Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Pasadena; Carnegie Observatories:
http://www.ociw.edu/ociw/symposia/series/symposium3/proceedings.html)

Evolution in $z \approx 1$ X-ray Clusters?

B. P. HOLDEN[1,2], S. A. STANFORD[1,2], P. ROSATI[3], P. EISENHARDT[4,5], and P. TOZZI[6]
(1) University of California, Davis, CA, USA
(2) Institute for Geophysics and Planetary Physics, Livermore, CA, USA
(3) European Southern Observatory, Garching, Germany
(4) Jet Propulsion Laboratory, Pasadena, CA, USA
(5) SIRTF Science Center, Pasadena, CA, USA
(6) INAF, Trieste, Italy

Abstract

We discuss our ongoing survey of a sample of $0.8 \leq z \leq 1.27$ X-ray selected clusters of galaxies. In our survey, we are measuring both X-ray properties and constructing magnitude limited catalogs of spectroscopically confirmed cluster members. We have two goals with this survey: to study the evolution in the observable quantities that are tied to the underlying mass distribution of the clusters, and to understand the evolution in the stellar populations of cluster galaxies. To date, we find no evolution in the X-ray luminosity – temperature relation, a controversial result that bears further investigation. We find hints of a disagreement between the low redshift X-ray temperature – velocity dispersion relation, which are borne out by results using the CNOC cluster survey. When investigating the galaxy populations of the clusters, we find that the colors of spectroscopically confirmed cluster members evolve in accordance with passively evolving stellar populations. Using the size–magnitude relation, we confirm this evolution for some of the early-type galaxies. This says that the early-type luminous cluster members, even at $z \simeq 1$, appear to be dominated by passively evolving stellar populations with stars that formed at $z \simeq 3$.

1.1 Introduction

The ROSAT Deep Cluster Survey (RDCS; Rosati *et al.* 1998) provides a unique sample of very high redshift X-ray selected clusters of galaxies. One portion of the RDCS, referred to as RDCS-1 in Borgani *et al.* 2001, consists of a small angular area, $\simeq 1$ square degree but the faint flux limits of $\simeq 1 \times 10^{-14}$ erg s^{-1} cm^{-2} in the 0.5–2.0 keV band. To date, this sample has yielded nine clusters of galaxies with $0.8 \leq z \leq 1.3$, comprising the largest sample of X-ray selected clusters of galaxies at these redshifts. In Figure 1.1, we plot the luminosity and redshift distribution of the RDCS-1 sample.

Given such a sample, there are two avenues we intend to explore. First, we will study the scaling relations of the clusters in the sample such as the relation between the X-ray luminosity and X-ray temperature of the intracluster medium or the X-ray temperature and galaxies' velocity dispersion. How such relations should scale and evolve with redshift is predicted using rather simple assumptions such as the gas and galaxies being virial equilibrium with the gravitational potential and that the X-ray emission process is simple thermal *bremsstrahlung*. It has been shown by multiple authors that the relation between the X-ray luminosity and X-ray temperature do not scale as one would simply expect (see Rosati *et al.* 2002 for a review of this issue). A number of models have come forward to predict

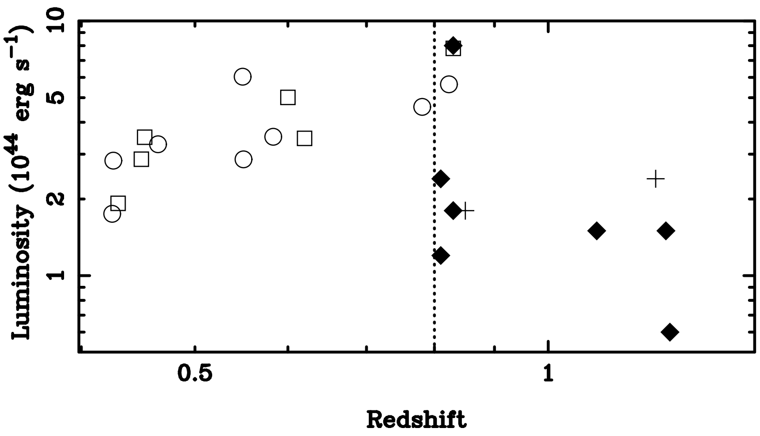

Fig. 1.1. The luminosity as a function of redshift for the RDCS sample discussed in this paper. Solid diamonds represent those objects with Chandra or XMM observations and the "+" symbols represent objects with pending observations. The open circles are the distribution from the EMSS and the open squares are the Bright SHARC survey. One of the clusters, Cl J0152.7-1357, was found by both the Bright SHARC and the RDCS, hence is shown with two symbols. The luminosities are in the 0.5–2.0 keV band.

