LOW X-RAY LUMINOSITY GALAXY CLUSTERS: MAIN GOALS, SAMPLE SELECTION, PHOTOOMETRIC AND SPECTROSCOPIC OBSERVATIONS

José Luis Nilo Castellón1,2, M. Victoria Alonso3,4, Diego García Lambas3,4, Carlos Valotto3,4, Ana Laura O’Mill3,4, Héctor Cuevas5, Eleazar R. Carrasco5, Amelia Ramírez5, José M. Astudillo6, Felipe Ramos3,

Marcelo Jaque Arancibia7, Natalie Ulloa1, and Yasna Órdenes8

1 Departamento de Física y Astronomía, Facultad de Ciencias, Universidad de La Serena, Cisternas 1200, La Serena, Chile
2 Dirección de Investigación, Universidad de La Serena, Av. R. Bitrán Nachary 1305, La Serena, Chile
3 Instituto de Astronomía Teórica y Experimental, (IATE-CONICET), Laprida 922, Córdoba, Argentina
4 Observatorio Astronómico de Córdoba, Universidad Nacional de Córdoba, Laprida 854, Córdoba, Argentina
5 Gemini Observatory/AURA, Southern Operations Center, Casilla 603, La Serena, Chile
6 Departamento de Ciencias Físicas, Universidad Andrés Bello, Av. República 252, 837-0134 Santiago, Chile
7 Instituto de Ciencias Astronómicas, de la Tierra y del Espacio (ICATE-CONICET), Av. España Sur 1512, J5402DSP, San Juan, Argentina
8 Argelander Institute für Astronomie der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

Received 2015 December 1; accepted 2016 March 22; published 2016 May 25

ABSTRACT

We present our study of 19 low X-ray luminosity galaxy clusters ($L_X \sim 0.5–45 \times 10^{43}$ erg s$^{-1}$), selected from the ROSAT Position Sensitive Proportional Counters Pointed Observations and the revised version of Mullis et al. in the redshift range of 0.16–0.7. This is the introductory paper of a series presenting the sample selection, photometric and spectroscopic observations, and data reduction. Photometric data in different passbands were taken for eight galaxy clusters at Las Campanas Observatory; three clusters at Cerro Tololo Interamerican Observatory; and eight clusters at the Gemini Observatory. Spectroscopic data were collected for only four galaxy clusters using Gemini telescopes. Using the photometry, the galaxies were defined based on the star-galaxy separation taking into account photometric parameters. For each galaxy cluster, the catalogs contain the point-spread function and aperture magnitudes of galaxies within the 90% completeness limit. They are used together with structural parameters to study the galaxy morphology and to estimate photometric redshifts. With the spectroscopy, the derived galaxy velocity dispersion of our clusters ranged from 507 km s$^{-1}$ for [VMF98]022 to 775 km s$^{-1}$ for [VMF98]097 with signs of substructure. Cluster membership has been extensively discussed taking into account spectroscopic and photometric redshift estimates. In this sense, members are the galaxies within a projected radius of 0.75 Mpc from the X-ray emission peak and with clustercentric velocities smaller than the cluster velocity dispersion or 6000 km s$^{-1}$, respectively. These results will be used in forthcoming papers to study, among the main topics, the red cluster sequence, blue cloud and green populations, the galaxy luminosity function, and cluster dynamics.

Key words: galaxies: clusters: general – galaxies: fundamental parameters – galaxies: photometry

1. INTRODUCTION

The hierarchical model of structure formation predicts that the progenitors of the galaxy clusters are relatively small systems that are assembled together at higher redshifts. Local cluster processes such as ram pressure stripping and galaxy harassment play an important role in explaining the difference between cluster and field galaxy populations at a fixed stellar mass (Berrier et al. 2009). The study of galaxy systems in a variety of masses at different redshifts may give invaluable physical insights into galaxy evolution.

The observed galaxy scaling relationships provide important tools for examining physical properties of galaxies and their systematics. These relations might be linked to the local galaxy density in rich clusters (e.g., Dressler 1980) or the galaxy morphology evolution (e.g., Butcher & Oemler 1984; Dressler & Gunn 1992). Their connection with different mechanisms such as galaxy collisions (Spitzer & Baade 1951) and interactions with intracluster gas (Gunn & Gott 1972) are crucial to understand galaxy formation and evolution. When a galaxy cluster is assembled, the morphology, luminosity, mass, and mean stellar age of their member galaxies are determined by these processes.

Kodama et al. (1998) studied the Color–Magnitude Relation (CMR) in distant clusters and suggested the monolithic model for the formation of early-type galaxies, but also mentioned other possibilities. In particular, an alternative scenario is the hierarchical merging model (Kauffmann & Charlot 1998; De Lucia et al. 2004). The red cluster sequence found in optical CMRs (hereafter RCS; Gladders et al. 1998; De Lucia et al. 2004; Gilbank et al. 2008; Lerchster et al. 2011 hereafter RCS), which is dominated by non-star-forming, early-type galaxies (Blanton & Moustakas 2009; Zhu et al. 2010) can be used to test these models. Changes in the slope and zero-point of this relation may be an indication of cluster evolution. In the CMRs, star-forming, late-type galaxies populate the “blue cloud.” The presence of these two populations emerges as a bimodality in the color distribution (Baldry et al. 2004) as well as a “green valley” between them (see, for instance, Mendez et al. 2011). The combination of deep images with multi-object spectrographs makes it possible to explore additional evidence related to the processes responsible for the observed properties of cluster members (Christlein & Zabludoff 2005) and to understand better their relationships with the environment (Finn et al. 2005).

In the last twenty years, there was an increased interest in studying galaxy populations in clusters due to the improvement in the observational facilities that resulted in a large number of surveys. The existence of the RCS; the blue galaxy population;
and interactions as a function of redshift and environments, are among the main issues addressed by these surveys. We can mention: the ESO Distant Cluster Survey (EDisCS, White et al. 2005) in a wide range of mass, with redshifts from 0.4 to almost 1.0; the X-ray-luminous clusters from the MACS survey at z ≈ 0.5 within a 1.2 Mpc diameter (Stott et al. 2007); the Observations of Redshift Evolution in Large-Scale Environments (ORELSE) Survey (Lubin et al. 2009), a systematic search for structure around well-known clusters at redshifts of 0.6 < z < 1.3; the galaxy populations in the core of a massive, X-ray luminous cluster (Strazzullo et al. 2010) at z = 1.39; and the IMACS Cluster Building Survey (Oemler et al. 2013) to understand the large-scale environment surrounding rich intermediate redshift clusters of galaxies.

