THE INTRACLUSTER MEDIUM IN Z > 1 GALAXY CLUSTERS

S.A. STANFORD1, BRADFORD HOLDEN1
Physics Department, University of California-Davis, Davis, CA 95616, USA
PIERO ROSATI
European Southern Observatory, Karl-Scharzschild-Strasse 2, D-85748 Garching, Germany
PAOLO TOZZI, STEFANO BORGANI
Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34131, Trieste, Italy
PETER R. EBENHARDT
Jet Propulsion Laboratory, California Institute of Technology, MS 169-327, 4800 Oak Grove, Pasadena, CA 91109
AND
HYRON SPINRAD
Astronomy Department, University of California, Berkeley, CA 94720

Draft version December 18, 2000

ABSTRACT

The Chandra X-ray Observatory was used to obtain a 190 ks image of three high redshift galaxy clusters in one observation. The results of our analysis of these data are reported for the two z > 1 clusters in this Lynx field, which are the most distant known X-ray luminous clusters. Spatially-extended X-ray emission was detected from both these clusters, indicating the presence of hot gas in their intracluster media. A fit to the X-ray spectrum of RX J0849+4452, at z = 1.26, yields a temperature of kT = 5.8_{-2.8}^{+2.8} keV. Using this temperature and the assumption of an isothermal sphere, the total mass of RX J0849+4452 is found to be 4.0^{+2.4}_{-1.5} \times 10^{14} h_{65}^{-1} M_{\odot} within r = 1 h_{65}^{-1} Mpc. The T_x for RX J0849+4452 approximately agrees with the expectation based on its L_{bol} = 3.3_{-0.5}^{+0.9} \times 10^{44} \text{erg s}^{-1} according to the low redshift L_x − T_x relation. The very different distributions of X-ray emitting gas and of the red member galaxies in the two z > 1 clusters, in contrast to the similarity of the optical/IR colors of those galaxies, suggests that the early-type galaxies mostly formed before their host clusters.

Subject headings: galaxies: clusters: general; X-rays: general

1. INTRODUCTION

Numerical simulations based on hierarchical clustering models such as cold dark matter (CDM) show the rate at which clusters form depends critically on \Omega_m, and weakly on \Lambda and the initial power spectrum. Thus, the observed evolution of the cluster number density of a given X-ray temperature and luminosity can determine \Omega_m. Oukbir & Blanchard 1992, Eke et al. 1998a. A critical component of such a measurement is an understanding of the thermodynamical evolution of the intracluster medium (ICM) Bower 1997, Borgani et al. 1999, Tozzi & Norman 2000. The study of ICM properties at high z is mostly unexplored territory. Until the advent of Chandra and XMM, X-ray observations with limited resolution and sensitivity were unable to provide conclusive measurements of the ICM at z > 1 associated with bona fide galaxy clusters. For example, ROSAT observations of high z radio galaxies possibly associated with galaxy clusters Crawford & Fabian 1996 provided only limited evidence that the observed X-ray emission originates from hot intracluster gas.

To assemble a well-defined sample for studying the properties of the ICM and cluster galaxy populations at z > 1, we have been using near-IR imaging and deep optical spectroscopy to complete the identification of the faintest candidate clusters in the Rosat Deep Cluster Survey (RDCS) Rosati et al. 1995, Rosati et al. 1998. Of the 4 RDCS clusters which have been identified at z > 1, two are separated by only 4.2 arcmin on the sky and 0.01 in redshift: RX J0849+4453 at z = 1.27 Stanford et al. 1997 and RX J0849+4452 at z = 1.26 Rosati et al. 1999. Keck LRIS spectroscopy has confirmed 20 member galaxies in these two clusters. In addition, a third moderate redshift cluster in this Lynx field already had been identified from the RDCS, RX J0848+4456 at z = 0.56 (Rosati et al. 1998; the Chandra results on this object will be presented elsewhere: Holden et al., in preparation). The Lynx field offers the opportunity to probe the physical parameters of the ICM over the redshift range 0.6–1.3 in a single deep Chandra pointing. H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.3, and \Lambda = 0.7 are assumed throughout this paper.