the observed scaling of X-ray temperature with X-ray luminosity using such mechanisms as cooling of the gas (for example, Voit *et al.* 2002) or additional sources of heating such as active galactic nuclei (for example, Cavaliere *et al.* 2002) or supernovae (see Bower *et al.* 2001 or Borgani *et al.* 2002 and Tozzi & Norman 2001 for a general treatment of additional heating). Such additional physical mechanisms not only change the shape of the X-ray luminosity – temperature relation, but predict different evolutionary histories for that relation. Thus, by creating a high redshift sample of X-ray properties for clusters of galaxies, we will be able to direct test these evolutionary predictions of the history of the intracluster medium.

The second avenue we wish to explore using this sample of clusters of galaxies is the evolution of the galaxies in the clusters. As shown in, say, van Dokkum *et al.* (2001), the fraction of cluster members that are early-type galaxies appears to be changing from $\simeq$80% to $\simeq$50% over the redshift range $0.3 \leq z \leq 1.3$. If this trend is confirmed, we will have an important indicator of the history and formation of cluster galaxies. To create a complete picture, we will need various indicators of the stellar populations and star formation histories of cluster galaxies in this redshift range. Given such data, we can then test such hypothesis as that the evolution we are witnessing is the transformation of spiral galaxies into S0 galaxies such as discussed in Dressler *et al.* (1997), or, rather, that the early-type galaxy population is being built up from the mergers of small groups of galaxies already dominated by old stellar populations (van Dokkum *et al.* 1999).

1.1.1 Scaling Relations

In Figure 1.2, we plot the X-ray luminosity versus the X-ray temperature of the clusters of galaxies observed in our sample. To date, not all of the data has been processed, but it is clear that our sample currently shows no evolution when compared with the low redshift relation from Markevitch (1998). We note here that our temperatures and luminosi-

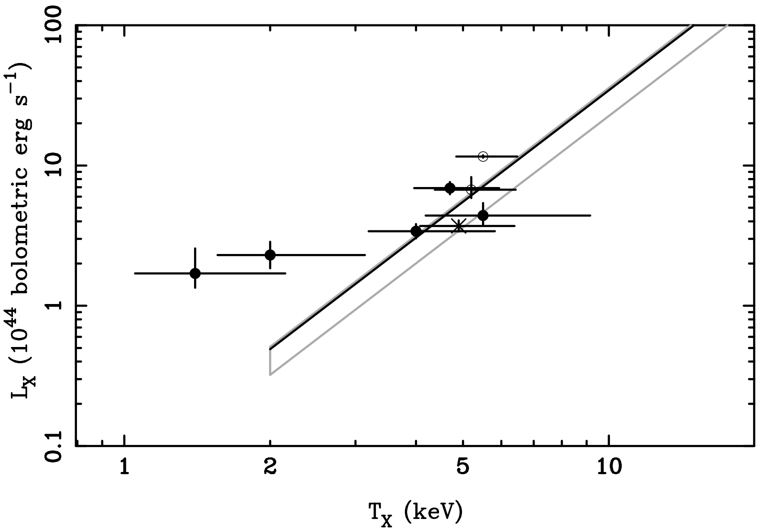

Fig. 1.2. The X-ray luminosity–temperature relation for RDCS clusters, as solid circles, observed to date. Error bars show 68% confidence limits. The open region is the high temperature X-ray luminosity – temperature relation from Markevitch (1998). The open circles represent the two components of Cl 0152.7-1357 from Maughan *et al.* 2003 and the cross, or "x", symbol represents the XMM observations of RX J1053.7+5735 from Hashimoto *et al.* (2002).

ties are different than those in the summary of Holden *et al.* (2002) for our current results we use the new absorption model for the ACIS imager to appropriately account for the time dependence in the low energy quantum efficiency. In addition to our measurements of the various RDCS clusters, we include the luminosities and temperatures for the two components of Cl J0152.7-1357 from Maughan *et al.* (2003) as open circles and the temperature and luminosity of RX J1053.7+5735 from Hashimoto *et al.* (2002) as a cross or "x". If these results are correct, the lack of evolution in the luminosity temperature relation immediately rules out such models as Bower *et al.* (2001) which requires that the normalization of the relation evolve as $(1+z)^{1.5}$.