On the other hand, regarding less massive clusters, Balogh et al. (2002) presented the first spectroscopic survey of low X-ray luminosity clusters (\(L_X < 4 \times 10^{43} h^{-2} \text{ erg s}^{-1}\) [0.1–2.4] keV) with Calar Alto spectroscopy and Hubble Space Telescope WFPC2 imaging at 0.23 < z < 0.3. These clusters have Gaussian velocity distributions, with velocity dispersions \(\sigma\) ranging from 350 to 850 kms\(^{-1}\), consistent with the local \(L_X-\sigma\) relation. The spectral and morphological properties of the galaxies in these systems were found similar to those in massive clusters at the same redshifts. Carrasco et al. (2007) analyzed the properties of the low luminosity X-ray cluster of galaxies RX J1117.4 + 0743 at z = 0.485 based on optical and X-ray data finding a complex morphology composed of at least two structures in velocity space. This cluster also presents an angular core radius \(\approx 1.0\) in a wide range of mass, with redshifts from 0.4 to 2.4. These luminosities could be affected by the presence of not removed point sources such as AGNs from the X-ray emission. This effect could be more important at lower luminosities, for instance groups containing an AGN could be wrongly included in the sample. The redshift range of our selection is 0.16–0.70 where we have excluded well-studied low-redshift clusters as well as the galaxy cluster [VMF98]061 at z > 1 previously analyzed by Rosati et al. (1999). Within these luminosity and redshift limits, we have a sample of 140 galaxy clusters with low X-ray luminosities. After visual inspection, we have avoided those fields with bright stars and also those extended objects that would require more than one image to cover the field with the available instruments and telescopes. In this way, our studied sample corresponds to a random selection of 19 low X-ray galaxy clusters. Table 1 presents a summary of the main characteristics of this studied galaxy cluster sample. Columns (1) and (2) show the Vikhlinin et al. (1998) and the ROSAT X-ray survey identifications. The equatorial coordinates of the X-ray centroid and the position uncertainties are in columns (3)–(5); the cluster angular core radius (in arcsec) and the corresponding error are given in columns (6) and (7); the X-ray luminosity in the [0.5–2.0] keV energy band and estimates of the lower bound of their uncertainties are in columns (8) and (9); and the mean redshift in column (10). Columns (3)–(7) are taken from Vikhlinin et al. (1998) while columns (8) and (10) are from Mullis et al. (2003). The mean X-ray luminosity is \(7.3 \times 10^{43} \text{ erg s}^{-1}\), an intermediate/low luminosity when compared to \(\approx 10^{42} \text{ erg s}^{-1}\) for groups with extended X-ray emission or larger values than \(\approx 5 \times 10^{44} \text{ erg s}^{-1}\) of rich clusters.

Figure 1 shows the distributions of X-ray luminosity, angular core radius (in arcsec), and redshift of our sample (shaded

2. LOW X-RAY LUMINOSITY CLUSTER SAMPLE

Vikhlinin et al. (1998) presented the catalog of 223 galaxy clusters based on the spatial extent of their X-ray emission, serendipitously detected in the ROSAT Position Sensitive Proportional Counters (PSPC) pointed observations with photometric redshift estimates. This catalog of extended X-ray sources was revised by Mullis et al. (2003) using optical imaging and spectroscopy to classify 200 galaxy clusters, excluding 23 false detections. The spectroscopic cluster redshifts were derived by long-slit and multiobject spectra with at least 2 or 3 concordant galaxy redshifts per cluster, always including the Bright Cluster Galaxy (BCG), and they entirely superseded the photometric estimates of Vikhlinin et al. (1998).
histograms) compared to the 140 galaxy clusters selected from Mullis et al. (2003). It can be appreciated that our sample of 19 galaxy clusters is biased toward low X-ray luminosities and lower redshifts since we aim at studying this particular regime. The mean angular core radius was about 35 arcsec and most of the galaxy clusters had values smaller than 60 arcsec.

Figure 2 shows the cluster X-ray luminosities ($L_{500}$ [0.1–2.4 keV]) versus redshifts of our galaxy cluster sample and the total sample from Mullis et al. (2003) represented with different circles. We also include other works: Girardi & Mezzetti (2001), Popesso et al. (2005), Wake et al. (2005), and Jensen & Pimbblet (2012). These studies analyze the cluster membership and the photometric properties as galaxy colors and CMRs as our study. All the X-ray luminosities are in the same system, extracted from Piffaretti et al. (2011) which is the largest X-ray galaxy cluster compilation based on publicly available ROSAT All Sky Survey data. In the redshift range studied here, we have chosen the galaxy clusters with lower X-ray luminosities after discarding those mentioned above.

The main goal of this work is to provide keys to understand the cluster assembly and the morphological evolution of galaxies in low X-ray luminosity clusters. These systems thus provide us an interesting environment to explore the efficiency of mergers and ram pressure effects, that can be significantly different from those of rich galaxy clusters. Our study is based on photometric observations of these low X-ray luminosity systems, where the high-quality images also allowed us to construct a morphological catalog to study galaxy morphologies and scaling relations. We are particularly interested in a detailed study of the RCS and an analysis of an eventual intermediate green galaxy population between the galaxy blue cloud and the RCS in these low X-ray systems (Mendez et al. 2011). For some galaxy clusters, we also carried out spectroscopic observations which allowed us to determine cluster membership and velocity dispersion estimates.

