THE ASTROPHYSICAL JOURNAL, 562:L153–L156, 2001 December 1
© 2001. The American Astronomical Society. All rights reserved. Printed in U.S.A.

NONHYDROSTATIC GAS IN THE CORE OF THE RELAXED GALAXY CLUSTER A1795

M. MARKEVITCH,[1] A. VIKHLININ,[1] AND P. MAZZOTTA[2]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; maxim@head-cfa.harvard.edu
Received 2001 August 31; accepted 2001 October 9; published 2001 November 15

ABSTRACT

Chandra data on A1795 reveal a mild edge-shaped discontinuity in the gas density and temperature in the southern sector of the cluster at $r = 60\ h^{-1}$ kpc. The gas inside the edge is 1.3–1.5 times denser and cooler than outside, while the pressure is continuous, indicating that this is a "cold front," the surface of contact between two moving gases. The continuity of the pressure indicates that the current relative velocity of the gases is near zero, making the edge appear to be in hydrostatic equilibrium. However, a total mass profile, derived from the data in this sector under the equilibrium assumption, exhibits an unphysical jump by a factor of 2, with the mass inside the edge being lower. We propose that the cooler gas is "sloshing" in the cluster gravitational potential well and is now near the point of maximum displacement, where it has zero velocity but nonzero centripetal acceleration. The distribution of this nonhydrostatic gas should reflect the reduced gravity force in the accelerating reference frame, resulting in the apparent mass discontinuity. Assuming that the gas outside the edge is hydrostatic, the acceleration of the moving gas can be estimated from the mass jump, $a \sim 800\ h$ km s^{-1} $(10^8$ yr$)^{-1}$. The gravitational potential energy of this gas that is available for dissipation is about half of its current thermal energy. The length of the cool filament extending from the cD galaxy (Fabian et al.) may give the amplitude of the gas sloshing, 30–40 h^{-1} kpc. Such gas bulk motion might be caused by a disturbance of the central gravitational potential by past subcluster infall.

Subject headings: galaxies: clusters: individual (Abell 1795) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

The hot gas that is filling clusters of galaxies delineates the gravitational potential of the cluster dark matter. This enables a derivation of the cosmologically important cluster masses from the X-ray data (e.g., Bahcall & Sarazin 1977; Sarazin 1988). Clusters form via mergers that stir the gas (e.g., Roettiger, Loken, & Burns 1997 and other simulations), after which the cluster should be left alone for a few gigayears to reach hydrostatic equilibrium for the mass measurement to work. Clusters with regular X-ray morphology and the X-ray brightness strongly peaked on a cD galaxy should have formed sufficiently long ago and are therefore believed to be the safest candidates for X-ray mass measurements. For a number of clusters, however, the X-ray–derived masses are systematically lower than the independent gravitational lensing measurements (e.g., Miralda-Escudé & Babul 1995 and later works). Both lensing and X-ray measurements can suffer from systematic effects such as line-of-sight substructure and inadequate X-ray modeling (e.g., Bartelmann & Steinmetz 1996; Allen, Ettori, & Fabian 2001).

A1795 ($z = 0.062$) is one of the most relaxed clusters in X-rays (e.g., Buote & Tsai 1996; Briel & Henry 1996). It has had sufficient time to develop a cool core (e.g., Edge, Stewart, & Fabian 1992), although its precise nature is debated (Tamura et al. 2001). Zooming in on the center with *Chandra*, Fabian et al. (2001) discovered a 40″ filament of cool gas extending from the cD galaxy, coincident with the optical Hα filament (Cowie et al. 1983). A total mass profile was derived from *Chandra* data by Ettori et al. (2000).

Below we analyze the same *Chandra* data set and show that even in the centers of such relaxed clusters as A1795, full hydrostatic equilibrium may not have been achieved, resulting in considerable X-ray mass underestimates. A similar finding was reported earlier for the otherwise relaxed cluster RX J1720+26 (Mazzotta et al. 2001b). We measure the bulk velocity and, for the first time, the acceleration of the gas near the cluster center by analyzing a mild brightness edge, similar to those detected by *Chandra* in several other clusters (Markevitch et al. 2000; Vikhlinin, Markevitch, & Murray 2001; Mazzotta et al. 2001a, 2001b). We use $H_0 = 100\ h$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$; if not specified, confidence intervals are 68% for one parameter.

