Another X-ray–Discovered Poor Cluster of Galaxies Associated with CL 0016+16

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universe

ABSTRACT

We report optical spectroscopic observations of RX J0018.8+1602, a ROSAT
X-ray source proposed to be an intermediate redshift cluster of galaxies.
Our observations confirm the identification of RX J0018.8+1602 and provide
measurements of its mean radial velocity ($z = 0.5406 \pm 0.0006$) and velocity
dispersion ($\sigma_p = 200^{+110}_{-80}$ km s$^{-1}$). This is the second poor cluster that has
been found to be a companion to CL 0016+16 ($z = 0.5455$), the other one
being RX J0018.3+1618 ($z = 0.5506$). The 0.2–2 keV band source-frame X-ray
luminosity summed over both companion clusters is $5 \times 10^{44}$ ergs s$^{-1}$, which is
a significant fraction $\sim 23\%$ of the X-ray luminosity of the main cluster. The
companions are located at angular distances of 10’ to 25’ (minimum physical
scales of 5 Mpc to 12 Mpc) from CL 0016+16 and we propose that they
represent a new large-scale component of the X-ray emission from clusters of
galaxies. Similar low X-ray luminosity poor clusters surrounding nearby Abell

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$^1$Optical observations reported here were obtained at the Multiple Mirror Telescope, a joint facility of the
Smithsonian Institution and the University of Arizona.
clusters can explain the excess power observed in the angular cross-correlation function between Abell clusters and the X-ray background on inferred physical scales of 14–20 Mpc (Soltan et al. 1996).

1. Introduction

In this article, we continue our studies of the environment of the moderately distant \((z = 0.5455)\) rich cluster of galaxies CL 0016+16. This cluster was the prime target of a deep (43 ks) ROSAT X-ray pointing that has been used in interpreting the cluster’s Sunyaev-Zel’dovich effect (Hughes & Birkinshaw 1997) and estimating its gravitational mass (Neumann & Böhringer 1997). We have been following-up selected serendipitous sources in the imaging data (there are \(\sim 80\) field sources detected by the ROSAT standard processing) in order to investigate the large scale structure or supercluster believed to exist near CL 0016+16 (Koo 1981, 1986; Connolly et al. 1996). The length of the observation, plus the high sensitivity of the ROSAT position sensitive proportional counter (PSPC), offsets to some extent the low source fluxes of objects at these redshift. On the other hand the large redshift provides a clear advantage for studying structure: the roughly \(1^\circ\) field of view of the PSPC corresponds to large physical scales at the cluster’s redshift: 30 Mpc or so. Throughout this article we assume \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\), \(q_0 = 0.15\).

Results to date corroborate the approach of using X-ray–selection to probe large scale structure. Previously we reported the discovery, based on the ROSAT data, of a poor cluster, RX J0018.3+1618, some \(9.5\) (4.6 Mpc) southwest of CL 0016+16, which our optical spectroscopy revealed to be at nearly the same redshift (Hughes, Birkinshaw, & Huchra 1995). Below we present new optical observations of a second X-ray source in this field, RX J0018.8+1602, proposed to be yet another galaxy cluster at roughly the same redshift (Connolly et al. 1996). Our observations confirm its identification and provide the first accurate measurements of its redshift and velocity dispersion. It is indeed another companion to CL 0016+16, located \(\sim 25'\) (12 Mpc) nearly due south.

We consider the existence of these two companions to CL 0016+16 in light of the recently discovered extended, low surface brightness X-ray “halos” apparently associated with Abell clusters of galaxies (Soltan et al. 1996). The evidence for these X-ray halos comes from a cross-correlation between the positions of Abell clusters and the X-ray background as measured by the ROSAT All-Sky Survey (RASS) that was found to show significant amplitude on angular scales of \(1^\circ\) to \(3^\circ\). Abell clusters are known to be highly clustered (e.g., Nichol, Briel, & Henry 1994) and are strong X-ray emitters, nevertheless Soltan et al. claim that the signal they detect is a factor of three larger than the correlation function
predicted from the known clustering properties of Abell clusters themselves, signifying that an additional, new component of sources, spatially correlated with Abell clusters and displaying soft X-ray emission, is required. The X-ray luminosity of the extended component is $\sim 10^{44}$ erg s$^{-1}$ in the ROSAT band. Soltan et al. offered two explanations for the halos: X-ray emission from either (1) a number of discrete sources associated with groups or poor clusters, or (2) a truly diffuse component of hot gas extended over tens of Megaparsecs. Note that the latter component has an inferred X-ray surface brightness that is about 2 orders of magnitude less than the soft X-ray background and thus it is unlikely that individual examples could be imaged directly by ROSAT.