### Table 1

| Id. | Source | R.A. (J2000) | decl. (J2000) | $\delta r$ (arcsec) | $r_c$ (arcsec) | $\delta r_c$ (arcsec) | $L_X$ (10^43 erg s^{-1}) | $\Delta L_X$ (10^43 erg s^{-1}) | $z$ |
|-----|--------|-------------|-------------|-------------------|---------------|---------------------|----------------|----------------|-----|
| 001 | RX J0030.5+2618 | 00 30 33.2 | +26 18 19 | 13 | 31 | 3 | 26.1 | 3.2 | 0.500 |
| 004 | RX J0054.0-2823 | 00 54 02.8 | -28 23 58 | 16 | 37 | 6 | 4.2 | 0.6 | 0.292 |
| 011 | RX J0124.5-0400 | 01 24 35.1 | +04 00 49 | 20 | 31 | 14 | 3.4 | 1.0 | 0.316 |
| 015 | RX J0136.4-1811 | 01 36 24.2 | -18 11 59 | 15 | 21 | 8 | 1.4 | 0.3 | 0.251 |
| 022 | RX J0206.3+1511 | 02 06 23.4 | +15 11 16 | 14 | 53 | 10 | 3.6 | 0.7 | 0.248 |
| 024 | RX J0210.2-3932 | 02 10 13.8 | -39 32 51 | 11 | 22 | 10 | 0.6 | 0.1 | 0.168 |
| 025 | RX J0210.4-3929 | 02 10 25.6 | -39 29 47 | 14 | 28 | 9 | 0.8 | 0.2 | 0.165 |
| 045 | RX J0533.8-5746 | 05 33 53.2 | -57 46 52 | 37 | 81 | 28 | 8.7 | 2.4 | 0.297 |
| 046 | RX J0533.9-5809 | 05 33 55.9 | -58 09 16 | 30 | 53 | 20 | 1.6 | 0.5 | 0.198 |
| 093 | RX J1053.3+5720 | 10 53 18.4 | +57 20 47 | 8 | 12 | 3 | 1.4 | 0.2 | 0.340 |
| 097 | RX J1117.4+0743 | 11 17 26.1 | +07 43 35 | 12 | 18 | 7 | 6.4 | 1.7 | 0.477 |
| 102 | RX J1124.0-1700 | 11 24 03.8 | -17 00 11 | 22 | 34 | 19 | 8.1 | 2.5 | 0.407 |
| 113 | RX J1204.3-0350 | 12 04 22.9 | -03 50 55 | 14 | 26 | 6 | 2.7 | 0.4 | 0.261 |
| 119 | RX J1221.4+4918 | 12 21 24.5 | +49 18 13 | 18 | 34 | 8 | 42.7 | 9.5 | 0.700 |
| 124 | RX J1252.0-2920 | 12 52 05.4 | -29 20 46 | 13 | 46 | 11 | 3.4 | 0.7 | 0.188 |
| 148 | RX J1342.8+4028 | 13 42 49.1 | +40 28 11 | 16 | 15 | 6 | 16.2 | 4.4 | 0.699 |
| 211 | RX J2247.4+0337 | 22 47 29.1 | +03 37 13 | 20 | 46 | 17 | 4.1 | 1.1 | 0.200 |
| 214 | RX J2305.4-3546 | 23 05 26.2 | -35 46 01 | 15 | 55 | 14 | 2.8 | 0.6 | 0.201 |
| 215 | RX J2305.4-5130 | 23 05 26.6 | -51 30 30 | 17 | 21 | 10 | 0.7 | 0.2 | 0.194 |
Eight galaxy clusters at $z < 0.32$ were observed at LCO using the 2.5 m du Pont telescope with the Wide Field Reimaging CCD Camera (TEK#5 CCD) for direct imaging with a scale of 0.77 arcsec/pixel over a field of 25 arcminute diameter using Chilean time allocation. The images were obtained in the $B, V, R, I$ and $I$ Johnson–Cousins filters in nights with variable atmospheric conditions. The seeing values were less than 1 arcsec in two galaxy clusters and between 1.2 and 1.8 arcsecs in the remaining systems. Six galaxy clusters were observed in the four passbands while the clusters [VMF98]011 and [VMF98]211 were observed only in the $B$ and $R$ passbands due to poor atmospheric conditions.

Three galaxy clusters at $0.19 < z < 0.30$ were observed at CTIO using the Victor Blanco 4 m telescope and the MOSAIC-II camera, which is an array of eight 2048 $\times$ 4096 SITe CCDs, with a scale of 0.27 arcsec/pixel, giving a total field of view (FOV) of $36 \times 36$ arcmin. The images were taken in the $B, V, R, I$ and $I$ Johnson–Cousins passbands using the Director Discretionary Time. The median seeing of the observations were about 0.85 arcsec.

Finally, eight galaxy clusters with $0.18 < z < 0.70$ were obtained using the 8 m Gemini north (GN) and south (GS) telescopes in the $g, r, i, z$ bands. The cluster [VMF98] 102 had only observations in the $r$ band and it is included in the sample as spectroscopic observations were also made. The Gemini Multi-Object Spectrograph (Hook et al. 2004, hereafter GMOS) was used in the image mode during the system verification process (SVP) and specific programmes using Argentinian time allocation, with the detector being an array of three EEV CCDs of $2048 \times 4608$ pixels. Using a $2 \times 2$ binning, the pixel scale is 0.1454 arcsec/pixel, which corresponds to a FOV of $5.5 \times 5.5$ arcmin$^2$ in the sky. All images were observed under photometric conditions with excellent seeing values, with mean estimates being less than 0.8 arcsec.

Table 2 shows cluster identifications and a summary of the photometric observations, including observatory, observation date, programme identification and number of exposures per filter with the individual exposure time given in seconds. The

![Figure 2. X-ray luminosities ($L_X [0.5–2.0]$) vs. redshifts for different galaxy cluster samples. The total sample of Mullis et al. (2003) and our cluster selection are represented by empty and filled circles, respectively. Other studies are also shown: Girardi & Mezzetti (2001, open squares); Popesso et al. (2005, open triangles); Wake et al. (2005, filled squares); and Jensen & Pinhães (2012, filled triangles). The X-ray luminosities are taken from the Piffaretti compilation.](image-url)
galaxy clusters and Landolt (1992) standard stars were observed with different filters, depending on the observational run.

3.2. Data Reduction

All of the observations were reduced using standard procedures in IRAF\(^9\) (Tody 1993) and specific packages depending on instruments and telescopes. The images were overscanned and bias subtracted, trimmed, and flat-fielded following the standard reduction algorithms. Individual images were put into a common position system and then combined to create final images. Figures 3–5 show the $R$ or $r'$ images of the galaxy cluster sample obtained with the LCO, CTIO, and Gemini telescopes, respectively. The images are 1.5 Mpc on a side, except for [VMF98]022, [VMF98]093, and [VMF98]214 which have a 1 Mpc side due to observational constraints. We have marked the galaxy members (as addressed in Section 5) and the BCG with circles.

3.2.1. Source Detection and Photometry

Extracting faint objects from deep images was a major concern in our study. The combination of SExtractor v2.19.5 (Bertin & Arnouts 1996) and PSFEx v3.17.1 (PSF Extractor, Bertin 2011) was used with different configurations in order to

\(^9\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
detect sources and to obtain the astrometric and photometric parameters, including position, magnitudes, colors, and structural properties. SExtractor creates photometric catalogs from the observed images and PSFEx extracts models of the point-spread function (PSF) from the images processed by SExtractor. The generated PSF models are used for model-fitting photometry and morphological analyses. In general, SExtractor was run on the \( r' \) or \( R \) passband images as reference, applying different Gaussian convolution filters, which depends on the image quality. For bright detections in crowded central regions, a filter width of 1.5 pix in 3 \( \times \) 3 pixels was used, while for extended low-surface brightness objects in more external parts, 2.0 pix in 5 \( \times \) 5 pixels was utilized. The minimum area for detections was defined with 7 pixels at lower redshifts and 4 pixels at higher redshifts. We have considered as detected sources those with 2\( \sigma \) above the detection limit. Deblending was performed with 16 sub-thresholds and a minimum contrast of 0.005 in flux. After running SExtractor, we checked the detections aiming to find spurious objects and false detections. These are typically located in the outer regions of the CCDs and they were removed by hand. SExtractor was then run in dual-image mode using the reference as the detection image. With this methodology, objects in all filters have the same aperture size, which is appropriate for measuring colors.