2. ANALYSIS

We have combined two archival ACIS-S observations of A1795 performed in 1999 December and 2000 March, limiting the analysis to the S3 chip. The standard data cleaning resulted in the total useful exposure of 36 ks. The background was modeled as in, e.g., Markevitch et al. (2000). The cluster 0.7–5 keV image is shown in Figure 1. In the center, there is the gas filament discovered by Fabian et al. (2001). South of the center, outside the filament region, one can see a subtle edge feature that is the subject of this work.

The radial brightness profile, extracted in the southern 60° sector centered on the cD galaxy (see Fig. 1*b*) is shown in Figure 2*a*. As other profiles below, it is derived in narrow elliptical segments parallel to the edge (the ellipse in Fig. 1*b*) and plotted as a function of the average emission-weighted radius in each segment. In the narrow sectors of interest, these segments are reasonably close to circular, so below we assume spherical symmetry for simplicity of our qualitative analysis. The brightness profile has the characteristic shape of a projected spherical gas density discontinuity. In the radial range 40″–140″ (within a factor of 2 of the edge radius), the profile is fitted very well by a gas density model consisting of two power laws (1.10 ± 0.06 and 1.42 ± 0.03) and a jump by a factor of 1.28 ± 0.03 (see Fig. 2*c*). The observed temperature differences (described below) have a negligible effect on the density

[1] Also at the Space Research Institute (IKI), Russian Academy of Sciences, 84/32 Profsojuznaya Str., 117810 Moscow, Russia.
[2] ESA Fellow.

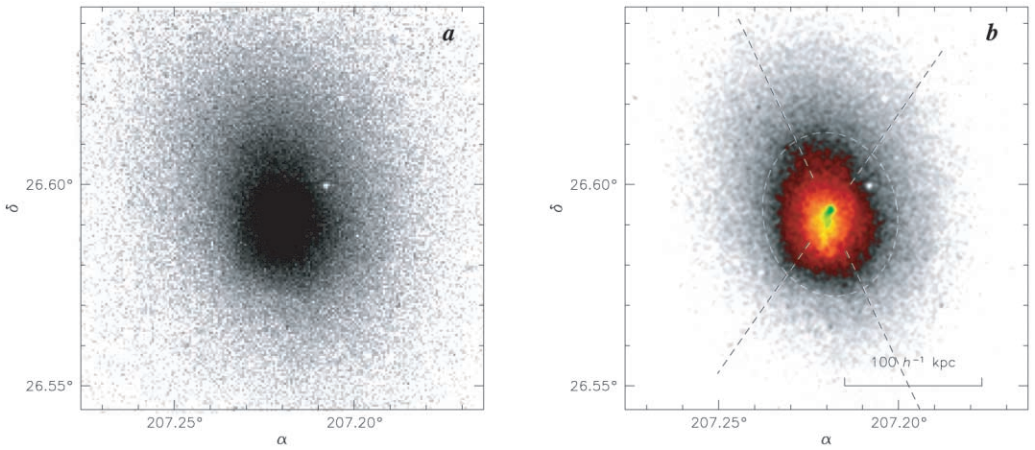


FIG. 1.—(*a*) ACIS image in the 0.7–5 keV band. Pixels are 2″; point sources are excluded. A mild brightness edge is seen 60 h^{-1} kpc south of the center. (*b*) Same image smoothed by a Gaussian with $\sigma = 1''$ (brightness increases from gray to red to green). The cool filament (Fabian et al. 2001) is seen in the center. The dashed ellipse centered on the cD galaxy approximately delineates the edge. The dashed lines show two 60° sectors used for extracting radial profiles.

model. Closer to the center lies the filament region, so we do not include smaller radii in the analysis and show them only for illustration. At larger radii, the density profile is known to steepen (Vikhlinin, Forman, & Jones 1999), but this is unimportant for our fits.

