AN X-RAY-SELECTED GALAXY CLUSTER AT $z = 1.11$ IN THE ROSAT DEEP CLUSTER SURVEY$^{1,2,3}$

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ABSTRACT

We report the discovery of an X-ray–luminous galaxy cluster at $z = 1.11$. RDCS J0910+5422 was selected as an X-ray cluster candidate in the ROSAT Position Sensitive Proportional Counter image. Deep optical and near-IR imaging reveal a red galaxy overdensity around the peak of the X-ray emission, with a significant excess of objects with $J-K$ and $I-K$ colors typical of elliptical galaxies at $z \sim 1$. Spectroscopic observations at the Keck II telescope secured nine galaxy redshifts in the range $1.095 < z < 1.120$, yielding a mean cluster redshift of $(z) = 1.106$. Eight of these galaxies lie within a 30 arcmin radius around the peak X-ray emission. A deep Chandra ACIS exposure on this field shows extended X-ray morphology and allows the X-ray spectrum of the intracluster medium to be measured. The cluster has bolometric luminosity $L_X = 2.48^{+0.33}_{-0.26} \times 10^{44}$ ergs s$^{-1}$, temperature $kT = 7.2^{+2.2}_{-1.4}$ keV, and mass within $r = 1$ Mpc of $7.0 \times 10^{14} M_{\odot}$ ($H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$). The spatial distribution of the cluster members is elongated, which is not due to an observational selection effect, and followed by the X-ray morphology. The X-ray surface brightness profile and the spectrophotometric properties of the cluster members suggest that this is an example of a massive cluster in an advanced stage of formation with a hot intracluster medium and an old galaxy population already in place at $z > 1$.

Key words: galaxies: clusters: general — galaxies: evolution — galaxies: formation — X-rays

1. INTRODUCTION

The identification and study of distant galaxy clusters is of great interest in current astronomical research. As the largest gravitationally bound structures in the universe, the properties and histories of galaxy clusters are highly sensitive to the physics of cosmic structure formation and to the values of the fundamental cosmological parameters (Eke, Cole, & Frenk 1996; Bahcall, Fan, & Cen 1997). While clusters in such well-defined samples as the ROSAT Deep Cluster Survey (RDCS; Rosati et al. 1998) have been used to constrain $\Omega_m$ and $\sigma_8$ (Borgani et al. 2001), the uncertainty in the relation between cluster mass and measurable such as $L_X$ or $T_X$ limits the precision obtainable in calculations of cosmological parameters to $\sim 50\%$. To improve on this, a better understanding of the mass-$T_X$ relation and its evolution is necessary. To that end, we need to study in detail a well-defined sample of clusters at high redshift, with independent measures of the cluster mass based on $T_X$ (Evrard, Metzler, & Navarro 1996) and weak lensing (Tyson, Wenk, & Valdes 1990).

Another equally important use of galaxy clusters lies in studying the formation and evolution of galaxy populations. Progress in understanding early-type galaxy evolution in clusters is being driven by the need to reproduce recent observational results indicating both lower number fractions (Dressler et al. 1997; Couch et al. 1998; van Dokkum et al. 2000) and strong homogeneity and slow evolution in the stellar populations of elliptical galaxies and S0s in moderate-redshift clusters (Aragón-Salamanca et al. 1993; Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998, hereafter SED98; Bahcall, Fan, & Cen 1997). A self-consistent explanation of these results can be achieved by invoking an observational bias: the progenitors of the youngest, low-redshift early-type drop out of samples constructed in high-redshift clusters. Van Dokkum & Franx (2001) have suggested how morphological evolution at $z \geq 2$ coupled with star formation at $z \sim 2–3$ ($\Omega_m = 0.3$, $\Lambda = 0.7$) can explain the results cited above. More complex semianalytic models of galaxy formation and evolution set in a cold dark matter (CDM) universe naturally predict the morphological evolution that is a central tenet in the currently fashionable paradigm of cluster galaxy evolution:
elliptical galaxies are formed by mergers at $0.5 < z < 1.5$ of sub-$L^*$ galaxies formed at $2 < z < 3$ (van Dokkum et al. 1999), and the Butcher-Oemler effect is the result of spiral galaxies being converted into S0s at moderate redshifts (Dressler et al. 1997). For example, the models of Kauffmann & Charlot (1998) are able to match the small scatter in the color-magnitude relation of the early types even at $z \sim 1$, and the $M/L$ evolution found, e.g., by van Dokkum et al. (1998a) can be predicted (Diaferio et al. 2001). However, the accuracy, as well as the details, of this scenario for galaxy evolution in clusters is yet open to debate. In the case of the early types, the arguments are based heavily on observations of only a few high-$z$ clusters, e.g., MS 1054-03 at $z = 0.82$ (van Dokkum et al. 1998a).