The objects were classified by performing the star-galaxy separation using three different parameters: ellipticity \( (\epsilon = 1 - b/a) \); CLASS_STAR; and half-light radius \( (r_{1/2}) \). \( b/a \) is the axial ratio and CLASS_STAR is the SExtractor parameter associated with the light distribution of the detected objects. Galaxies are defined as those objects satisfying simultaneously \( \epsilon < 0.9 \); CLASS_STAR < 0.8; and \( r_{1/2} > 5 \) pixels. Figure 6 shows an example of these parameters used to define the galaxies in the cluster [VMF98]124: \( \epsilon \), CLASS_STAR, and \( r_{1/2} \) in pixels as a function of \( r' \) total magnitudes. The adopted criteria allow us to remove spurious objects in the galaxy cluster fields, where saturated or overlapped objects in projection were among the most frequent problems.

We have adopted PSF magnitudes as the galaxy total magnitude and aperture magnitudes to obtain colors. Using the same aperture diameter for the whole galaxy cluster sample may introduce some systematic effects due to considering different parts of the galaxies. We have used an aperture size equivalent to a diameter of 10 kpc at the cluster redshift for aperture magnitudes. This diameter is a compromise value that takes into account the typical galaxy size avoiding external contaminations.

### 3.2.2. Magnitude Calibration

In order to check the photometric calibration, objects classified as stars obtained with SExtractor in the observed images were compared with the USNO-A2.0 catalog (Monet et al. 2003) for \( B, R, \) and \( I \) magnitudes; the NOMAD catalog (Zacharias et al. 2005) for \( V \) magnitudes and the Sloan Digital Sky Survey—DR12 (Alam et al. 2015, hereafter SDSS) for \( g', r', \) and \( i' \) magnitudes. In general, saturated stars or objects fainter than the catalog limiting magnitude were not used as possible misclassifications may contribute with inaccurate magnitudes, particularly at fainter levels. The galaxy cluster [VMF98]124 is not covered by the SDSS and we have first converted the USNO stellar magnitudes into the SDSS system using Fukugita et al. (1996) relations. Table 3 shows these magnitude offsets corresponding to the different observed passbands for each galaxy cluster. These values were taken into account for the final magnitudes and colors. The magnitudes are in the AB system and have been corrected for galactic extinction by using reddening maps from Schlegel et al. (1998) and the Cardelli et al. (1989) relations.

### 3.2.3. Limiting Magnitudes and Completeness

In order to check the SExtractor behavior at fainter magnitudes, we have estimated magnitude limits and completeness levels using simulated catalogs and images created with the Astromatic packages STUFF and SKYMAKER (Bertin 2009). STUFF simulates field galaxy catalogs in a Poisson distribution, for different redshift slices from \( 0 < z < 20 \), with the number of galaxies and their absolute luminosities being taken from a non-evolving Schechter Luminosity Function (Schechter 1976). Galaxy profiles were modeled by the contribution of two components: a de Vaucouleurs bulge and an exponential disk (for details, see Erben et al. 2001). The photometric, structural, and astrometric parameters for all objects were generated in all passbands using the filter transmission curves and spectral energy distributions.
SKYMAKER produces realistic ground-based PSFs using STUFF catalogs taking into account the instrumentation and observing conditions.

Using these packages, we have reproduced our observations generating synthetic images and catalogs. We have run SExtractor in these simulated images and the resulting catalogs were compared with those created by SKYMAKER. Figure 7 shows an example of the number of object detections per magnitude bin (upper panel) obtained from the $r'$ simulated catalog and those sources detected by SExtractor from the synthetic images. The distributions are shown in logarithmic scale as short and long dash lines, respectively. In the lower panel, the fraction of these detected distributions per magnitude bin are displayed indicating the 50% and 90% completeness fractions. This figure indicates that the number of detections are similar; in this example, the SKYMAKER and SExtractor magnitudes are in good mutual agreement up to $r'$ of about 23 mag. For each galaxy cluster, the observing conditions were simulated with this procedure and magnitude limits were obtained. Table 4 shows the limiting magnitudes within 90% completeness.

As the magnitude errors provided by SExtractor are underestimated (White et al. 2005), our error estimates were based on the comparison between the synthetic magnitudes derived from SKYMAKER and those obtained with SExtractor. Within a 90% completeness level, the mean magnitude errors were found to be approximately 0.1 mag.
The three adopted star-galaxy indicators vs. $r'$ total magnitude. The gray zones indicate the typical regions where point sources are located. The dashed line marks our limit to separate galaxies and stars.

The comparison lamp (CuAR) spectra were taken after each science exposure.

We have obtained spectroscopic data for galaxies in the fields of four galaxy clusters: [VMF98]022, [VMF98]097, [VMF98]102, and [VMF98]124. The spectroscopic targets were based on the photometric catalogs generated with SExtractor, as described in the previous section. In order to study cluster galaxy population, we selected objects brighter than $r' = 23$ mag, without any color criteria (Carrasco et al. 2007). Observations were performed with two masks for the clusters [VMF98]097 and [VMF98]102. Objects brighter than $r' = 20$ mag were observed in a single mask with shorter exposure time than the fainter ones. Table 5 shows the observed cluster identification, with a summary of the spectroscopic observations including observation date, exposure time, and number of observed spectra per mask.

### 4.2. Data Reduction

The observations including comparison lamps and spectroscopic flats were bias subtracted and trimmed using the Gemini IRAF package. The flats were processed by removing the calibration unit plus the GMOS spectral response and the calibration unit uneven illumination, which were then normalized to leave only the pixel-to-pixel variation and fringing.