As we show below, the locations of the new clusters relative to CL 0016+16 and their X-ray luminosities and temperatures are broadly consistent with what is needed to explain the correlation function results in terms of discrete sources. This conclusion is further strengthened by the significant number of low redshift groups of clusters that may represent nearby examples of this phenomenon.

2. Observations

2.1. X-ray

The reprocessed data from a 43 ks ROSAT PSPC observation were used to study the X-ray properties of the proposed new cluster. RX J0018.8+1602 is approximately 25$'$ off-axis, where the imaging resolution of the PSPC has a broad core ($\sim 2'$ FWHM) due to the off-axis aberrations of the ROSAT X-ray mirrors, which makes detailed analysis of the spatial structure difficult. Another complication arises from the presence of a second X-ray source about 3$'$ to the southwest. Both sources can be seen clearly in Figure 1 (Plate L00) where the contour map shows the X-ray data. Note that the absolute accuracy of PSPC source positions was verified to be better than 2$''$ based on agreement between the X-ray and optical positions of five point sources (Hughes et al. 1995).

We fit the X-ray imaging data within a 4$'$ radius of RX J0018.8+1602 using a model consisting of background, a point source, and an isothermal-$\beta$ model cluster profile of the form $\Sigma = \Sigma_0[1 + (\theta/\theta_C)^2]^{-3\beta+0.5}$ (Cavaliere & Fusco-Femiano 1976). For background we used the background image provided as part of the standard processing. The data strongly require, at about the 3-$\sigma$ level, that the northern source be extended, although the core radius parameter in the cluster model, $\theta_C$, is not well-constrained due to the large image blur at the source’s off-axis position. With $\theta_C$ fixed to the value 0.44 found earlier for RX J0018.3+1618 (Hughes et al. 1995), we find $\Sigma_0 \approx 1.1 \times 10^{-2}$ counts s$^{-1}$ arcmin$^{-2}$ and
$\beta \approx 0.75$ for the candidate new cluster. The position of the cluster model (from maximum likelihood fits to the image) is $00^h18^m47.9^s$, $16^\circ02'22''$ (J2000) with an uncertainty of about 5$''$ in each coordinate. In the spectral analysis presented next, we were careful to select the spectral extraction regions so that the X-ray emission from the two sources was kept separate.

The point-like X-ray source to the south (at $00^h18^m42.6^s$, $15^\circ59'37''$) has a count rate within a radius of 1.5 of $(5.8 \pm 0.6) \times 10^{-3}$ PSPC counts s$^{-1}$. Although there are too few counts ($\lesssim 200$) to do a detailed spectral analysis, the hardness ratios are consistent with a low column density ($N_H \lesssim 10^{19}$ cm$^{-2}$) and a spectrum that cuts-off above $\sim$1 keV, similar to that expected from a Galactic star. The unabsorbed X-ray flux is $\sim 3.3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.

The northern source, i.e., the cluster candidate, has an observed count rate (within a radius of 1.8) of $(9.4 \pm 0.8) \times 10^{-3}$ PSPC counts s$^{-1}$ based on a total of approximately 310 counts. The spectrum can be fit well by a thermal plasma model using the Galactic column density ($N_H = 4.1 \times 10^{20}$ cm$^{-2}$) and fractional elemental abundances of $\frac{1}{4}$ solar. Anticipating the results in §2.3 below, we set the redshift to 0.5406 and obtained a best-fit source-frame temperature of $kT = 1.4^{+0.7}_{-0.3}$ keV (1 $\sigma$ uncertainty), in good agreement with Connolly et al. (1996). The unabsorbed X-ray flux is $1.5 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ over the 0.2–2 keV band.