Finding clusters at moderate redshifts has become almost routine by using serendipitous X-ray searches. The advent of the ROSAT Position Sensitive Proportional Counter (PSPC), with its unprecedented sensitivity and spatial resolution, enabled archival searches for extended X-ray sources to become a very efficient method to construct large, homogeneous samples of galaxy clusters out to $z \simeq 0.9$ (Rosati et al. 1998; Scharf et al. 1997; Collins et al. 1997; Vikhlinin et al. 1998). The RDCS has shown no evidence of a decline in the space density of galaxy clusters of X-ray luminosity $L_X < L_X^*$ over a wide redshift range, $0.2 < z < 0.8$ (see Rosati 2000 for a recent review), though the evolution of the bright end remains controversial. The fact that the bulk of the X-ray cluster population is not evolving significantly out to this large redshift increases the chances of finding clusters at even higher redshifts, since $L_X^* > 0$ clusters at $z > 1$ ($\approx 4 \times 10^{46}$ ergs s$^{-1}$ in the 0.5–2.0 keV band, roughly the Coma cluster) can be detected as extended X-ray sources in deep ROSAT pointed observations, provided that the X-ray surface brightness profile does not evolve significantly.

At fainter fluxes ($F_X < 3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the RDCS) the identification of real clusters becomes more difficult because of the increasing confusion and low signal-to-noise ratio of the X-ray sources, which makes it more difficult to discriminate between pointlike and extended sources. Below $F_X < 2 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ the X-ray completeness level can be as low as 50%, and the spurious rate as high as 50%. But it is at these flux levels that the most distant clusters in the survey are expected. To improve the success rate of identifying very high redshift clusters in the RDCS, we have been carrying out a program of near-infrared imaging of faint unidentified X-ray candidates. Relative to the optical, near-IR imaging is advantageous at high redshifts because the expected k-correction significantly dims the dominant population of early-type cluster galaxies in even the observed $I$ band for $z \gtrsim 1$. Stanford et al. (1997, hereafter S97) have shown that optical–infrared colors can be used to considerably enhance the contrast of high-redshift cluster galaxies against the field galaxy population and, at the same time, to obtain a useful estimate of the cluster redshift. The cluster found by S97, RDCS J0848+4453, at $z = 1.27$, and its neighbor, RDCS J0849+4452, at $z = 1.26$ (Rosati et al. 1999), have been used to push the study of evolution in the colors and morphology of early-type galaxies beyond $z > 1$. But such studies continue to be severely limited by the dearth of such high-redshift clusters (Dickinson 1997; Fabian, Crawford, & Sanders 2001).

In this paper, we describe the imaging and spectroscopic follow-up observations of the extended X-ray source RDCS J0910+5422, which has led to the discovery of a galaxy cluster at $z = 1.106$. Unless otherwise stated, we adopt the parameters $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. Observations

2.1. Optical and IR Imaging

The extended X-ray source RDCS J0910+5422 was selected from a deep ROSAT PSPC observation; details of the selection procedure are given in Rosati et al. (1999). The candidate field was observed in the optical at the Palomar 5 m telescope with COSMIC, which contains a TEK3 CCD that provides 0.28 pixels over a 9.5 field of view. An exposure of 2820 s was obtained in the Gunn $i$ band on 1999 February 18 UT under nonphotometric conditions with 1" seeing. The field was observed again with COSMIC in the Gunn $i$ band in photometric conditions for 300 s on 2000 April 30. Five standard stars were observed on the latter night and used to calibrate the photometry onto the Vega system. The data were reduced using standard methods. The second observation was used to calibrate the deeper, nonphotometric image before the two reduced images were summed.