### Table 3: Photometric Calibration: Magnitude Offsets

| ID          | $\Delta B$   | $\Delta V$   | $\Delta R$   | $\Delta I$   | $\Delta g'$  | $\Delta r'$  | $\Delta i'$  |
|-------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 001         | ...          | ...          | ...          | ...          | ...          | ...          | ...          |
| 004         | 0.198 ± 0.014| 0.215 ± 0.096| 0.012 ± 0.069| −0.274 ± 0.052| ...          | −0.090 ± 0.059| 0.137 ± 0.042|
| 011         | 0.040 ± 0.007| ...          | −0.102 ± 0.024| ...          | ...          | ...          | ...          |
| 015         | −0.113 ± 0.010| 0.101 ± 0.032| −0.102 ± 0.026| ...          | −0.224 ± 0.023| ...          | ...          |
| 022         | ...          | ...          | ...          | ...          | ...          | 0.276 ± 0.019| −0.244 ± 0.027|
| 024         | 0.178 ± 0.004| 0.193 ± 0.018| −0.111 ± 0.038| 0.268 ± 0.039| ...          | ...          | ...          |
| 025         | 0.212 ± 0.011| 0.177 ± 0.046| −0.285 ± 0.033| −0.099 ± 0.006| ...          | ...          | ...          |
| 045         | 0.030 ± 0.091| −0.265 ± 0.024| 0.142 ± 0.025| 0.160 ± 0.037| ...          | ...          | ...          |
| 046         | 0.101 ± 0.211| 0.244 ± 0.217| −0.137 ± 0.021| −0.212 ± 0.050| ...          | ...          | ...          |
| 093         | ...          | ...          | ...          | ...          | ...          | 0.181 ± 0.014| 0.264 ± 0.016|
| 097         | ...          | ...          | ...          | ...          | 0.221 ± 0.089| 0.299 ± 0.061| ...          |
| 102         | ...          | ...          | ...          | ...          | ...          | 0.114 ± 0.091| ...          |
| 113         | 0.052 ± 0.511| 0.091 ± 0.055| 0.103 ± 0.018| 0.099 ± 0.027| ...          | ...          | ...          |
| 119         | ...          | ...          | ...          | ...          | 0.049 ± 0.084| 0.040 ± 0.101| ...          |
| 124         | ...          | ...          | ...          | ...          | 0.222 ± 0.027| 0.060 ± 0.011| ...          |
| 148         | ...          | ...          | ...          | ...          | 0.323 ± 0.049| 0.224 ± 0.170| ...          |
| 211         | 0.026 ± 0.022| ...          | 0.278 ± 0.042| ...          | ...          | ...          | ...          |
| 214         | 0.300 ± 0.290| 0.193 ± 0.015| −0.111 ± 0.040| 0.268 ± 0.039| ...          | ...          | ...          |
| 215         | 0.211 ± 0.167| 0.108 ± 0.048| −0.123 ± 0.006| 0.221 ± 0.009| ...          | ...          | ...          |

### 4. Spectroscopy

#### 4.1. Observations

The GMOS instrument was used in the MOS mode at the Gemini north and south telescopes during the SVP in 2003, under photometric conditions with typical seeing of about 0.6 and 0.9 arcsec. A GMOS grating of 400 lines/mm ruling density centered at 6700 Å was used, covering a wavelength range of 4400 to 9800 Å. The spectra had a resolution of about 5.5 Å, with a dispersion of 1.37 Å/pix, and offsets of ~35 Å were applied between exposures in the spectral direction toward the blue and/or the red to fill the gaps between CCDs.
the R-value (Tonry & Davis 1979) used to define the quality of the measured radial velocities (Carrasco et al. 2007). For $R > 3.5$, the observed radial velocity was associated to the template that produced lower uncertainties. However, in the case of $R \leq 3.5$, absorption features were searched for and line-by-line Gaussian fits were obtained. Both RVIDLINES and FXCOR routines are part of the RV package in IRAF.

We have obtained radial velocities of objects selected in the neighborhoods of the four galaxy clusters and, for further analysis we need to know the completeness levels of their magnitude distributions. For the photometric samples, the limiting magnitudes and completeness levels are extensively discussed in Section 3.2.3. For the spectroscopy, the magnitude distributions of the clusters [VMF98]022, [VMF98]097 and [VMF98]102 show a brighter limiting magnitude of $r' \sim 20.5$ mag, reaching a 90% completeness levels similar to the photometric samples. The cluster [VMF98]124 has been observed with only one mask with shorter exposure time, resulting in about 50% completeness at the same limiting magnitude.

5. CLUSTER MEMBERSHIP

In order to understand better the cluster assembly and morphological evolution of galaxies in low X-ray luminosity clusters, it is crucial to define cluster membership. Even when precise radial velocities are available for a large number of objects, the galaxy assignment of a cluster is not guaranteed. In effect, relatively distant infalling galaxies onto the cluster will appear closer to the cluster kinematic center. On the other hand, interlopers, namely, galaxies that are not confined to the cluster region may appear in projection with a low clustercentric relative velocity and therefore could be wrongly assigned as members. Using mock galaxy redshift surveys, van den Bosch et al. (2004) found that the velocity distribution of interlopers is strongly peaked toward the cluster mean radial velocity, thus introducing a bias in the cluster member assignment, especially at higher velocity dispersions.

We have selected galaxies within a projected radius of 0.75 Mpc from the X-ray emission peak. This choice is based on the angular size of the lowest redshift clusters and the available instrument FOVs. The relatively small radius minimizes foreground/background galaxy contamination and correspond to the densest cluster regions. It must be noted that by exploring the central regions of galaxy clusters, our study will focus on those galaxies mostly affected by the cluster environment at these redshifts. Thus, our analysis does not address the properties of galaxies far from the cluster core, which could be potentially different than those in the higher density regions.

5.1. Spectroscopic Membership and Substructures

In our cluster sample, only four galaxy clusters: [VMF98]022, [VMF98]097, [VMF98]102 and [VMF98]124 have spectroscopic redshift measurements. The cluster membership was defined using the projected radius and also the spectroscopic restriction $\Delta V < \sigma$, with $\Delta V$ defined as the difference between a given galaxy radial velocity and the cluster redshift given by Mullis et al. (2003). Testing membership assignment using 1 or 2 $\sigma$ show in general, small differences between the samples. However, there are some variations in the cluster [VMF98]097 with signs of a more complex morphology (Carrasco et al. 2007; Nilo Castellón et al. 2014). As previously mentioned, although membership cannot be totally guaranteed, we believe that the use of 1$\sigma$ restriction is appropriate to minimize interlopers. The number of cluster members are shown in Column 5 of the Table 5.