However, Vikhlinin *et al.* (2002) find exactly that evolution, the normalization of the luminosity – temperature relation evolving as $(1+z)^{1.5}$, using Chandra measurements of a sample of 22 $z > 0.4$ clusters of galaxies, including all of the RDCS clusters in the $0.8 \leq z \leq 1.3$ sample. In Figure 1.3 we plot the data from Vikhlinin *et al.* (2002), except for those clusters shown in Figure 1.2. The dashed line is the best fitting evolution for the moderate redshift clusters in that sample. For the measurements of the highest redshift clusters in Vikhlinin *et al.* (2002), the best fitting evolution is shown with a solid line. It is clear that, though Vikhlinin *et al.* (2002) and we agree on the temperatures of the clusters, Vikhlinin *et al.* (2002) find higher luminosities. The resolution of this is an important problem. Part of the solution will come from an analysis of the XMM observations of three of the RDCS clusters. Each of these three are to be or have been observed with both XMM and Chandra. The combination of Chandra's high resolution to flag and remove contaminating point sources and

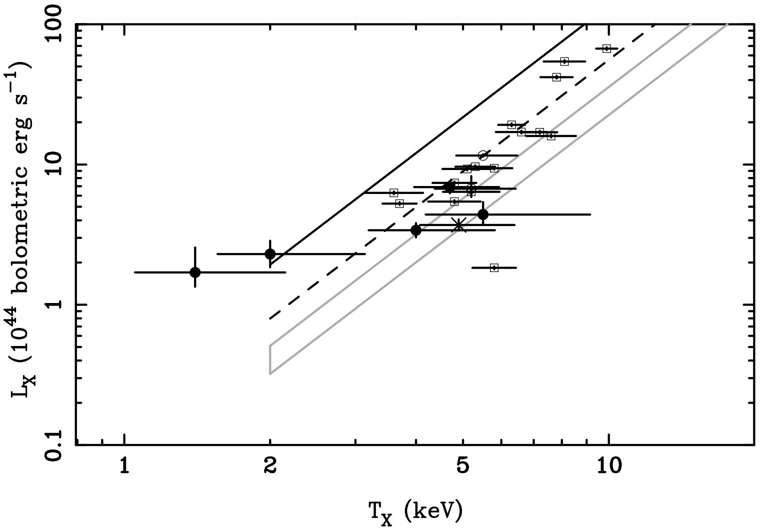

Fig. 1.3. The X-ray luminosity=temperature relation showing the data for moderate redshift clusters, as open squares, and the resulting evolution at moderate redshifts (dashed line) and for the highest redshift clusters (solid line) from Vikhlinin *et al.* 2002. The other symbols are the same as Figure 1.2

XMM's greater collecting area will go a long in determining an accurate and independent measurement of the total flux and luminosity of the clusters.

Given the current uncertainty in the measurements of the X-ray luminosities of high redshift clusters, we explore the relation between the X-ray temperature and the velocity dispersion. Both the X-ray temperature and the velocity dispersion should trace the depth of the potential well. Evolution in this relation could show a signature of either additional non-gravitational heating or that the galaxies themselves are not in equilibrium with the underlying potential. We plot in Figure 1.4 the temperature – velocity dispersion relation. We include two moderate redshift clusters, RX J0848+4456 and CL J0848.8+4455 (Holden *et al.* 2001), as solid squares in addition to the high redshift clusters, represented by large solid circles, for which we have velocity dispersions. The solid line represents the best fitting temperature – velocity dispersion relation from Horner (2001), for galaxies with at least 30 members in the velocity dispersion measurement, while the dashed lines represent the error in that fit. We add the CNOC velocity dispersions, specifically those from Borgani *et al.* 1999, and the X-ray temperatures as measured in Henry (2000), plotted with open circles. All of the high redshift RDCS clusters observed have less than 30 members for the velocity dispersions, though the measurements of the dispersions of the two moderate redshift clusters do meet the 30 member requirement. Thus, a disagreement with the best fitting model from Horner (2001) is not unexpected for at least the highest redshift systems (see the thesis for further discussion on this point). The CNOC clusters, however, have large uniformly selected samples but seem, on average, to have lower than expected velocity dispersions for their temperatures when compared with the sample of Horner (2001). This poses an interesting puzzle as no evolution is expected in this relation, especially at such low redshifts. Likely, there is a further discrepancy in measuring the velocity dispersions that make up the

