A Spectroscopic Census of X-Ray Systems in the COSMOS Field

Jubee Sohn, Margaret J. Geller, and H. Jabran Zahid
Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
Received 2019 March 8; revised 2019 May 28; accepted 2019 June 16; published 2019 August 5

Abstract

We investigate spectroscopic properties of galaxy systems identified based on deep X-ray observations in the Cosmic Evolution Survey (COSMOS) field. The COSMOS X-ray system catalog we use includes 180 X-ray systems to a limiting flux of $1.0 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, an order of magnitude deeper than the future e-ROSITA survey. We identify spectroscopic members of these X-ray systems based on the spectroscopic catalog constructed by compiling various spectroscopic surveys including 277 new measurements; 146 X-ray systems are spectroscopically identified groups with more than three spectroscopic members. We identify 2196 spectroscopic redshifts of member candidates in these X-ray systems. The X-ray luminosity ($L_X$)–velocity dispersion ($\sigma_v$) scaling relation of the COSMOS X-ray systems is consistent with that of massive X-ray clusters. One of the distinctive features of the COSMOS survey is that it covers the X-ray luminosity range where poor groups overlap the range for extended emission associated with individual quiescent galaxies. We assess the challenges posed by the complex morphology of the distribution of systems with low X-ray luminosity, including groups and individual quiescent galaxies, in the $L_X$–$\sigma_v$ plane.

Key words: cosmology: observations – large-scale structure of universe – galaxies: clusters: general – X-rays: galaxies: clusters

Supporting material: machine-readable tables

1. Introduction

Detection of hot X-ray-emitting gas from galaxy clusters was a groundbreaking discovery that provided a powerful tool for studying the formation and evolution of gravitationally bound galaxy systems (see review by Sarazin 1988). The X-ray observations trace extended thermal emission from the intergalactic medium in galaxy systems (e.g., Forman et al. 1972; Kellogg et al. 1972). The extended X-ray emission is detected not only in massive galaxy clusters but also in less massive galaxy groups (Ponman et al. 1996; Mahdavi et al. 2000). Hot X-ray-emitting gas is also detected around individual galaxies (Fabbiano 1989; Kim et al. 2019). The X-ray luminosity and temperature of the hot gas are well correlated with the mass of its parent dark matter halo (e.g., Stanek et al. 2006; Böhringer & Werner 2010).

A simple theoretical calculation based on the hydrostatic equilibrium predicts the scaling relations between X-ray properties and the other physical properties of a galaxy system. For example, the X-ray luminosity ($L_X$) and the X-ray temperature ($T_X$) of a system scale with the measured velocity dispersion (Solinger & Tucker 1972). Study of scaling relations probes the underlying cluster physics. Extension of the scaling relations to a wider X-ray luminosity range allows for exploration of the nature of X-ray emission from lower mass systems. Extension to a broader redshift range probes the evolution of galaxy systems.

A number of systematic surveys identify galaxy systems in the X-ray (e.g., Ebeling et al. 1998; Böhringer et al. 2000, 2017; Reiprich & Böhringer 2002; Burenin et al. 2007; Pacaud et al. 2016). Verification of these X-ray systems depends on optical imaging combined with spectroscopic observations. For example, Sloan Digital Sky Survey (SDSS) spectroscopy combined with ROSAT and XMM imaging (Clerc et al. 2016) yields a large catalog of galaxy clusters. Sohn et al. (2018a) used the deeper HectoMAP redshift survey (Geller & Hwang 2015) and ROSAT X-ray imaging to identify galaxy clusters.

The search for galaxy systems also extends to lower-mass galaxies. The All-Wavelength Extended Groth International Survey (AEGIS; Erfanianfar et al. 2013) describes a catalog of galaxy systems including systems with very low X-ray luminosity with a few spectroscopically identified members. The XXL survey, based on XMM data, is a more extensive systematic survey for galaxy systems including groups with low X-ray luminosity (Pacaud et al. 2016; Adami et al. 2018). Many XXL galaxy groups are confirmed based on extensive spectroscopic surveys. In general, X-ray systems verified with the spectroscopic redshifts provide an important basis for studying the nature and evolution of galaxy systems.

The Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) is a unique field where extensive multiwavelength data enable a study of X-ray systems with a large range of X-ray luminosity and redshift. The COSMOS survey covers a ~2 deg$^2$ field. The X-ray observations for the COSMOS field are very deep ($f_X=3 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, Gozaliasl et al. 2019), an order of magnitude deeper than the future e-ROSITA survey (Merloni et al. 2012). Based on these deep X-ray observations, Finoguenov et al. (2007) first identified extended X-ray emission corresponding to galaxy groups and clusters. George et al. (2011) and Gozaliasl et al. (2019) extended the search for X-ray systems with even deeper X-ray data. These studies also identify optical counterparts of the extended X-ray sources. However, these analyses have relied primarily on photometric redshifts.

Dense spectroscopic surveys covering the field add an additional dimension to the COSMOS field. zCOSMOS is the first of these systematic spectroscopic surveys (Lilly et al. 2007, 2009). Several large spectroscopic surveys include high-redshift objects in the COSMOS field (e.g., Silverman et al. 2015; Hasinger et al. 2018). Remarkably, these deep surveys include only very sparse coverage for redshifts $z \lesssim 0.7$. To remedy this situation, hCOSMOS (Damjanov et al. 2018) is a shallower but complete (>90%) redshift survey to $r=20.6$.
covering the central \( \sim 1 \text{deg}^2 \) of the COSMOS field. Taken together, these redshift surveys provide an opportunity for a spectroscopic census of the galaxy system candidates.

Here, we examine extended X-ray sources as candidate galaxy systems in the COSMOS field. We combine the COSMOS galaxy catalog (George et al. 2011) with all available spectroscopic redshifts. We identify spectroscopic members associated with the extended X-ray sources, and we discuss the brightest galaxy in each system as a possible marker of the bottom of the potential well. We include the catalog of the spectroscopic members of the X-ray systems.

One of the most important applications of spectroscopic data for extended X-ray sources is the \( L_X - \sigma_v \) scaling relation, where \( L_X \) is the X-ray luminosity and the \( \sigma_v \) is the velocity dispersion of a galaxy system. Theoretical calculations suggest \( L_X \propto \sigma_v^4 \) (Solinger \& Tucker 1972; Quintana \& Melnick 1982). Many observational studies of rich clusters derive a slope (\( \alpha \)) of the scaling relation that is consistent with theoretical expectations (Ortiz-Gil et al. 2004; Popesso et al. 2005; Zhang et al. 2011; Rines et al. 2013; Clerc et al. 2016). For log \( L_X \gtrsim 43 \), the scatter in the scaling relation results from variation in the detailed dynamical state of the systems (Zhang et al. 2011) or from sparse sampling of the member galaxies. In contrast with the scaling relation for massive systems, the slope of the scaling relation for groups with low X-ray luminosity (\( 41.4 < \log L_X < 42.5 \)) remains uncertain. Several studies report totally different slopes for low X-ray luminosity systems, for example, from \( \alpha \sim 4.3 \) from Mulchaey \& Zabludoff (1998) to \( \alpha \sim 0.4 \) from Mahdavi et al. (2000).

The COSMOS X-ray systems provide a unique opportunity to extend the X-ray scaling relation to very low X-ray luminosity (\( 41.4 < \log L_X < 42.5 \)). The large spectroscopic data set enables measurement of the velocity dispersions of an essentially complete set of systems. The COSMOS X-ray data are so deep that they begin to probe the luminosity range where individual quiescent galaxies and poor systems overlap in X-ray luminosity. We highlight some of the complexity in the \( L_X - \sigma_v \) plane introduced by this overlap. We also examine the possible implications of the related \( L_X - \sigma_v \) relation for individual galaxies.

We describe the observations in Section 2. We demonstrate the spectroscopic survey completeness in Section 3. In Section 4, we explore the spectroscopic catalog of the COSMOS X-ray systems, including spectroscopic membership identification. We construct the X-ray scaling (\( L_X - \sigma_v \)) relation in Section 5. In Section 6 we consider some of the limitations of the analysis, and we highlight the complex morphology of the distribution of extended X-ray sources in the \( L_X - \sigma_v \) plane. We summarize in Section 7. In the Appendix, we supplement the X-ray ID with a brief overview of corresponding photometrically identified clusters. We use the standard ΛCDM cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \) throughout.

### 2. The Data

COSMOS is a deep multiwavelength survey (Scoville et al. 2007) covering a 2 deg\(^2\) field at (RA, Dec.) = (150.1192, +2.2058). The field has been observed over a wide range of wavelengths from X-ray to radio with major observing facilities. Here, we use optical photometry and spectroscopy to investigate galaxies in candidate COSMOS X-ray systems. We describe the galaxy catalog and photometry in Section 2.1, the spectroscopic data in Section 2.2, and the COSMOS spectroscopic sample that combines photometric and spectroscopic data in Section 2.3. In Section 2.4, we describe the X-ray system catalogs we use.