The bi-weight estimator (Beers et al. 1990) is statistically more robust and efficient for computing the central location of the redshift distribution than the standard mean. Biviano et al. (2006) have used this estimator for galaxy clusters with more than 15 members. We have obtained bi-weight $\sigma$ estimates for

![Figure 7. Completeness levels using simulated data. The upper panel shows the SKYMAKER (short dash line) and SExtractor synthetic (long dash line) total magnitude distributions in logarithmic scale. In the lower panel, the ratio of these two distributions are shown. The two horizontal lines correspond to 50% and 90% completeness levels.](image-url)
the galaxy clusters with spectroscopic measurements. Using cluster members, columns 6 and 7 of Table 5 shows the mean redshift and the line of sight velocity dispersion obtained with this estimate. The uncertainties derived from a bootstrap resampling technique were approximately 0.001 for redshifts and 90 km s$^{-1}$ for velocity dispersions. We have also computed with cluster members, the mean redshift and velocity dispersion using the jackknife error estimates, which are shown in columns 8 and 9, respectively. We can see from this table that the velocity dispersion values using the two estimators are in agreement within the uncertainties, except for the galaxy cluster [VMF98]097. The higher value obtained using the jackknife estimate is a consequence of the complex cluster morphology. In the cluster [VMF98]124 which has only 12 galaxy members, we have also used the gapper statistics obtaining a higher $\sigma \sim 751$ km s$^{-1}$, which is in agreement with the other estimates.

Figure 8 shows the observed redshift distribution in the neighborhoods of the four galaxy clusters with available spectroscopy, where the shaded parts correspond to the distributions within $1\sigma$ of the mean cluster redshift. Gaussian function fits provide a suitable approximation to the line of sight distribution. The foreground and background structures are also present in the figure. In the right corner, a detail of this distribution and the Gaussian fit are displayed. In the case of [VMF98]097, two peaks at redshifts 0.482 and 0.494 are clearly observed. This is the only galaxy cluster with well defined substructure, as also reported by Carrasco et al. (2007). For the cluster [VMF98]102, there is a second peak corresponding to a probable background system in the line of sight. On average, the uncertainties of the radial velocities were less than 55 km s$^{-1}$.

### 5.2. Photometric Redshifts

The determination of cluster members using spectroscopic redshifts is certainly the most accurate method, but it is much more expensive in telescope time, especially at fainter magnitudes. Colors trace the spectral energy distribution of galaxies at different redshifts and the intersection of a given set of observed colors with the allowed redshift ranges can be used to assess the redshift of a galaxy. For this reason, redshift estimates of large and deep samples of galaxy clusters can be obtained by using broadband photometry.

Photometric redshift estimates have been widely used as an efficient way to study the galaxy properties using statistical tools (Koo 1985; Connolly et al. 1995; Gwyn & Hartwick 1996; Hogg et al. 1998; Fernández-Soto et al. 1999; Benítez 2000; Budavári et al. 2000; Csabai et al. 2000), as for example luminosity, colors and morphology. Even with larger uncertainties, they provide a powerful tool for studying evolutionary galaxy properties of faint galaxies. Two groups of methods are used to estimate photometric redshifts. The template fitting technique makes use of a small set of model galaxy spectra derived from the $\chi^2$-based spectral template-fitting package (Bolzonella et al. 2000; Csabai et al. 2003). This approach consists in the reconstruction of the observed galaxy colors in order to find the best combination of template spectra at different redshifts. The main disadvantage of this method is the relatively small number of available templates in the library for different passbands. The second group is the empirical fitting technique which is based on empirical data (Connolly et al. 1995; Brunner et al. 1999; Collister & Lahav 2004) requiring a large amount of a priori redshift information (training set), which may be in some cases a disadvantage. However, the main goal of this procedure is to obtain redshift estimates as a function of the photometric parameters as inferred from the training set.

We consider photometric redshift estimates (Photo-z) to assign membership for the fifteen galaxy clusters without spectroscopic measurements.

#### 5.2.1. Photo-z with Annz

We have used the Artificial Neural Network (ANnz, Collister & Lahav 2004), an empirical fitting method to obtain photo-z as described in O’Mili et al. (2012). To calibrate the code, we have used 12,280 galaxies with spectroscopic redshifts derived from the Canadian Network for Observational Cosmology (Yee et al. 1996 CNOC). This data set was randomly divided into two subsamples, thereby generating the training and validation set.

The ANNz produces better estimates when more observations in different passbands are available. We have used aperture magnitudes as defined in Section 3.2.1 for the nine galaxy clusters observed in four passbands: $B$, $V$, $R$, and $I$ at the LCO and CTIO telescopes, defining a subsample of galaxies reaching the CNOC limiting magnitudes. The photometric redshift estimates take into account the telescope characteristics and the adopted filters through the training and validation sets. The resulting ANNz architecture adopted here was 4:8:8:1. Therefore, they were obtained using the photometric catalogs and the distributions are related to the limiting magnitudes and completeness levels of these photometric samples (Section 3.2.3). Abdalla et al. (2011) and Dahlen et al. (2013) have discussed associated bias and related uncertainties.
in the photometric redshift estimates obtained with different methods by a comparison with spectroscopic measurements. Abdalla et al. (2011) have found that the ANNz method has an almost constant, small bias and a 1σ scatter of about 0.06. The clusters [VMF98]011 and [VMF98]211 have been observed at LCO in only two passbands (B and R) and the photometric redshifts using ANNz are not accurate enough for our purposes of membership and they are not consider in this work.

5.2.2. Photo-z from the SDSS

The photometric data observed with the Gemini telescopes were obtained in two passbands; for the reasons mentioned above, determining photo-z was not possible with the use of the ANNz method. For the galaxy clusters [VMF98]001, [VMF98]093, [VMF98]119, and [VMF98]148 without spectroscopy, we have used photometric redshifts extracted from the PHOTOZ tables (http://skyserver.sdss.org/CasJobs) of the SDSS-DR8. These photometric redshifts use machine learning techniques with training sets, similar to those of ANNz. The SDSS is 95% complete for point sources up to $r^\prime \sim 22.2$ mag. For the galaxy clusters in our sample with photometric redshifts from SDSS, the magnitude distributions are in agreement with the SDSS limiting magnitudes and completeness levels. In order to estimate photometric redshift uncertainties, which are significantly larger than spectroscopic measurements, we have made a comparison with two galaxy clusters: [VMF98]022 and [VMF98]097 with both spectroscopic and photometric redshifts. Figure 9 shows the comparisons between our spectroscopic redshift estimates with the photometric redshifts from the SDSS-DR8. In the left panels, the projected distribution of objects with spectroscopic (empty squares) and photometric (filled circles) redshifts are shown within the 0.75 Mpc region represented by the dashed circles. The right panels correspond to the differences $z_{sp} - z_{ph}$ SDSS as a function of $z_{sp}$. The mean of these differences are $-0.014 \pm 0.087$ for [VMF98]022 and $0.033 \pm 0.063$ for [VMF98]097, which are comparable to the uncertainties obtained by O’Mill et al. (2012). These mean values are represented with dashed lines and the 1σ scatter by the gray region.