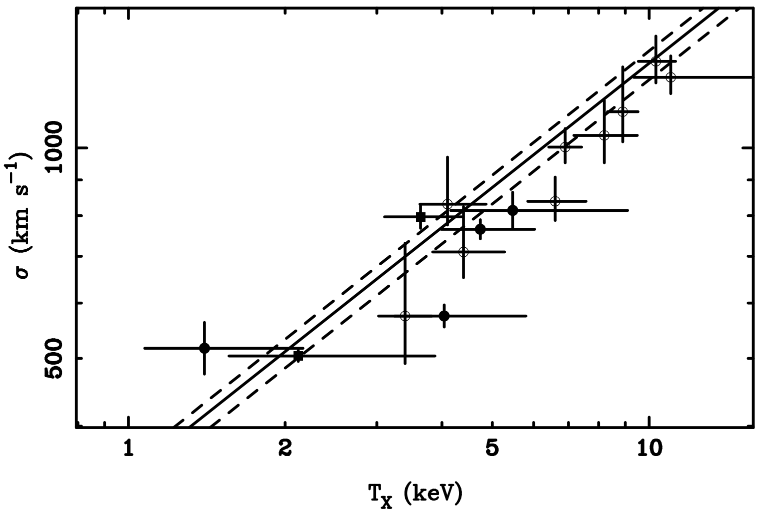

Fig. 1.4. The velocity dispersion as a function of X-ray temperature for high-redshift RDCS clusters, represented by solid circles. Those objects with solid squares as symbols are two objects at $z \simeq 0.55$. The plot shows, in addition, the CNOC clusters with temperatures as measured by Henry (2000) with open circles. The solid is the relation as measured by Horner (2001) and the dashed lines represent the scatter in the fit on that relation.

Horner (2001) sample. Ideally, all dispersions would be measured in a manner such as the CNOC survey i.e., using magnitude limited samples with uniform sampling out to and beyond the virial radius. We note here, however, that even the Horner (2001) sample does not measure a relation of $\sigma \propto T_x^{0.5}$ as predicted by simple scaling laws, but rather $\sigma \propto T_x^{0.59 \pm 0.03}$, a three sigma difference from the expected result.

1.2 Cluster Member Evolution

The red envelope or sequence of cluster galaxies has long been used as a way of studying the oldest stellar populations in clusters. Evolution in the colors of the reddest cluster members can be used to measure epoch of star formation for those galaxies. As the reddest galaxies at low redshift are massive elliptical galaxies, by dating the epoch of star formation we can determine when the stars of the most massive galaxies formed. In turn, the formation of those same stars could be a source of additional heating in the intracluster medium. By constraining the epoch and amount of star formation, we could in addition constrain when and how much addition heating was provided to the intracluster medium.

Figure 1.5 shows the beginning of our exploration of this. We show color – magnitude diagrams for RDCS J0910+54, a cluster of galaxies at $z = 1.102$ (Stanford *et al.* 2002a) with a velocity dispersion of 575 +/- 21 km s^{-1}. RDCS J0910+54 was observed in the I, J, and K_s bands. The I and J correspond to rest-frame U and V, thus provide a useful measure of evolution in the colors stellar populations. Every galaxy in Figure 1.5 is a spectroscopically confirmed member. The photometric data were obtained and analyzed using the same techniques as outlined in Stanford *et al.* (1998) and Stanford *et al.* (2002b). Using the approach of Stanford *et al.* (1998) and Holden *et al.* (2004), we have computed the expected