### 2.2. Optical Imaging

The candidate cluster was observed at the Whipple Observatory 1.2-m telescope on 1996 July 17 under fair to poor conditions for 1800 s in $R$. The focal plane detector CCD was binned to produce an effective pixel scale of 0$''$.64. Using standard IRAF tasks, we bias-subtracted the data, eliminated cosmic rays and bad pixels, and flat-fielded using dome flats. The positions of four $HST$ guide stars were used to register the image to the celestial sphere; a positional uncertainty of $\lesssim 0.5'$ was obtained. Stellar images were about 1$''$.8 [FWHM], which is not unusual for this telescope.

Figure 1 (Plate L00) shows a portion of the $R$-band image with contours of X-ray emission superposed. Numerous faint galaxies are associated with the diffuse X-ray emission, with a dominant bright galaxy (labeled 4) within 7$''$ of the center of the X-ray emission. DAOPHOT was run on the frame to detect objects and of order 300 were found. The sharpness parameter was used to discriminate between stars and galaxies for the follow-up optical spectroscopy.
Toward the south there is a bright \((m_V = 8.6)\) star (HD 1450) of spectral type F5 that is positionally coincident with the southern X-ray source. Using the flux quoted above, we estimate an X-ray to optical flux ratio for the star of \(\log f_X/f_V \sim -4.7\) (using the relationship in Stocke et al. 1991) that is in the range expected for Galactic stars of spectral type B-F. We conclude that HD 1450 is the counterpart to the southern X-ray source.

2.3. Optical Spectroscopy

We obtained optical spectra at the Multiple Mirror Telescope on 1996 November 12 and 13 using the Red Channel with aperture plates (Fabricant, McClintock, & Bautz 1991). Four aperture plates were machined several weeks before the run with slitlets cut for seven candidate galaxies on each plate. Our spectral resolution was \(~15 \, \text{Å} (\text{FWHM})\) and all spectra included the wavelength range 5500 – 8500 Å. Multiple exposures (2700 s duration) of each plate were taken for total integration times ranging from 5400 s to 13500 s. He-Ne-Ar lamp exposures were done before and after each exposure and dome flats were done at the beginning or end of the night.

Standard IRAF routines were used for cosmic ray removal, bias-level subtraction, flat-fielding, and to trace and extract the one-dimensional spectra. Wavelength calibration used \(~45\) lines from the comparison lamp spectra fit to a cubic spline (root-mean-square residuals were \(~1.0 \, \text{Å}\)). We verified the wavelength of the 6300.2 Å night sky line in our spectra when the data were extracted without sky subtraction. Differences were \(~1 \, \text{Å}\) and our derived redshifts were corrected for this shift \((\Delta z \sim 0.0002)\). To derive recessional velocities our reduced spectra were cross-correlated (task FXCOR) over the observed wavelength range 5600–7500 Å with a spectrum of the galaxy NGC 4486B.

The spectrum of the bright central galaxy (# 4) is shown in Figure 2. The 4000 Å break, as well as absorption features due to Ca II H and K, the G-band, and Mg b2, are all clearly visible. Our redshift \(z = 0.5413 \pm 0.0007\) is consistent with the recent value of \(0.541 \pm 0.004\) presented by Connolly et al. (1997). Strong correlations \((R > 4.0)\) were obtained for the 15 galaxies listed in Table 1, which turn out to be all absorption line objects. We point out object g in the table, which is the radio galaxy 54W084 (Windhorst, Koo, & Kron 1984). Our redshift is consistent with a less accurate value by R. Windhorst from an unpublished low signal-to-noise, low resolution Palomar spectrum.

We were unable to identify or determine redshifts for the remaining 13 objects on the various plates. Our “success” rate was highly correlated with the weather conditions. On the first night (clear to hazy conditions) 10 out of 14 of our observed spectra resulted in
redshift measurements, while on the second night (hazy to partly cloudy conditions) only 5 out of 14 did. Of the 21 objects observed within 1′/6 of the cluster center, 12 were identified as galaxies and 8 are members of the cluster. On the other hand, all of the identified galaxies beyond 1′/4 have radial velocities that are inconsistent with cluster membership.