Since it is also seen that for $\Delta V = 6000$ km s$^{-1}$, contamination is less than 10% with a still large number of true members, we have adopted this galaxy photometric redshift difference with respect to the cluster spectroscopic redshift in order to assess membership.

5.3. Membership Summary

Cluster members are then, the galaxies within a projected radius of 0.75 Mpc from the X-ray emission peak and with spectroscopic $\Delta V = 1\sigma$ or photometric $\Delta V \sim 6000$ km s$^{-1}$. Mean values of the cluster redshift with the members were
obtained and the comparison with Mullis et al. (2003) gives mean differences of about 0.002 ± 0.005. Table 6 shows the final membership summary with the number of members assigned to the clusters in column 2, our mean redshift estimates in column 3 and the redshift source in column 4. Our spectroscopic measurements are identified as \( z_{\text{sp}} \) while our photometric estimates with \( z_{\text{ph}} \) and the SDSS estimates with \( z_{\text{ph}} \text{SDSS} \). As mentioned above, we could not obtain the galaxy members of the clusters [VMF98]011 and [VMF98]211 because they have been observed in only two passbands. Also, the clusters [VMF98]024 and [VMF98]025 have redshifts similar to some members in common (see Figure 3).

6. FINAL COMMENTS AND FUTURE PLANS

Our project is centered on the study of low X-ray luminosity clusters of galaxies at intermediate redshifts and the analysis of the morphological galaxy content. At the end of the project, the photometric and spectroscopic data will be available at http://astro.userena.cl/science/LowXrayClusters/.

This paper presents our sample and main goals. Nineteen galaxy clusters were selected with X-ray luminosities of \( L_X \sim 0.5-45 \times 10^{43} \text{ erg s}^{-1} \) in the redshift range of 0.16–0.70, which were observed at LCO, CTIO, and Gemini Observatory with different instruments and passbands. We extensively

---

**Table 6**

Member Assignment for the Sample of Low X-Ray Galaxy Clusters

| [VMF98] | Number of Cluster Members | Our Mean Redshift | Redshift Source |
|--------|--------------------------|-------------------|----------------|
| 001    | 22                       | 0.495             | \( z_{\text{ph}} \text{SDSS} \) |
| 004    | 32                       | 0.292             | \( z_{\text{ph}} \) |
| 011    | ⋯                        | ⋯                 | ⋯              |
| 015    | 44                       | 0.249             | \( z_{\text{ph}} \) |
| 022    | 26                       | 0.247             | \( z_{\text{ph}} \text{SDSS} \) |
| 024    | 51                       | 0.168             | \( z_{\text{ph}} \) |
| 025    | 46                       | 0.163             | \( z_{\text{ph}} \) |
| 045    | 29                       | 0.292             | \( z_{\text{ph}} \) |
| 046    | 38                       | 0.200             | \( z_{\text{ph}} \) |
| 093    | 14                       | 0.357             | \( z_{\text{ph}} \text{SDSS} \) |
| 097    | 37                       | 0.482             | \( z_{\text{ph}} \text{SDSS} \) |
| 102    | 22                       | 0.409             | \( z_{\text{ph}} \) |
| 113    | 35                       | 0.258             | \( z_{\text{ph}} \text{SDSS} \) |
| 119    | 20                       | 0.692             | \( z_{\text{ph}} \text{SDSS} \) |
| 124    | 12                       | 0.185             | \( z_{\text{ph}} \text{SDSS} \) |
| 148    | 16                       | 0.697             | \( z_{\text{ph}} \text{SDSS} \) |
| 211    | ⋯                        | ⋯                 | ⋯              |
| 214    | 41                       | 0.198             | \( z_{\text{ph}} \) |
| 215    | 53                       | 0.194             | \( z_{\text{ph}} \) |

---

**Figure 9.** Spectroscopic and photometric redshift comparison. Upper panels show the projected distribution of galaxies in the [VMF98]022 field (left) and the differences between spectroscopic and photometric redshift estimates vs. spectroscopic values (right). In this panel, the mean value is represented by a dashed line and the 1σ scatter correspond to the gray region. Lower panels are the same for galaxies in the cluster [VMF98]097.
discussed the photometric and spectroscopic observations and the data reduction, which includes the galaxy identification and cluster membership together with the spectroscopic and photometric redshifts and their error estimates.

The second paper of the series (Nilo Castellón et al. 2014) considered the optical properties and morphological content of the seven galaxy clusters observed with Gemini north and south telescopes at 0.18 < z < 0.70. The main results are an increment of the blue galaxy fraction and a reduction of the lenticular fraction with redshifts. The early-type fraction remains almost constant in the whole redshift range. These results are in agreement with those observed for massive clusters.

The third paper of the series (Gonzalez et al. 2015) presented the weak lensing analysis of the galaxy clusters observed with Gemini telescopes. We determined the masses of seven galaxy clusters, six of which were measured for the first time. The weak lensing mass determinations correlate with the X-ray luminosities in the redshift range of 0.18–0.70. Also, M. V. Alonso et al. (2016, in preparation) will present an analysis of the CDMs, the RCS, color–color diagrams, and density profiles for the galaxy clusters observed at LCO and CTIO in the redshift range of 0.16–0.30. Finally, in H. Cuevas et al. (2016, in preparation), we will study the morphological evolution taking into account the 19 galaxy clusters in the sample.

A second part of this project includes more spectroscopic measurements, which will allow us to search for substructures and global cluster dynamics. The combination of photometric and spectroscopic data analysis could provide useful hints to trace the evolutionary scenario of these low X-ray galaxy clusters.

J.L.N.C., M.J., and F.R. acknowledge the financial support from Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET). This work was partially supported by grants by CONICET, Secretaría de Ciencia y Técnica (Secyt) of Universidad Nacional de Córdoba and Ministerio de Ciencia y Tecnología (MINCyT, Córdoba).