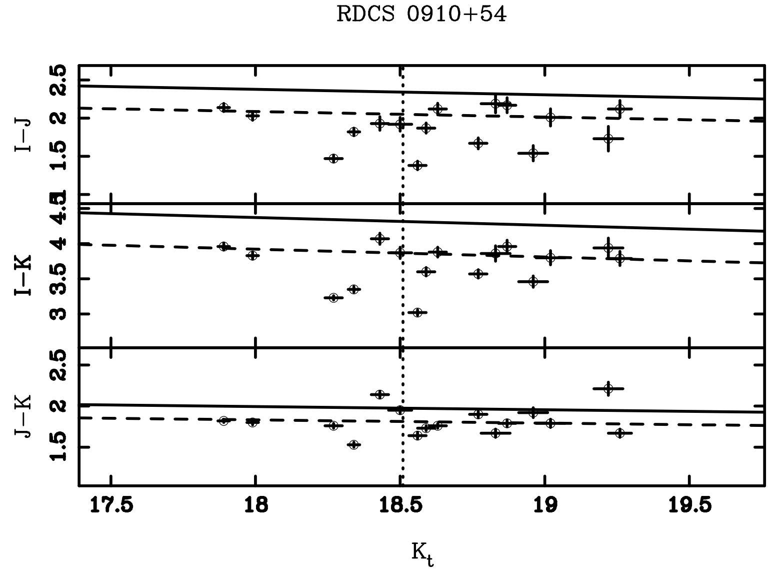

Fig. 1.5. The color magnitude diagram for RDCS J0910+54, a cluster at $z = 1.102$. Plotted are the colors and magnitudes for only confirmed cluster members. The solid line is the no-evolution relation for the color – magnitude sequence based on the Coma cluster of galaxies. The dashed lines are the no-evolution slope but with the zero point shifted as predicted based on an evolving stellar population which formed at $z_{formation} = 3$.

color – magnitude relation of the Coma cluster of galaxies (Eisenhardt *et al.* 2004) at this redshift. We represent those relations with a solid line. The measured color – magnitude sequence is clearly bluer, as expected, than the Coma no-evolution relation. We also plot, with a dashed line, the expected passive evolution for a single stellar population that formed with $z_{formation} = 3$, a solar metal abundance in a starburst with a time-scale of 0.1 Gyr from the Bruzual & Charlot (1993) models using the 2000 update. This passive evolution is only computed as an offset from the Coma no-evolution relation, there is no change in the slope of the color – magnitude relation. The no-evolution slope, even in the $I-K$ color, roughly a rest-frame $U-J$, is rather shallow. We measure no statistically significant difference between the slope of the reddest cluster members and of the no-evolution slope. In general the lack of evolution in the slope and the color evolution agree with the results of Stanford *et al.* (1998) and Holden *et al.* (2004). Identifying which galaxies are early-types, however, will wait for the Advanced Camera for Surveys.

1.3 Conclusions

In this paper we have shown initial results from our survey of a sample of X-ray selected clusters of galaxies spanning the redshift range $0.8 \leq z \leq 1.3$. We have finished compiling the X-ray observations, which yield temperatures, luminosities and surface brightness profiles. We have begun our optical follow-up program, which will yield magnitude limited redshift samples for every cluster as well as multi-band photometry in rest-frame U and V along with J, H, and K. The clusters will be observed with the SIRTF Infrared Array Camera in four near-infrared bands. These observations will sample the rest-frame J, H and K, and

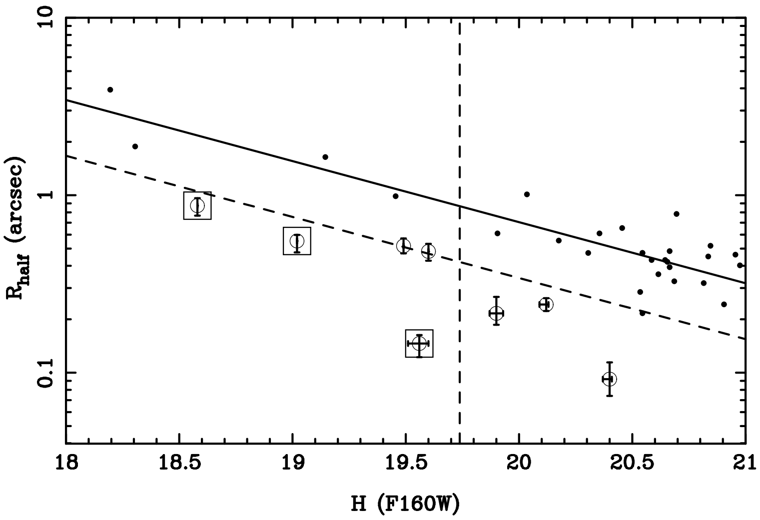

Fig. 1.6. We plot, with open circles, the sizes and F160W total magnitudes of early-type galaxies in the cluster RDCS J0848+4453. The small solid dots are the transformed Gunn *r* sizes and magnitudes from Jorgensen, Franx, & Kjaergaard (1995) with the solid line being the best fit to all galaxies brighter than $M_{\star}+1$. The dashed line is the prediction assuming no evolution size – magnitude relation beyond that from passively evolving stellar populations. The three objects with large boxes are from the fundamental plane study of van Dokkum & Stanford (2003)