#### 2.1. Galaxy Catalog

We use the COSMOS Galaxy and X-ray Group Membership Catalog\(^1\) (George et al. 2011) as the basis of our study. This catalog includes 115,844 galaxies with \( m_{B_{814}} < 24.2 \) (MAG_{AUTO}) from the COSMOS Advanced Camera for Survey catalog (Leauthaud et al. 2007). The catalog also lists photometric redshifts (Ilbert et al. 2009) and membership probabilities for galaxies in the candidate X-ray systems (Section 2.4, George et al. 2011). Hereafter, we refer to this catalog as the COSMOS galaxy catalog.

We match the COSMOS galaxy catalog to the UltraVISTA photometric catalog (Muzzin et al. 2013) to obtain optical photometry of the galaxies. The UltraVISTA photometric catalog provides point-source function matching photometry over 30 photometric bands. We use a 0.5 arcsec search radius for matching. We obtain \( \text{Subaru} g^{+}r^{+}i^{+}z^{+}y^{+} \) photometry of 110,375 galaxies from the UltraVISTA catalog. There are a number of objects without UltraVISTA photometry, due to the small field of view of the UltraVISTA survey relative to the COSMOS galaxy catalog.

We supplement galaxy magnitudes using the COSMOS photometry catalog\(^2\) (Capak et al. 2007), because many objects in the COSMOS galaxy catalog are located outside the UltraVISTA coverage. This catalog also offers \( \text{Subaru} g^{+}r^{+}i^{+}z^{+}y^{+} \) photometry of the galaxies in the COSMOS field. However, the magnitudes from the COSMOS photometry catalog are not identical to the UltraVISTA photometry. Therefore, we need to transform the magnitudes from the COSMOS photometry catalog \( (m_{\text{C07}}) \) into the UltraVISTA magnitudes \( (m_{\text{UVIS}}) \).

Based on the 24,591 bright galaxies \( (16 \leq r^{+} \leq 23) \) with both COSMOS and UltraVISTA photometry, we derive empirical transformations from \( m_{\text{C07}} \) into \( m_{\text{UVIS}} \). For example, the \( r^{+} \)-band magnitude transformation is

\[
 r^{+}_{\text{UVIS}} = (1.11 \pm 0.01) \times r^{+}_{\text{C07}} - (2.93 \pm 0.21).
\]

Because we use the photometry only to estimate the spectroscopic survey completeness and to identify the brightest cluster galaxies (BCGs), the empirical transformation is sufficient.

#### 2.2. Spectroscopy

We use spectroscopy to determine the membership of the COSMOS X-ray systems. We first compile spectroscopic redshifts from several surveys covering the COSMOS field (Section 2.2.1). In addition, we carried out spectroscopic observations to obtain additional redshifts in the field (Section 2.2.2).

#### 2.2.1. Previous COSMOS Redshift Surveys

\( z \text{COSMOS} \) (Lilly et al. 2007, 2009) is the largest spectroscopic survey covering the COSMOS field using VIMOS mounted on the Very Large Telescope (VLT)/UT 8 m telescope. The \( z \text{COSMOS} \) DR3 catalog we use lists 20,689 redshifts of galaxies with \( z_{\text{lim}} < 22.5 \) with an average accuracy of \( \sim 110 \text{ km s}^{-1} \). \( z \text{COSMOS} \) provided a confidence class \( (z_{\text{Conf}}) \) for the redshift

\(^1\) https://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-dd?catalog=cosmos_xgal
\(^2\) https://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-dd?catalog=cosmos_phot
measurements. We include zCOSMOS redshifts with high confidence class \((z_{\text{conf}} \geq 3)\). Using a 0.5 matching tolerance, we obtain 13,935 redshifts for galaxies in the COSMOS galaxy catalog.

hCOSMOS (Damjanov et al. 2018) is a dense spectroscopic survey of a magnitude-limited sample with \(r \leq 21.5\) in the COSMOS field. The hCOSMOS survey was done with the multiﬁber-fed spectrograph Hectospec (Fabricant et al. 2005) mounted on the MMT 6.5 m telescope. The hCOSMOS survey includes 4362 redshifts within the central 1 deg\(^2\) field; 1701 redshifts are new. Damjanov et al. (2018) showed that the average difference between hCOSMOS and zCOSMOS redshift measurements is \(\sim 0.2 \pm 0.2 \text{ km s}^{-1}\), smaller than the typical uncertainty in each redshift measurement \(\sim 0.5 \text{ km s}^{-1}\). Thus, we use redshifts from hCOSMOS and zCOSMOS without correction. We compile 4399 redshifts from the hCOSMOS catalog.