We obtained $J$ and $K_s$ imaging at the Palomar 5 m telescope with the Prime-Focus Infrared Camera (Jarrett et al. 1994). This camera provides a 2/1 field of view with 0.494 pixels. RDCS J0910+5422 was observed under photometric conditions on 1998 March 24. The flux scale was calibrated using observations of three UKIRT standard stars obtained on the same night. The data were taken using a sequence of dither motions with a typical amplitude of 15" and a dwell time between dithers of 30 s. The data were linearized using an empirically measured linearity curve and reduced using DMSUM. The total integration times and resolutions of the resulting images are 2310 s and 1.0" at $J$, and 2880 s and 0.9" at $K_s$.

A catalog of objects in the $K_s$-band image was obtained using SExtractor (Bertin & Arnouts 1996) after first geometrically transforming the $K$ and $J$ images to match the $i$-band frame. The resolution of the IR images was also degraded to match that of the $i$-band image. For reference the 3σ detection limit is $K_3 \sim 21.3$ in a 2" aperture. All detected objects down to this limit were inspected visually to eliminate false detections. The catalog was then applied to the $J$- and $i$-band images to obtain matched aperture photometry.

2.2. Keck Spectroscopy

Spectroscopic observations of galaxies in a ~6'' region around RDCS J0910+5422 were obtained using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck II telescope. Objects were assigned slits based on their $I-K$ and $J-K$ colors. Spectra were obtained using the 150 lines mm$^{-1}$ grating, which is blazed at 7500 Å and covers the entire optical region, with a gradual blue cutoff imposed by the LRIS optics at ~5000 Å. The dispersion of ~4.8 Å pixel$^{-1}$ resulted in a spectral resolution of 23 Å as

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Footnote: Deep Infrared Mosaicing Software, a package of IRAF scripts available at ftp://iraf.noao.edu/contrib/dimsnumV2.
measured by the FWHM of emission lines in arc lamp spectra. Usually each mask was observed in a series of 1800 s exposures, with small spatial offsets along the long axis of the slitlets. One slit mask on the field was used to obtain spectra on 1999 March 10 with a total exposure time of 7200 s, and a second slit mask was used on 2000 February 18 for a total of 10,800 s.

The slit mask data were separated into individual slitlet spectra and then reduced using standard long-slit techniques. A fringe frame was constructed for each exposure from neighboring frames in the observation sequence and then subtracted from each exposure to greatly reduce fringing in the red. The exposures for each slitlet were reduced separately and then co-added. One-dimensional spectra were extracted for each of the targeted objects. Wavelength calibration of the one-dimensional spectra was obtained from arc lamp exposures taken immediately after the object exposures. A relative flux calibration was obtained from long-slit observations of the standard stars HZ 44 and G191B2B (Massey et al. 1988; Massey & Gronwall 1990). While these spectra do not straightforwardly yield an absolute flux calibration of the slit mask data, the relative calibration of the spectral shapes is accurate.

2.3. Chandra Imaging

RDCS J0910+5422 was observed for a total of 200 ks in two pointings in observation 800166 with ACIS-I. The first pointing, exposure ID 452, was performed on 2001 April 24 for 76 ks, while the second pointing, exposure ID 227, was conducted on 2001 April 29 for 124 ks. For each pointing, we removed events from the level 2 event list with a status not equal to zero and with grades 1, 5, and 7. In addition, we used Alexei Vikhlinin’s software for removing background events in data observed with the very faint telemetry mode. We then cleaned bad offsets and examined the data on a chip-by-chip basis, removing times when the count rate exceeded 3 standard deviations from the mean count rate per 3.3 s interval. For chip 1, we specifically excluded the three brightest objects. One of these objects, identified with HD 237786, a G5 V star, underwent a flare in the second pointing. Usually each mask was observed in a series of 1800 s exposures, with small spatial offsets along the long axis of the detection region.

To measure the X-ray flux in the ACIS-I image, we centered a circular aperture with a radius of 100″ at 09h10m44.9s, +54d22m08.9s (J2000.0). The position was identified from the smoothed contour map overlaid on the composite optical and near-infrared image. We then cleaned each chip for flickering pixels, i.e., times when a pixel had events in two sequential 3.3 s intervals. We finally merged the event lists from the two pointings using the COMBINE_OBSID shell script provided for this purpose. The resulting effective exposure time for the summed data is 163 ks. The main reason for the relatively large amount of time lost from the total exposure is flaring from the bright star in the field.