allow us to determine the underlying stellar mass. Many of the clusters in this sample will be imaged as part of the Advanced Camera for Surveys Guaranteed Time program. Such data will provide multi-band morphological information. We can use such data to determine galaxy types, surface brightness profiles and color-gradients, all addition pieces to the puzzle of how galaxy evolution occurs in high redshift clusters. An example of what is possible with such data is shown below in Figure 1.6. We plot the size – magnitude relation for RDCS J0848+4453 based on NICMOS F160W observations. Every object is a morphologically identified early-type galaxy with a spectroscopic redshift. The three galaxies shown with large boxes are discussed in van Dokkum & Stanford (2003), who measure velocity dispersions of the galaxies and use them to measure evolution in the mass to light ratio. The faintest object in that sample shows, in addition to a smaller than expected size half light radius, a smaller than expected velocity dispersion. Thus, the combination of spectra and high resolution imaging allow us to pick objects with morphologies of early-type galaxies but with, possibly, much younger stellar populations. With the addition of multi-band IRAC photometry and HST imaging, not only can we confirm that this object is a low stellar mass, post-starburst object, but we will be able to survey for a number of such objects, and possibly understand their role in the evolution of the early-type galaxies we see in clusters today.

We would like to thank the organizers of the meeting for putting together an enjoyable and fascinating symposium. Support for SAS came from NASA/LTSA grant NAG5-8430 and for BH from NASA/Chandra GO0-1082A. Both BH and SAS are supported by the Institute for Geophysics and Planetary Physics (operated under the auspices of the US Department of Energy by the University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48). Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality, many of the observations presented herein would not have been possible.

References

Borgani, S., Governato, F., Wadsley, J., Menci, N., Tozzi, P., Quinn, T., Stadel, J., & Lake, G. 2002, MNRAS, 336, 409

Borgani, S. *et al.* 2001, ApJ, 561, 13

Borgani, S., Girardi, M., Carlberg, R. G., Yee, H. K. C., & Ellingson, E. 1999, ApJ, 527, 561

Bower, R. G., Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2001, MNRAS, 325, 497

Bruzual A., G. & Charlot, S. 1993, ApJ, 405, 538

Cavaliere, A., Lapi, A., & Menci, N. 2002, ApJ, 581, L1

Dressler, A. *et al.* 1997, ApJ, 490, 577

Eisenhardt, P., de Propris, R., Stanford, S. A., & Dickinson, M. 2004, in preparation

Hashimoto, Y., Hasinger, G., Arnaud, M., Rosati, P., & Miyaji, T. 2002, A&A, 381, 841

Henry, J. P. 2000, ApJ, 534, 565

Holden, B. P., Stanford, S. A., Eisenhardt, P., & Dickinson, M. 2004, in preparation

Holden, B. P., Stanford, S. A., Squires, G. K., Rosati, P., Tozzi, P., Eisenhardt, P., & Spinrad, H. 2002, AJ, 124, 33

Holden, B. P. *et al.* 2001, AJ, 122, 629

Horner, D. 2001, Ph.D. thesis, University of Maryland.

Jorgensen, I., Franx, M., & Kjaergaard, P. 1995, MNRAS, 273, 1097

Markevitch, M. 1998, ApJ, 504, 27

Rosati, P., Borgani, S., & Norman, C. 2002, ARA&A, 40, 539

Rosati, P., Della Ceca, R., Norman, C., & Giacconi, R. 1998, ApJ, 492, L21

Stanford, S. A., Holden, B., Rosati, P., Eisenhardt, P. R., Stern, D., Squires, G., & Spinrad, H. 2002a, AJ, 123, 619

Stanford, S. A., Eisenhardt, P. R., Dickinson, M., Holden, B. P., & De Propris, R. 2002b, ApJS, 142, 153

Stanford, S. A., Eisenhardt, P. R., & Dickinson, M. 1998, ApJ, 492, 461

Tozzi, P. & Norman, C. 2001, ApJ, 546, 63

van Dokkum, P. G. & Stanford, S. A. 2003, ApJ, 585, 78

van Dokkum, P. G., Stanford, S. A., Holden, B. P., Eisenhardt, P. R., Dickinson, M., & Elston, R. 2001, ApJ, 552, L101

van Dokkum, P. G., Franx, M., Fabricant, D., Kelson, D. D., & Illingworth, G. D. 1999, ApJ, 520, L95

Vikhlinin, A., VanSpeybroeck, L., Markevitch, M., Forman, W. R., & Grego, L. 2002, ApJ, 578, L107

Voit, G. M., Bryan, G. L., Balogh, M. L., & Bower, R. G. 2002, ApJ, 576, 601