Hasinger et al. (2018) provide a catalog of 10,718 objects in the COSMOS field, including 6617 objects with high-quality spectra observed with the DEep Imaging Multi-Object Spectrograph (DEIMOS) on the Keck II telescope. Hereafter, we refer to this survey as dCOSMOS. Similar to zCOSMOS, dCOSMOS provides a conﬁdence class for the redshift measurements. Following the zCOSMOS matching process, we obtain 2672 dCOSMOS redshifts with a high conﬁdence flag \((z_{\text{conf}} \geq 3)\). There are 1185 dCOSMOS objects with zCOSMOS redshift measurements. We compute the mean difference in the redshift measurement using these objects. The typical offset between dCOSMOS and zCOSMOS redshifts is \(\sim 0.12 \pm 0.12 \text{ km s}^{-1}\), and the typical uncertainty of the dCOSMOS redshifts is \(\sim 0.60 \text{ km s}^{-1}\) (inferred from other DEIMOS observations).

Besides these three large surveys, several additional spectroscopic surveys cover the COSMOS ﬁeld. We also obtain the redshifts from these surveys. Compiling the redshift measurements from these previous surveys is not straightforward. These surveys obtained spectra using different instruments that yield spectra with varying spectral resolution and wavelength coverage. Therefore, there may be some systematic differences between these redshift measurements and those from zCOSMOS, hCOSMOS, and dCOSMOS. Furthermore, the redshift measurements from these surveys may have large uncertainties that can compromise membership determination. These surveys often omit individual uncertainties from their catalogs.

Table 1 summarizes the previous spectroscopic surveys we compile and lists the number of redshifts for galaxies and member candidates of the X-ray groups/clusters. We also investigate the number of objects in each of these previous spectroscopic surveys that also have a zCOSMOS redshift. Based on these repeat measurements, we calculate the systematic differences between the redshift measurements from zCOSMOS and the other surveys \((\Delta z/(1 + z_{\text{COSMOS}}))\). We brieﬂy review these previous spectroscopic surveys.

Prescott et al. (2006): This survey measured redshifts of galaxies and quasars in the COSMOS ﬁeld using MMT/Hectospec. We obtained 279 redshifts from this survey for objects in the COSMOS galaxy catalog. The typical uncertainty of the redshift measurements is \(\sim 0.63 \text{ km s}^{-1}\). zCOSMOS also measured redshifts for 83 objects from this survey. We compute the difference between the redshift (radial velocity) measurements \((\Delta z/(1 + z_{\text{COSMOS}}))\) from this survey and zCOSMOS. The mean difference estimated after 3\(\sigma\) clipping is \(0.62 \pm 0.8 \text{ km s}^{-1}\). Because the redshift difference is smaller than the uncertainty in the zCOSMOS redshift measurement, we do not apply a systematic correction.

Trump et al. (2009): This survey provided optical spectroscopy for X-ray point-like sources identiﬁed from the XMM-Newton data. The majority \((\sim 2/3)\) of spectra were obtained with the Inamori Magellan Areal Camera and Spectrograph on the Magellan (Baade) telescope, and the rest of the spectra were obtained with MMT/Hectospec or SDSS. Trump et al. (2009) provided a conﬁdence flag \((z_{\text{conf}})\) for the redshift measurements. We take 463 redshifts with \(z_{\text{conf}} = 3\) or 4, where \(z_{\text{conf}} = 3\) indicates that the redshift was measured based on one strong and one weak feature, and \(z_{\text{conf}} = 4\) indicates that the redshift is considered unambiguous. Based on the 86 objects with repeat redshift measurements, we computed a mean difference of \(-0.51 \pm 0.16 \text{ km s}^{-1}\) compared with the zCOSMOS redshifts.