3. RESULTS

3.1. Optical and Near-IR

The presence of a group of very red galaxies at the position of RDCS J0910+5422 is obvious in Figure 1. The spatial distribution of the very red galaxies in Figure 1 is somewhat linear from the northeast to the southwest; we will return to this point when discussing the Chandra imaging. Figure 2 shows the I–K and J–K color-magnitude diagrams for all objects in a 200″ area around RDCS J0910+5422. A red sequence characteristic of a galaxy cluster may be seen at I–K ~ 4.0 in Figure 2 (bottom). This sequence lies some 0.5 mag to the blue of the predicted no-evolution location for early-type galaxies at the cluster redshift. This prediction was made using photometry of Coma galaxies as detailed in SED98. This amount of bluing in the I–K color is consistent with the color change due to passive evolution of a single-age Z⊙ stellar population formed in a 0.1 Gyr burst at zf = 3 (using the GISSEL models of G. Bruzual & S. Charlot 2000, private communication). There is an indication that the red sequence in RDCS J0910+5422 has a flatter slope relative to the Coma sequence, but this result is very uncertain. The slope difference is not likely to be due to differences in the photometry of the galaxies in Coma and RDCS J0910+5422—e.g., apertures of the same physical size were used on both clusters. A similarly flatter slope was tentatively found in RDCS J0848+4453, at z = 1.27 (van Dokkum et al. 2001). The observed scatter in the I–J colors of the member galaxies is 0.09 mag and the measurement error is 0.08 mag, indicating a very small amount of intrinsic scatter, ~0.04, in the restframe ~U–V colors.

The optical spectra for the nine member galaxies are presented in Figure 3. Redshifts were calculated both by visual identification of emission and absorption features and by cross-correlating the spectra with an E template from Kinney et al. (1996) by using the IRAF package RVSAO/XCSAO (Kurtz et al. 1992) and are listed in Table 1. The redshift measurements primarily are based on major features such as Ca II H and K and O II λ3727 and are also sensitive to spectral breaks such as D4000 and B2900. Spectra were obtained for a total of 15 color-selected targets; of these, redshifts were determined for 13 and eight are cluster members (one serendipitous spectrum belongs to a member). The locations of the member galaxies are shown on the color composite image in Figure 1. ID 161, which lies outside our Ks image, was discovered serendipitously in an LRIS mask to be at the cluster redshift and has relatively strong [O II] emission, while the remaining member galaxies have spectra typical of early-type galaxies in the present epoch, albeit with smaller D4000.

3.2. X-Ray

To measure the X-ray flux in the ACIS-I image, we centered a circular aperture with a radius of 100″ at 09h10m44.9s, +54d22m08.9s (J2000.0). The position was chosen by the flux-weighted centroid of all events at 0.5–2.0 keV within 20″ of the visual center of the cluster. From this circular aperture, we excluded seven point sources. Each point source was identified from the smoothed contour map overlaid on the composite optical and near-infrared image. We then fitted an elliptical β-model and a constant background to the events within the 0.5–2.0 keV map. We used a map binned into 1″ pixels and fitted the model by using the CIAO package SHERPA (Freeman, Kashyap, & Siemens 2000) with the Cash statistic (Cash 1979). We first explored the parameter space with 3000 Monte Carlo samples and then refined the best-fitting Monte Carlo result. Our best-fitting model has a core radius of 19″4 ± 0.6 and $β = 0.887^{+0.028}_{-0.026}$. Our best-fitting model was mildly elliptical, with an ellipticity of 0.045^{+0.048}_{-0.044}. At the redshift of the cluster, the core radius would be 171.1 ± 5.3 kpc. These values are typical of low-redshift clusters. (See Fig. 4.)

For an estimate of the background spectrum, we chose three separate regions. Each background region was visu-
ally inspected, which resulted in the removal of bright point sources. We fitted all three regions jointly, using the program XSPEC (Arnaud 1996), with a two-component model (referred to as a background model in the program XSPEC) consisting of a power law, not convolved with the telescope effective area, and a Gaussian for the 2.1 keV Au emission line. Each region had a separate normalization for the two components. We used separate response matrices for each region, and we generated these using Alexei Vikhlinin’s CALCARF/CALCRMF tools.