2. OBSERVATIONS AND REDUCTIONS

New Lynx field X-ray data were obtained by Chandra using the Advanced CCD Imaging Spectrometer imaging (ACIS-I) detector. Two exposures were obtained in the faint mode when ACIS was at a temperature of −120 K. The first observation (Obs ID 1708) was taken on 2000 May 3 for 65 ks, and the second (Obs ID 927) on 2000 May 4 for 125 ks. The Level 1 data were processed using the calibration files available as of 15 September 2000 for the aspect so-

1Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory
lution and the quantum efficiency uniformity, which cor-
rect the effective area for loss due to charge transfer inef-
ficiency. The data were filtered to include only the stan-
ard event grades 0, 2, 3, 4, and 6. All hot pixels and 
columns were removed, as were the columns close to the 
border of each node, since the grade filtering is not ef-
cient in these columns. The removal of columns and pixels 
slightly reduces the effective area of the detector, the effect 
of which has been included when calculating the total ex-
posure maps. Time intervals with background rates larger 
than 3σ over the quiescent value (0.30 counts s⁻¹ per chip 
in the 0.3 - 10 keV band) were removed. This procedure 
gave 61 ks of effective exposure in the first observation, 
and 124 ks in the second, for a total of 185 ks.

3. RESULTS

Both $z > 1$ clusters were detected and found to contain 
spatially extended X-ray emission (left panel of Figure 1). 
The emission in RX J0848+4453 is weak and amorphous, 
while in RX J0849+4452 it is symmetric and centrally con-
centrated in a way similar to that seen in relaxed clusters 
at lower redshift. The radial surface brightness profile for 
RX J0849+4452 is shown in the right panel of Figure 1 
along with a β model fit. In both clusters there are rel-
atively strong point sources within the ROSAT detection 
area. In both cases, approximately 40% of the flux as 
measured by ROSAT is from point sources unlikely to be 
associated with the clusters, showing the importance of 
obtaining high spatial resolution data. Further analyses 
of the point sources found in the Chandra observation, 
including their optical-IR identifications, will be presented 
by Stern et al. (in preparation).

The spectra of the two clusters were determined in the 
following way. After removing the point sources, events at 
0.5−6.0 keV in an $r = 35''$ ($\sim$0.32 Mpc) circular aperture 
centered on each cluster were extracted. Events in a sur-
rounding background region, with the cluster and point 
source excised, were also extracted. The background 
model consists of a broken power law and a Gaussian for 
the instrumental Au emission line at 2.1 keV. The back-
cround models for both clusters were fit separately and 
the instrumental Au emission line at 2.1 keV. The back-
ground and the cluster spectra. The models are folded 
through the appropriate response matrices and then ran-
domly sampled. The simulated output is fit in the same 
way as the original spectra. The resulting distribution of 
temperatures is asymmetric but the median temperature 
matches the input temperature, showing no strong biases 
in our method of measuring $T_{\text{e}}$.

A total mass can be estimated from the $T_{\text{e}}$, assuming 
an isothermal sphere and extrapolating the X-ray emission to 
r = 1 Mpc using the best fit profile shown in the right 
panel of Figure 1. The total mass of RX J0849+4452 
derived from the new X-ray data is $4.0^{+2.4}_{-1.9} \times 10^{14} M_\odot$ 
within $r = 1 h_{65}^{-1}$ Mpc. No estimate was calculated 
for RX J0848+4453 due to its strong departure from 
spherical symmetry and uncertain $T_{\text{e}}$. The new $L_{\text{e}}$ 
for RX J0848+4453 is approximately in line with the expe-
tation according to the present epoch $L_{\text{e}} - T_{\text{e}}$ relation (e.g. 
Edge & Stewart 1991; Borgani et al. 1999b) for the esti-
mate we have made of the velocity dispersion $\sigma = 650\pm170$ 
km s⁻¹ of its 9 member galaxies for which we have suffi-
ciently high resolution spectra. Member galaxy redshifts 
have not yet been obtained with sufficient accuracy to en-
able the calculation of a meaningful velocity dispersion 
for comparison to the total mass estimate in the case of 
RX J0849+4452.

