Press)
Soker, N. 2003, MNRAS, 342, 463
Spitzer, J. 1962, Physics of Fully Ionized Gases (New York: Interscience)
Springel, V., & Hernquist, L. 2002, MNRAS, 333, 649
———. 2003, MNRAS, 339, 289
Springel, V., Yoshida, N., & White, S. D. M. 2001, NewA, 6, 79
Tormen, G., Bouchet, F. R., & White, S. D. M. 1997, MNRAS, 286, 865
Tornatore, L., et al. 2003, MNRAS, 342, 1025
Vikhlinin, A., Markevitch, M., Forman, W., & Jones, C. 2001, ApJ, 555, L87
Voigt, L. M., & Fabian, A. C. 2004, MNRAS, 347, 1130
Voit, G. M., Bryan, G. L., Balogh, M. L., & Bower, R. G. 2002, ApJ, 576, 601
Zakamska, N. L., & Narayan, R. 2003, ApJ, 582, 162