We extracted a spectrum of the cluster by using an elliptical aperture. The semimajor axis of the ellipse was twice the core radius of the cluster. We fixed the background to the values from the best-fitting model above, with the normalizations rescaled by the relative area in the aperture. Freezing the background and the absorption by galactic hydrogen at \( N_{\text{H}} = 10^{20} \text{ cm}^{-2} \), obtained from the 100 \( \mu \text{m} \) maps of Schlegel, Finkbeiner, & Davis (1998), we fitted a Raymond-Smith spectrum by using the Cash statistic to the spectrum shown in Figure 5 in the source aperture. We found a best-fitting temperature of \( kT = 7.2^{+1.4}_{-1.2} \) keV. The
best-fitting flux in the ROSAT band of 0.5–2.0 keV was 1.06$^{+0.07}_{-0.06} \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ within the 38" aperture. The flux as measured in the RDCS in the same band from ROSAT data was 2.0$^{+10^{-14}}_{-10^{-14}}$ ergs cm$^{-2}$ s$^{-1}$. Most of the difference between the ROSAT and Chandra fluxes is due to the exclusion of the point sources detected in the ACIS image from the latter flux. The total bolometric luminosity of RDCS J0910+5422 is $2.48^{+0.33}_{-0.26} \times 10^{44}$ ergs s$^{-1}$ when integrated over the whole of the $\beta$-model. The errors on the temperature, flux, and luminosity were determined using 2000 iterations of the fakeit command in XSPEC. Unfortunately we are unable to determine the metallicity of the intracluster medium (ICM) to see whether the canonical $1/3 Z_\odot$ seen in clusters up to $z \sim 0.8$ (Donahue et al. 1999; Mushotzky & Loewenstein 1997) continues beyond $z = 1$.

Fig. 3.—LRIS spectra of cluster members obtained at Keck. The rest-frame wavelengths are shown along the top for $z = 1.10$, and the associated positions of major spectral features (from left to right: B2900, B3260, L3727, and D4000) are marked by vertical dashed lines. The flux calibration is relative.
The total mass of RX J0910+5422 derived from the new X-ray data is $7^{+0.6}_{-0.3} \times 10^{14} M_{\odot} h^{-1}$. Recent results obtained with Chandra and XMM on the ICM in lower redshift clusters indicate that, apart from drops in the central regions due to cooling flows, the temperature profiles are fairly constant out to large radii, implying that mass estimates based on the assumption of isothermality are reasonable (Borgani 2002).

Several point sources were detected in the vicinity of the extended X-ray emission of the cluster, demonstrating the importance of high spatial resolution when attempting to accurately measure the properties of the ICM in high-$z$ clusters. One of the fainter point sources is associated with a cluster member, ID 23, which has weak emission lines and a relatively blue continuum. This object has $L_x = 5.1 \times 10^{42}$ ergs s$^{-1}$ in the 0.5–10 keV band. As seen in Figure 1 there is a close neighbor with which ID 23 could be interacting; higher resolution imaging will be useful to answer this question. ID 23 is probably a low-luminosity active galactic nucleus (AGN), though we did not find evidence of the Ne v line at $\lambda 3426$ in our LRIS spectrum, which is usually detected in such objects. A second much brighter X-ray point source ($F_x = 0.73 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$) just to the northeast of the cluster center is associated with the $K$-band object ID 21, which has the colors $(J-K = 1.86$ and $I-K = 3.85$) of a cluster galaxy but for which we have no Spectrophotometric Properties of Galaxies in RDCS J0910+5422