The formal velocity uncertainties generated by FXCOR from the width of the correlation function vary from galaxy to galaxy over the range 100 km s\(^{-1}\) to 250 km s\(^{-1}\). In addition we include an estimate of the velocity uncertainty due to sky subtraction, obtained by carrying out the reduction twice using slightly different parameters of the fitting function for the sky and taking the difference between the resulting redshift values as the additional uncertainty. In general this quantity is comparable in magnitude to the previous uncertainty; we find values ranging from 80 km s\(^{-1}\) up to 330 km s\(^{-1}\). We also include an uncertainty of 60 km s\(^{-1}\) due to wavelength calibration and an uncertainty of 90 km s\(^{-1}\), due to variation of the parameters of the cross-correlation, e.g., the order of the continuum fits and the wavelength range over which the cross-correlation was done. The final uncertainty quoted in Table 1 is the root-sum-square of the individual components.

3. Discussion

The mean redshift of the new cluster based on the eight galaxies indicated as members in Table 1 is 0.5406 ± 0.0006 and the radial component of its velocity dispersion is 200\(^{+110}_{-80}\) km s\(^{-1}\) (1 σ uncertainties), calculated using the formulae in Danese, De Zotti, & di Tullio (1980). Although galaxies b, f, and g in the lower part of the table have redshifts near 0.5, they are unlikely to be members of the cluster because they lie at the outskirts of the cluster (more than 1′/5 from the central galaxy), and their redshifts are more than 8 σ away from the mean of the cluster. They are possibly related to the sheet of galaxies identified by Connolly et al. (1996).

The X-ray luminosity of RX J0018.8+1602 is 3 \(\times\) 10\(^{44}\) ergs s\(^{-1}\) over the 0.2–2 keV band in the source frame. From the measured temperature, the imaging results, and the standard assumption of a symmetric, isothermal cluster in hydrostatic equilibrium, we estimate the cluster’s mass within a 2 Mpc radius to be 3 \(\times\) 10\(^{14}\) M\(_{\odot}\). The ratio of gas mass to total mass within this same radius is 33%. These values are similar to those of the other poor cluster, RX J0018.3+1618 (Hughes et al. 1995) associated with CL 0016+16. In Table 2 we present a comparison between the observed and physical characteristics of the two new clusters. (Note that the temperature of RX J0018.3+1618 was determined for this article from a joint fit of ROSAT PSPC and ASCA GIS data.) The luminosity of CL 0016+16 is 2 \(\times\) 10\(^{45}\) ergs s\(^{-1}\), which is 4 times the combined X-ray emission from the
companions. Finally we note for completeness that the X-ray luminosities of the companion clusters are quite a bit larger than the average X-ray luminosity of nearby galaxy groups ($L_X \sim 10^{41} - 10^{42}$ ergs s$^{-1}$, Mulchaey et al. 1996).

Energy considerations were used by Hughes et al. (1995) to show that CL 0016+16 and RX J0018.3+1618 were not unlikely to form a bound system: on the assumption of random projections of the separation vector and relative velocity vector of these clusters, and using the mass estimates out to radii of 2 Mpc, the a priori probability that these two clusters form a bound system is about 38%. We have repeated this calculation taking into account the extra kinetic and potential energies contributed by RX J0018.8+1602. The a priori probability that all three clusters form a bound system can be shown to be about 11%. This is smaller than previously calculated, because RX J0018.8+1602 contributes less to the potential than the kinetic energy — it is rapidly moving relative to, and distant from, the center of mass of the composite system for most choices of projection angles. If CL 0016+16 is taken, instead, to have a radius of 5 Mpc, then the mass increases by a factor 2.5 and the probability that the entire system is bound rises to about 30%. These a priori probability estimates are likely to be pessimistic about the chances that the overall system is bound, since they ignore the indications of further clumped masses in the field of CL 0016+16 (based on optical material: Connolly et al. 1996).

If we assume that the projection angles of the companion clusters relative to CL 0016+16 are less than 60$^\circ$ (i.e., the three clusters lie within a sphere of radius $\sim 25$ Mpc centered on CL 0016+16), then a conservative lower limit to the local space density of clusters is $N \sim 5 \times 10^{-5}$ Mpc$^{-3}$. This is 2 orders of magnitude larger than the space density of Abell clusters with $L_X \gtrsim 2 \times 10^{44}$ ergs s$^{-1}$ from a complete sample of clusters over several hundred square degrees at high Galactic latitude (Briel & Henry 1993).