4. DISCUSSION

The spatially extended X-ray emission seen in 
RX J0849+4452 clearly shows that a hot intracluster 
medium exists in galaxy clusters at $z > 1$. In this 
cluster the ICM has a regular, centrally concentrated 
spatial distribution, similar to the relaxed appearance 
RX J0849+4452 presents in the optical/IR (Figure 3). But 
the ICM in the other $z > 1$ cluster, RX J0848+4453, is 
very weak and appears to be divided between the two sides 
of the cluster. Two groups may be in the process of merg-
ing, as appears to be seen also in the distribution of the 
red galaxies (Figure 3). Using photometric redshifts 
for all galaxies at K < 20.6, nearly 50% of the member galaxies 
lie within the central 20 arcsec of RX J0849+4452, 
while only 10% of the probable members are in the same 
region of RX J0849+4453 (van Dokkum et al., in prepara-
While the two clusters show rather different distributions both in the optical/IR and in the X-ray, they contain galaxy populations dominated by red galaxies which appear to have little or no recent star formation Stanford et al. 1997, Rosati et al. 1999. The median colors of these red galaxies are the same within 0.05 in \( I-K \), and HST imaging of RX J0848+4453 shows them to be overwhelmingly early-types (van Dokkum et al. in preparation). This suggests that the early-type galaxies found in clusters were largely formed prior to cluster formation.

We thank Scott Wolk for assistance with planning our Chandra observation, and Patrick Wojdowski for help with Chandra data analysis, and the referee for a timely report. Support for SAS came from NASA/LTSA grant NAG5-8430 and for BH from NASA/Chandra GO0-1082A, and both are supported by the Institute of 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). Portions of this work were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

### REFERENCES


### Table 1

<table>
<thead>
<tr>
<th>Cluster</th>
<th>( z )</th>
<th>( F_{0.5-2.0} ) (( 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} ))</th>
<th>( L_{0.5-2.0} ) (( 10^{44} \text{ erg s}^{-1} ))</th>
<th>( L_{\text{bol}} ) (( 10^{44} \text{ erg s}^{-1} ))</th>
<th>( T_x ) (keV)</th>
<th>( M_{\text{total}}(&lt;1\text{ Mpc}) ) (( 10^{14} \text{ M}_\odot ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXJ0848+4453</td>
<td>1.27</td>
<td>( 1.4^{+0.3}_{-0.3} )</td>
<td>( 0.49^{+0.16}_{-0.11} )</td>
<td>( 0.68^{+0.27}_{-0.17} )</td>
<td>( 1.6^{+0.8}_{-0.6} )</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>RXJ0849+4452</td>
<td>1.26</td>
<td>( 9.0^{+0.9}_{-0.9} )</td>
<td>( 0.51^{+0.05}_{-0.05} )</td>
<td>( 3.3^{+0.9}_{-0.5} )</td>
<td>( 5.8^{+2.8}_{-1.7} )</td>
<td>( 4.0^{+2.4}_{-1.9} )</td>
</tr>
</tbody>
</table>

\( a \) \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.3, \) and \( \Lambda = 0.7 \) are assumed.

\( b \) \( r = 35'' \) aperture

\( c \) aperture corrected to total
Fig. 1.—(left) Greyscale image of the ACIS-I data showing a 6 × 6 arcmin field. The image has been smoothed by a two-dimensional Gaussian with $\sigma = 2.1$ arcsec. The apertures used for making spectra are shown by dashed circles around the two higher-$z$ clusters; the point sources in these apertures were excluded when creating the spectra. (right) Radial profile of the X-ray emission centered on RX J0849+4452 shown by the small circles with one $\sigma$ errorbars. A $\beta$ model fit is shown by the line, and the best fit parameters are indicated.

Fig. 2.—ACIS-I unfolded spectra of RX 0848+4453 at $z = 1.27$ (left) and RX J0849+4452 (right; $z = 1.26$) with the fitted models.

Fig. 3.—$B1K$ images Stanford et al. 1997, Rosati et al. 1999 showing a 2 × 2 arcmin field on RX J0848+4453 (left; $z = 1.27$) and RX J0849+4452 (right; $z = 1.26$) with contour overlays (at the levels of 2, 5, 7, 15$\sigma$) of the X-ray emission detected by Chandra/ACIS-I. The strong X-ray point sources centered on optical objects in the vicinity of the cluster cores are unlikely to be associated with the clusters. In RX J0848+4453 (left), the relatively bright source at lower left, which is associated with a red galaxy, is a known quasar at $z = 1.194$. In RX J0849+4452 (right), the relatively bright X-ray source to the north of the cluster core is associated with a quasar at $z = 1.329$. 

$\beta = 0.61 \pm 0.12$

$r_c = 11.14 \pm 3.41''$

$r_c = 100.2 \pm 30.7$ kpc