For spectral modeling, we averaged the position-dependent telescope effective area, the detector nonuniformity, and spectral response over a given region with the cluster brightness as weight. Response matrices released in 2001 August 8 were used. The temperature profile in the southern sector, derived using Galactic absorption and the Kaastra (1992) plasma model, is shown in Figure 2*b*. For the bins inside the edge, we have subtracted the projected contribution from the outer, hotter gas, assuming a 6.7 keV temperature (the average for the three outer

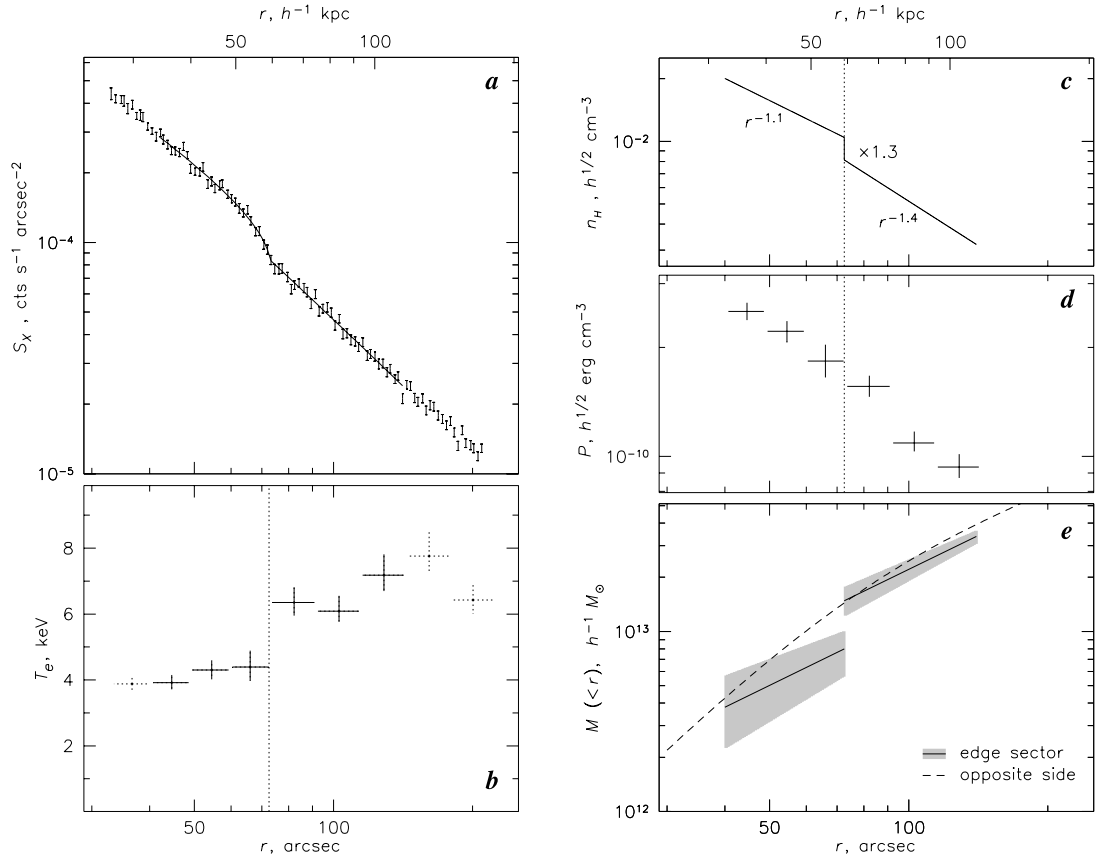


FIG. 2.—Profiles from the southern 60° sector containing the edge. Errors are 68%. The vertical dotted lines show the edge position. (*a*) Surface brightness in the 0.7–5 keV band. The line is a fit in the $r = 40''$–$140''$ range; the corresponding density model is shown in (*c*). (*b*) Temperature profile with approximate deprojection (see text). The solid crosses show values used for the derivation of the pressure and total mass across the edge. (*d*) Pressure profile. (*e*) Total mass within a given radius (confidence bands are shown in gray). For comparison, a fit in the sector opposite to the edge (see Figs. 1*b* and 3) is shown by a dashed line; they must show the same mass if the gas is in hydrostatic equilibrium.