Notwithstanding this large local space density of clusters, it is our opinion that the CL 0016+16 system is not particularly exceptional but may merely represent an intermediate redshift example of essentially similar nearby systems. We offer two pieces of evidence in support of this. One is the high frequency of pairs observed in the X-ray flux-limited sample of low redshift ($z < 0.2$) clusters from Lahav et al. (1989). The other is the presence of extended, low surface brightness X-ray haloes associated with Abell clusters mentioned in the Introduction. We discuss each of these below.

Out of the 55 clusters in the all-sky sample of the brightest X-ray clusters (Lahav et al. 1989, Edge et al. 1990), there are six close pairs with physical separations of roughly 20 Mpc or less. Since both clusters must appear in the list, this number is clearly a lower limit to the fraction of such pairs. A better estimate can be obtained by searching for companions from the ROSAT X-ray brightest Abell clusters (the XBACs sample, Ebeling
et al. 1997) which goes to a much lower flux limit (nearly a factor of 10). Of the 46 clusters in the Edge et al. sample at high Galactic latitude \((b > 20^\circ\) which is also the XBACs limit), we find that as many as 19 have X-ray emitting companions nearby (i.e., within physical separations of 25 Mpc or less), for a fraction of clusters with close companions of 41%. Again this is a lower limit since the XBACs sample was derived from the (optically-selected) Abell clusters.

In the XBACs sample itself there are 30 systems that contain two, three, four, or even five individual clusters in close proximity (25 Mpc). The median \(L_X\) of the sample consisting of the dominant cluster in each system is \(3.5 \times 10^{44} \text{ erg s}^{-1}\), while the median luminosity of all the companion clusters (of which there are 41) is \(1.9 \times 10^{44} \text{ erg s}^{-1}\), which is nearly identical to the luminosity of RX J0018.3+1618 and RX J0018.8+1602. If, for each individual system, one compares the companion’s X-ray luminosity (summed over all companions in systems with more than one) to that of the dominant cluster, one finds that the ratio varies over a large range, 0.17 to 1.5, as plotted in Fig. 3. The filled circle shows the CL 0016+16 system. These results firmly establish that the CL 0016+16 system is entirely consistent with the close cluster groupings from the low redshift XBACs sample.

The second piece of evidence for structure on ten Megaparsec scales associated with nearby clusters of galaxies comes from a cross-correlation between the angular positions of Abell clusters and the intensity of the soft X-ray background as measured by ROSAT (Soltan et al. 1996). To explain their cross-correlation results Soltan et al. need a new component of X-ray emission from structure on scales 20–30 times larger than the size of the cluster itself, or physical scales of \(\sim 20 \text{ Mpc}\). The spectral character of the emission needs to be softer than the X-ray background in general, due to limits set by the Ginga satellite over the higher energy 4–12 keV band (from the auto-correlation function of the X-ray background, Carrera et al. 1991, 1993). Sources with little emission above \(\sim 4 \text{ keV}\) are required and thermal spectra with \(kT \leq 5 \text{ keV}\) would be consistent with this limit. And as mentioned in the Introduction the mean luminosity of the extended component is \(L_X \sim 10^{44} \text{ ergs s}^{-1}\).

One possible explanation for this new component of X-ray emission is the hot gas that may be contained in filaments connecting galaxy clusters. Such filaments are a common feature of numerical models of structure formation in the Universe; there is also observational support for their existence from galaxy redshift surveys (e.g., Da Costa et al. 1994). Recently, however, Briel & Henry (1995) derived a limit on the X-ray emission from such filaments that is significantly less than what would be needed to explain the excess correlation power. On the other hand, in all direct observational aspects: spatial scale, low X-ray temperature, and soft X-ray luminosity, the companion clusters to CL 0016+16...
satisfy the observational requirements demanded of the extended halo emission component. Our results therefore strongly suggest that the origin of the extended halos around Abell clusters should be interpreted as arising from physically associated discrete sources, specifically poor clusters or groups of galaxies, rather than a truly diffuse extended halo of hot gas. Whether on the average the companion clusters are few and have luminosities consistent with poor clusters ($\sim 10^{44}$ ergs s$^{-1}$) or are more common but less luminous, like groups, remains to be seen.