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, University of Florida, the French Participation Group, the German Participation Group, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

REFERENCES

Abdalla, B. F., Banerji, M., Lahav, O., & Rashkov, V. 2011, MNRAS, 417, 1891
Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681
Balogh, M., Bower, R. G., Smail, I., et al. 2002, MNRAS, 337, 256
Balogh, M. L., McGee, S. L., WIlman, D. J., et al. 2011, MNRAS, 412, 2303
Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32
Benitez, N. 2000, ApJ, 536, 571
Berrier, J. C., Stewart, K. R., Bullock, J. S., et al. 2009, ApJ, 690, 1292
Bertin, E. 2009, MSAIS, 80, 422
Bertin. E. 2011, adass XX, 442, 435
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Biviano, A., Murante, G., Borgani, S., et al. 2006, A&A, 456, 23
Blanton, M. R., & Moustakas, J. 2009, ARA&A, 47, 159
Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, A&A, 363, 476
Brunner, R. J., Djorgovski, S. G., Gal, R. R., & Odewahn, S. C. 1999, BAAS, 31, 1492
Budavári, T., Szalay, A. S., Connolly, A. J., Csabai, I., & Dickinson, M. 2000, AJ, 120, 1588
Butcher, H., & Oemler, A., Jr. 1984, ApJ, 285, 426
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Carrasco, E. R., Cypriano, E. S., Neto, G. B. L., et al. 2007, ApJ, 664, 777
Christlein, D., & Zabludoff, A. I. 2005, ApJ, 621, 201
Collister, A. A., & Lahav, O. 2004, PASP, 116, 345
Connelly, J. L., Wilman, D. J., Finoguenov, A., et al. 2012, ApJ, 756, 139
Connolly, A. J., Csabai, I., Szalay, A. S., et al. 1995, AJ, 110, 2655
Csabai, I., Budavári, T., Connolly, A. J., et al. 2003, AJ, 125, 580
Csabai, I., Connolly, A. J., Szalay, A. S., & Budavári, T. 2000, AJ, 119, 69
Dahlen, T., Mobasher, B., Faber, S. M., et al. 2013, ApJ, 775, 93
De Lucia, G., Poggianti, B. M., Aragón-Salamanca, A., et al. 2004, ApJL, 610, L77
Dressler, A. 1980, ApJS, 42, 565
Dressler, A., & Gunn, J. E. 1992, ApJS, 78, 1
Erben, T., Van Waerbeke, L., Bertin, E., Mellier, Y., & Schneider, P. 2001, A&A, 366, 717
Fernández-Soto, A., Lanzetta, K. M., & Yahil, A. 1999, ApJ, 513, 34
Finn, R. A., Zaritsky, D., McCarthy, D. W., Jr., et al. 2005, ApJ, 630, 206
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Gilbank, D. G., Yee, H. K. C., Ellington, E., et al. 2008, ApJ, 673, 742
Gilrudi, M., & Mezzetti, M. 2001, ApJ, 548, 79
Gladders, M. D., Lopez-Cruz, O., Yee, H. K. C., & Kodama, T. 1998, ApJ, 501, 571
Gonzalez, E. J., Foëx, G., Nilo Castellón, J. L., et al. 2015, MNRAS, 452, 2225
Gunn, J. E., & Gott, J. R., III 1972, ApJ, 176, 1
Gwyn, S. D. J., & Hartwick, F. D. A. 1996, ApJL, 468, L77
Hogg, D. W., Cohen, J. G., Blandford, R., et al. 1998, AJ, 115, 1418
Houk, I. M., Jorgensen, I., Allington-Smith, J. R., et al. 2004, PASP, 116, 425
Jeltema, T. E., Mulchaey, J. S., Lubin, L. M., Rosati, P., & Böhringer, H. 2006, ApJ, 669, 649
Jensen, P. C., & Pimbblet, K. A. 2012, MNRAS, 422, 2841
Kaufmann, G., & Charlot, S. 1998, MNRAS, 294, 705
Kodama, T., Arimoto, N., Barger, A. J., & Aragón-Salamanca, A. 1998, A&A, 334, 99
Koo, D. C. 1985, AJ, 90, 418
Landolt, A. U. 1992, AJ, 104, 340
Lerchster, M., Seitz, S., Brimioulle, F., et al. 2011, MNRAS, 411, 2667
Lubin, L. M., Gal, R. R., Lemaux, B. C., Kocevski, D. D., & Squires, G. K. 2009, AJ, 137, 4867
Mendez, A. J., Coil, A. L., Lotz, J., et al. 2011, ApJ, 736, 110
Monet, D. G., Levine, S. E., Cazian, B., et al. 2003, AJ, 125, 984
Mulchaey, J. S., Lubin, L. M., Fassnacht, C., Rosati, P., & Jeltema, T. E. 2006, ApJ, 664, 133
Mullis, C. R., McNamara, B. R., Quintana, H., et al. 2003, ApJ, 594, 154
Nilo Castellón, J. L., Alonso, M. V., Lambas, D. G., et al. 2014, MNRAS, 437, 2607
Oemler, A., Jr., Dressler, A., Gladders, M. G., et al. 2013, ApJ, 770, 61
O’Mill, A. L., Duplancic, F., Garcia Lambas, D., Valotto, C., & Sodré, L. 2012, MNRAS, 421, 1897
Piffaretti, R., Arnaud, M., Pratt, G. W., Pointecouteau, E., & Melin, J-B. 2011, A&A, 534, A109
Popesso, P., Biviano, A., Böhringer, H., Romaniello, M., & Voges, W. 2005, A&A, 433, 431
Rosati, P., Stanford, S. A., Eisenhardt, P. R., et al. 1999, AJ, 118, 76
Schechter, P. 1976, ApJ, 203, 297
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Spitzer, L., Jr., & Baade, W. 1951, ApJ, 113, 413
Stott, J. P., Smail, I., Edge, A. C., et al. 2007, ApJ, 661, 95
Strazzullo, V., Rosati, P., Pannella, M., et al. 2010, A&A, 524, A17
Tody, D. 1993, adass II, 52, 173
Tonry, J., & Davis, M. 1979, AJ, 84, 1511
van den Bosch, F. C., Norberg, P., Mo, H. J., & Yang, X. 2004, MNRAS, 352, 1302
Vikhlinin, A., McNamara, B. R., Forman, W., et al. 1998, ApJ, 502, 558
Wake, D. A., Collins, C. A., Nichol, R. C., Jones, L. R., & Burke, D. J. 2005, ApJ, 627, 186
White, S. D. M., Clowe, D. I., Simard, L., et al. 2005, A&A, 444, 365
Yee, H. K. C., Ellingson, E., & Carlberg, R. G. 1996, ApJS, 102, 269
Zacharias, N., Monet, D. G., Levine, S. E., et al. 2005, yCat, 1297, 0
Zhu, G., Blanton, M. R., & Moustakas, J. 2010, ApJ, 722, 491