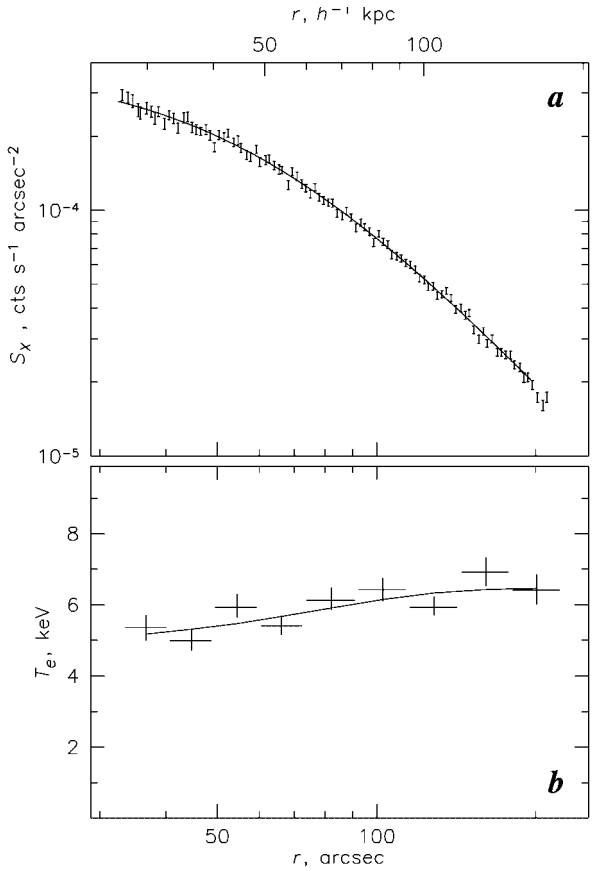


FIG. 3.—Profiles from the northern 60° sector opposite to the edge. (*a*) Surface brightness. The line shows a fit by a β-model. (*b*) Projected temperature profile. The line shows a best-fit model used to estimate the total mass (Fig. 2*e*). Errors are 68%.

bins) and the best-fit density model. The resulting profile is consistent with two constants inside and outside the edge; thus, any more complex deprojection is not warranted. The outside temperature is in agreement with the 6–7 keV average observed at larger radii (e.g., Markevitch et al. 1998; Arnaud et al. 2001).

Since our analysis includes regions with short cooling time, we checked if the presence of any multicomponent gas could bias our measurements. We first tried to fit our spectra with a simple two-temperature or standard cooling flow model, which did not improve the fits. On the other hand, the spectrum of the central region ($r < 30''$) exhibits lines of ionized Si and S at 1.9 and 2.4 keV (rest frame), respectively, that can be fitted with a heavily absorbed ($N_{\rm H} > 10^{22}$ cm^{-2}), cool ($T \sim 0.5$ keV) thermal component, in addition to the main 3–4 keV gas. The origin of this emission is beyond the scope of this Letter, but we have looked for a similar contaminant in the regions of our interest. For this, only the second observation taken at the ACIS temperature of -120°C was used, for which the current response matrices have adequate accuracy (the -110°C matrices are sufficient to fit the continuum shape but not the lines). In the combined three spatial bins outside the edge (the solid crosses in Fig. 2*b*), such a component is not required. For the inner three bins, the fit is marginally improved ($\Delta\chi^2 = 8$ for 3 additional degrees of freedom); however, the best-fit temperature of the main gas does not change, and the fit does not allow a significant filling factor for these cool clouds. Also, the cool component gives only 2% of the flux in the 0.7–5 keV band and cannot bias our density profile for the main gas. Thus, the derived quantities for the diffuse gas in our regions of interest should not be affected.

3. DISCUSSION

The temperature profile reveals that the edge is a "cold front," or a contact discontinuity between two moving gases, similar to (although not quite as prominent as) those discovered by *Chandra* in several other clusters. From the edge geometry, the denser gas should be moving away from the center (or the outer gas flowing onto the center). Multiplying the gas density by its temperature, we obtain a profile of thermal pressure across the edge (Fig. 2*d*). It is continuous; if we fitted the inner three and outer three temperature values (the solid crosses in Fig. 2*b*) by power-law functions of radius, the pressure jump is 1.0 ± 0.2 (a 90% error including the scatter of the power-law slopes). This leaves little or no room for a relative gas motion since the ram pressure from such a motion would cause the inner thermal pressure to be higher compared with that on the outside (beyond the small stagnation region), as is indeed seen in A3667 (Vikhlinin et al. 2001). The above upper limit on the pressure jump corresponds to a 90% upper limit on the Mach number of 0.5 (see, e.g., Fig. 6 in Vikhlinin et al. 2001). The limit is probably even stronger because by fitting the temperature profiles with power laws in narrow radial intervals, we may allow too much unphysical freedom. If instead one assumes constant temperatures inside and outside, the Mach number should be very close to 0.