We thank Ale Milone for taking the R-band images of RX J0018.8+1602 and for her efforts as MMT operator during the run in November. Thanks are extended to Paul Callanan and Mike Garcia for sharing their 1.2-m time and we acknowledge the generosity of the CfA TAC for awarding us MMT time. We thank the referee, Rogier Windhorst, for his helpful comments. This research was partially supported by a PPARC grant to MB and NASA Long Term Space Astrophysics Grant NAG5-3432 to JPH.

REFERENCES


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Fig. 1.— R-band image from the Mount Hopkins 1.2 m telescope of a portion of the field containing the X-ray–discovered cluster, RX J0018.8+1602, overlaid with contours of constant X-ray surface brightness. Contour values increase in multiplicative steps of 1.476 from a minimum value of $2.0 \times 10^{-4}$ PSPC counts s$^{-1}$ arcmin$^{-2}$ to a maximum value of $1.4 \times 10^{-3}$ PSPC counts s$^{-1}$ arcmin$^{-2}$. The 8 galaxies with measured redshifts in the range 0.538 – 0.542 (Table 1) are numbered. Galaxies labelled a to g have spectroscopic redshifts outside this range and are believed to be foreground or background objects. Coordinates are quoted in epoch J2000.

Fig. 2.— Optical spectrum of the brightest galaxy in the new cluster RX J0018.8+1602. The 4000Å break, as well as absorption lines characteristic of late type stellar spectra are clearly visible. We indicate with filled circles features in the galaxy spectrum due to Ca II K and H, the G-band, Fe I λ4383.6, Mg I λ5172.7 (Mg b2), and Fe I λ5269.6. Telluric absorption from the O$_2$ B and A bands are noted with ⊕ symbols. For this display only, the spectrum was smoothed with a 15Å [FWHM] gaussian, which is approximately the spectral resolution.

Fig. 3.— The X-ray luminosity in the 0.1–2.4 keV ROSAT band of the dominant cluster (horizontal axis) compared to the summed luminosity of companion clusters within a radius of 25 Mpc. The vertical axis plots the luminosity ratio of the companions to the dominant cluster. Clusters from the low redshift XBACs sample are shown as crosses, and the filled circle shows the intermediate redshift CL 0016+16 system.
Table 1. Spectroscopic Results

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<th>n</th>
<th>Position (J2000)</th>
<th>α</th>
<th>δ</th>
<th>z</th>
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<td></td>
<td>RX J0018.8+1602 Cluster Members</td>
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<tr>
<td>1</td>
<td>0^h18^m52.9^s</td>
<td>16°02'08&quot;</td>
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<td>2</td>
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<td>02'15&quot;</td>
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<td>47.3^s</td>
<td>02'19&quot;</td>
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<td>7</td>
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<td>8</td>
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<td>Probable Non-members</td>
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<td>a</td>
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<td>b</td>
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<td>g</td>
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<td>02'10&quot;</td>
<td>0.5491 ± 0.0012</td>
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*aRadio galaxy 54W084 (Windhorst, Koo, & Kron 1984)
Table 2. Clusters Associated with CL 0016+16 a

<table>
<thead>
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<th>Parameter</th>
<th>RX J0018.3+1618</th>
<th>RX J0018.8+1602</th>
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<tr>
<td>$z$</td>
<td>0.5506 ± 0.0012</td>
<td>0.5406 ± 0.0006</td>
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<td>$\sigma_P$ (km s$^{-1}$)</td>
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<td>200$^{+110}_{-80}$</td>
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<td>$kT$ (keV)</td>
<td>3.1$^{+2.8}_{-1.4}$</td>
<td>1.4$^{+0.7}_{-0.3}$</td>
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<td>$1.5 \times 10^{-13}$</td>
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<td>$L_X^c$ (erg s$^{-1}$)</td>
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<td>$3 \times 10^{44}$</td>
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<td>$M_{\text{gas}}(&lt;2\text{ Mpc})$ (M$_\odot$)</td>
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<td>$1 \times 10^{14}$</td>
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<td>$2 \times 10^{14}$</td>
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<td>Projected linear (Mpc)</td>
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<td>11.7</td>
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aUncertainties quoted at the 1 $\sigma$ confidence level

bUnabsorbed flux over 0.2–2 keV band (observed frame)

cOver 0.2–2 keV band (source frame)
$z = 0.5413$