| ID  | R.A.   | Decl. | $K$   | $J-K$  | $I-K$  | $z$  |
|-----|--------|-------|-------|--------|--------|------|
| 23  | 9 10 48.34 | 54 22 29 | 17.86 | 2.15   | 4.02   | 1.1108 |
| 24  | 9 10 44.99 | 54 22 02 | 17.89 | 1.82   | 3.96   | 1.1075 |
| 35  | 9 10 44.88 | 54 21 59 | 18.39 | 1.75   | 3.84   | 1.1196 |
| 37  | 9 10 46.27 | 54 22 11 | 18.43 | 2.14   | 4.07   | 1.105  |
| 38  | 9 10 42.85 | 54 21 43 | 18.50 | 1.95   | 3.87   | 1.0951 |
| 54  | 9 10 45.34 | 54 22 04 | 18.83 | 1.67   | 3.86   | 1.0997 |
| 57  | 9 10 48.30 | 54 22 24 | 18.96 | 1.92   | 3.46   | 1.0989 |
| 68  | 9 10 50.15 | 54 21 03 | 19.22 | 2.21   | 3.94   | 1.107  |
| 161  | 9 10 30.08 | 54 18 45 | …   | …   | …   | 1.1136 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Object outside area covered by our $K$-band image.

Fig. 4.—$K_s$-band image of RDCS J0910+5422. The X-ray contours of the ACIS data are from the 0.5–2.0 keV events smoothed with a 5′ FWHM Gaussian. The X-ray emission is not centered on an obvious brightest-cluster galaxy, and its shape is slightly elongated in the same direction as that of the member galaxy distribution. The bright X-ray point source just northeast of the cluster, ID 21, is associated with a photometric cluster member. The fainter X-ray point source even farther to the northeast (located at R.A. = 9h10m48s, decl. = 54°22′29″) is associated with galaxy ID 23, a spectroscopic cluster member. No spectral information is available for ID 27, which does not have the colors expected of a cluster member.
spectrum. A third point source, ID 61, is also of interest because it is a hard X-ray source and a photometric member. Such galaxies are of particular value as they may represent a source of early heating during the formation of the ICM.

Though the X-ray morphology largely appears to be that of a relaxed system, there are indications that this cluster is still forming. Indeed given its high redshift and the expectations of cluster building, which should occur at these redshifts according to $\Lambda$CDM simulations, evidence, e.g., of mergers is to be expected. As shown in Figure 6, there is some evidence in the ACIS data for temperature structure or merging in the ICM. The soft component dominates the central area of the X-ray emission, while to the south there is a harder component. Such a temperature distribution in the ICM could be due to an infalling group or to mass streaming in along a filament. Indeed, the spatial distribution of the galaxies in the cluster gives the impression of filamentary structure, reminiscent of that seen in CDM simulations of cluster formation (Frenk et al. 1999).

4. SUMMARY

4.1. Cluster Galaxy Population

The spectrophotometric properties of all the known members in RDCS J0910+5422 are summarized in Table 1. Two of the member galaxies show signs of current star formation, and one of these may be an AGN because of its X-ray emission. The spectra and colors of six of the spectroscopic members are broadly similar to those of a passively evolving elliptical galaxy formed at $z \sim 3$. But from these data alone, it is unclear whether the luminous galaxies in the red sequence formed via hierarchical merging at $z < 3$ or as a single object at $z > 3$. Age dating the spectra could provide additional information on the formation epoch of the galaxies, but such detailed modeling is burdened with its own uncertainties due to the age-metallicity degeneracy. Progress on the issue of the assembly of early-type galaxies in clusters is most likely to occur with determining the morphologies of the member galaxies by using high-resolution Hubble Space Telescope imaging on a large sample within RDCS J0910+5422, and in other similarly high-$z$ clusters.

4.2. ICM

The Chandra data conclusively show the presence of hot gas trapped in the potential well of a massive cluster. This is the third instance in the RDCS of a cluster at $z > 1$ with a well-defined ICM. The ACIS spectra yield $kT = 7.2^{+2.1}_{-1.4}$ keV and total $L_X = 2.48^{+0.33}_{-0.26} \times 10^{44}$ ergs s$^{-1}$, both near the values for an $L^*$ cluster in the present epoch. Furthermore, the position of RDCS J0910+5422 in a plot of $L_X$ versus $T_X$, shown in Figure 7, shows little if any evolution in the $L$-$T$ relation at $z > 1$, in keeping with the results of Borgani et al. (2001b). Along with the well-defined red envelope, these properties indicate that RDCS J0910+5422 is another example of a massive cluster with an old galaxy population and a hot ICM already in place at $z > 1$.

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Fig. 7.—X-ray luminosity vs. X-ray temperature for various cluster samples as detailed in the legend, with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. 

7.