Thus, the inner and outer gases appear very nearly at rest and in pressure equilibrium. Therefore, one expects them to be in hydrostatic equilibrium in the cluster gravitational potential. Under this assumption and that of spherical symmetry, we can derive the cluster total mass profile in this radial range using our power-law fits to the temperature and density profiles in the immediate vicinity of the edge. This mass profile is shown in Figure 2*e* (the error bands include uncertainties of the local temperature gradients; uncertainties on the density gradients are negligible in comparison). The profile reveals an unphysical discontinuity by a factor of 2, with a formal significance of 99%. For comparison, we analyzed the northern sector of the cluster opposite to the edge. A brightness profile there shows no features and is well fitted by the customary β-model (Fig. 3*a*). The temperature is nearly constant, but for exactness, we have modeled its slow radial rise by a smooth function. Its emission-weighted projection is overlaid on the data in Figure 3*b*. The total mass profile derived using these fits is shown by a dashed line in Figure 2*e*. Outside the edge radius, the masses derived from the two opposite sectors agree, as they must. This indicates that the gas immediately outside the edge is indeed near hydrostatic equilibrium, while the gas inside the edge is not.

Similar mass discontinuities at the cold fronts were observed in A3667 (Vikhlinin et al. 2001) and RX J1720+26 (Mazzotta et al. 2001b). However, in the former, the cold front is a boundary of a subcluster flying with the sonic velocity where one does not expect hydrostatic equilibrium. The latter cluster is apparently relaxed on large scales, so the situation is similar to A1795, but there, too, a high velocity of the front could not be excluded. Mazzotta et al. (2001b) proposed that the core of RX J1720+26 is moving relative to the rest of the cluster as a result of the peculiar history of that cluster's collapse. However, such an explanation for A1795 (as well as several other generally relaxed clusters with similar features; M. Markevitch et al. 2001, in preparation) may require too much of a coincidence.

We propose instead that the cool gas just inside the edge is

"sloshing" north-south in the central potential well (which may be static at present) and is now observed near the point of maximum displacement, where it has zero velocity but nonzero centripetal acceleration. Such a gas would not be in hydrostatic equilibrium with the potential—instead, its distribution would reflect the reduced gravity force in the accelerating reference frame, resulting in the apparent mass underestimate. Assuming that the gas outside the edge is hydrostatic, the acceleration of the inner gas can be estimated from the mass jump ΔM as $a \sim G\Delta M r^{-2} \approx 3 \times 10^{-8}\ h$ cm s^{-2} or 800 h km s^{-1} $(10^8\ \mathrm{yr})^{-1}$, where r is the radius of the edge.

It is interesting to estimate the gravitational potential energy of this gas. Approximately, $E \sim G\Delta M r^{-1} \approx 5 \times 10^{15}$ ergs g^{-1}. For a 4 keV gas, this is about half of its thermal energy. As the gas accelerates, this energy becomes available for dissipation. Thus, such sloshing can produce significant heating in the cluster center that may offset some radiative cooling.

Unlike A3667 (the site of the most prominent cold front) where the cool gas is retained by a merging subcluster and travels together with its distinct dark matter halo (A. Vikhlinin et al. 2001, in preparation), here the moving gas is probably not attached to any underlying moving dark matter body. Indeed, simulations of cluster mergers (e.g., Roettiger et al. 1997) predict that late into a merger, the gas decouples from dark matter and sloshes in the changing gravitational potential for a significant time before coming to a hydrostatic equilibrium. However, a recent major merger in A1795 is unlikely because of the exceptional regularity of its X-ray image. Also, the gas temperature decreases toward the center, indicating that either the gas has had time to cool ($t_{\mathrm{cool}} \approx 10^{10}$ yr at the edge radius) or the cool gas from subcluster infall has had time to settle down, both processes requiring the absence of significant disturbance. Perhaps a localized gas motion in the core might be caused by a disturbance of the central gravitational potential by an infalling small subcluster. Such a disturbance would supply kinetic energy to the low-entropy gas accumulated over time in the cluster center, which is more responsive to small potential perturbations than the hotter outer gas. Alternatively, in clusters where the central active galactic nucleus produces large bubbles of hot plasma (e.g., Churazov et al. 2000; McNamara et al. 2000), such activity could supply kinetic energy to the surrounding cool gas. There are no obvious large bubbles in A1795.

We note that the central cool filament, extending southward from the cD galaxy (Fig. 1*b*), is aligned with the apparent direction of the most recent gas movement. This suggests that the cD galaxy in A1795 does not move with the gas but probably stays with the gravitational potential (to within its observed small 150 km s^{-1} velocity relative to the cluster average; Oegerle & Hill 1994). The filament is probably a cooling wake arising as the cD galaxy is moving relative to the gas, as proposed by Fabian et al. (2001), only their relative motion is not due to the cD galaxy's oscillations in the potential but rather to the sloshing of the gas. The filament length, 30–40 h^{-1} kpc, should then give the amplitude of the gas oscillations in the central potential well.

The observed mass discontinuity may have a significant effect on X-ray measurements of the total mass at the cluster centers. It is at these radii where strong lensing often implies 2–3 times higher values (e.g., Miralda-Escudé & Babul 1995 and later works), although more accurate X-ray modeling was shown to reduce the discrepancy (e.g., Allen et al. 2001). Given the filament, the edge, and the overall image geometry, it appears likely that most of the gas at small radii in A1795 participates in the gas bulk flow and is therefore nonhydrostatic, even though we can see the effect on the mass profile only in the southern sector where sloshing produces a brightness edge. *Chandra* data on a number of other relaxed clusters reveal similar fronts in the cluster central regions (M. Markevitch 2001, in preparation), so such nonequilibrium may be common. Note that the volume inside the edge radius contains only ~1% of the gas within the virial radius, so our finding cannot be generalized to the whole cluster.

In summary, we have studied a mild gas density edge near the center of the otherwise relaxed cluster A1795. The gas on two sides of the edge appears at rest; however, the inner gas has significant centripetal acceleration, indicating that the gas is sloshing in the cluster gravitational potential. If one assumes hydrostatic equilibrium, one obtains an underestimate of the total mass near the center.

We thank Harvey Tananbaum for useful discussions. Support for this study was provided by NASA contract NAS8-39073, NASA grant NAG5-9217, and an ESA fellowship.

REFERENCES

Allen, S. W., Ettori, S., & Fabian, A. C. 2001, MNRAS, 324, 877
Arnaud, M., Neumann, D. M., Aghanim, N., Gastaud, R., Majerowicz, S., & Hughes, J. P. 2001, A&A, 365, L80
Bahcall, J. N., & Sarazin, C. L. 1977, ApJ, 213, L99
Bartelmann, M., & Steinmetz, M. 1996, MNRAS, 283, 431
Briel, U. G., & Henry, J. P. 1996, ApJ, 472, 131
Buote, D. A., & Tsai, J. C. 1996, ApJ, 458, 27
Churazov, E., Forman, W., Jones, C., & Böhringer, H. 2000, A&A, 356, 788
Cowie, L. L., Hu, E. M., Jenkins, E. B., & York, D. G. 1983, ApJ, 272, 29
Edge, A. C., Stewart, G. C., & Fabian, A. C. 1992, MNRAS, 258, 177
Ettori, S., et al. 2000, poster paper in X-Ray Astronomy 2000
Fabian, A. C., Sanders, J. S., Ettori, S., Taylor, G. B., Allen, S. W., Crawford, C. S., Iwasawa, K., & Johnstone, R. M. 2001, MNRAS, 321, L33
Kaastra, J. S. 1992, An X-Ray Spectral Code for Optically Thin Plasmas (Internal SRON-Leiden Rep., updated version 2.0)
Markevitch, M., Forman, W. R., Sarazin, C. L., & Vikhlinin, A. 1998, ApJ, 503, 77
Markevitch, M., et al. 2000, ApJ, 541, 542
Mazzotta, P., Markevitch, M., Forman, W. R., Jones, C., Vikhlinin, A., & VanSpeybroeck, L. 2001a, ApJ, submitted (astro-ph/0108476)
Mazzotta, P., Markevitch, M., Vikhlinin, A., Forman, W. R., David, L. P., & VanSpeybroeck, L. 2001b, ApJ, 555, 205
McNamara, B. R., et al. 2000, ApJ, 534, L135
Miralda-Escudé, J., & Babul, A. 1995, ApJ, 449, 18
Oegerle, W. R., & Hill, J. M. 1994, AJ, 107, 857
Roettiger, K., Loken, C., & Burns, J. O. 1997, ApJS, 109, 307
Sarazin, C. L. 1988, X-Ray Emission from Clusters of Galaxies (Cambridge: Cambridge Univ. Press)
Tamura, T., et al. 2001, A&A, 365, L87
Vikhlinin, A., Forman, W., & Jones, C. 1999, ApJ, 525, 47
Vikhlinin, A., Markevitch, M., & Murray, S. S. 2001, ApJ, 551, 160