Roseboom et al. (2012): This Subaru/FMOS survey obtained the infrared spectroscopy of Herschel-selected

| References         | \(N_z\) | \(N_z(P_{\text{mem}} > 0)\) | \(N_{\text{overlap}}(\text{zCOSMOS})\) | \(\text{Mean } \Delta z_{\text{COSMOS}} \text{ (km s}^{-1}\) |
|--------------------|--------|---------------------------|---------------------------------|---------------------------------|
| Prescott et al. (2006) | 279    | 13                        | 83                              | \(62 \pm 8\)                   |
| Trump et al. (2009)   | 463    | 27                        | 86                              | \(-51 \pm 16\)                 |
| Roseboom et al. (2012) | 85     | 0                         | 8                               | \(-460 \pm 160\)               |
| Onodera et al. (2012) | 18     | 0                         | 0                               | ...                             |
| Balogh et al. (2014)  | 603    | 130                       | 17                              | \(-12 \pm 35\)                 |
| Comparat et al. (2015)| 1445   | 36                        | 152                             | \(27 \pm 10\)                  |
| Kartaltepe et al. (2015) | 119   | 4                         | 40                              | \(-46 \pm 24\)                 |
| Kriek et al. (2015)   | 411    | 0                         | 0                               | ...                             |
| Silverman et al. (2015)| 329  | 0                         | 3                               | \(-103 \pm 4\)                 |
| Masters et al. (2017) | 940    | 22                        | 12                              | \(14 \pm 41\)                  |
| Tasca et al. (2017)   | 367    | 1                         | 3                               | \(350 \pm 2\)                  |
| Straatman et al. (2018)| 1809 | 143                       | 544                             | \(12 \pm 4\)                   |
galaxies in the COSMOS field. We obtain 85 redshifts in the redshift range 0.70 < z < 1.57. Eighteen objects overlapped with zCOSMOS, and the mean difference is large: −460 ± 160 km s⁻¹.

Onodera et al. (2012): This study includes 18 spectroscopic redshifts of passive galaxies at z ≥ 1.4 in the COSMOS field. The redshifts are measured from Subaru/MORIRS observations. There is no overlap between these redshifts and zCOSMOS.

The GEEC2 spectroscopic survey (Balogh et al. 2014): The Galaxy Environment Evolution Collaboration 2 (GEEC2) spectroscopic survey presented a catalog based on the Gemini-South GMOS spectroscopy of 11 galaxy groups at 0.8 < z < 1 in the COSMOS field. This catalog lists 603 unique redshifts with high confidence and with a typical uncertainty of ~100 km s⁻¹. Balogh et al. (2014) claim that there is an ~180 km s⁻¹ unexplained systematic offset compared to zCOSMOS redshifts. However, we only observe a much smaller offset (~12 ± 35 km s⁻¹) based on 17 repeat measurements with high confidence (zconf > 3), smaller than typical uncertainties in both GEEC2 and zCOSMOS redshift measurements. Therefore, we compile GEEC2 redshifts without correction.

Comparat et al. (2015): This survey used FOCAL Reducer and the low dispersion Spectrograph (FORS2) for the VLT to obtain the redshifts and emission-line fluxes of galaxies at 0.1 < z < 1.65. Comparat et al. (2015) investigated the [O II] luminosity function using this spectroscopic sample. The redshift catalog includes a confidence flag for the redshift measurements similar to the zCOSMOS confidence flag. We compile 1445 redshifts with zconf = 3 or 4. The mean redshift difference from zCOSMOS redshifts measured from 152 duplicated objects is 27 ± 10 km s⁻¹.

Kartaltepe et al. (2015): The FMOS-COSMOS survey published redshifts measured from the FMOS near-infrared spectrograph on the Subaru telescope. From this survey, we compile 119 redshifts within the range 0.5 < z < 1.7. There is a small overlap (40 objects) with the zCOSMOS sample: the mean redshift difference is −46 ± 24 km s⁻¹.

Silverman et al. (2015): We obtain redshifts from Silverman et al. (2015), who also published redshifts from the FMOS-COSMOS survey over the redshift range 0.7 < z < 2.5. There are 329 redshifts from this catalog, but none are X-ray system member candidates (Section 2.4). The overlap of this sample with zCOSMOS is negligible. The typical velocity resolution from the FMOS spectroscopy is ~115 km s⁻¹ (Silverman et al. 2015).

Kriek et al. (2015): The MOSFIRE Deep Evolution Field (MOSDEF survey) obtained spectra for 616 COSMOS objects at 1.37 ≤ z ≤ 3.80. We use 411 redshifts that are measured based on multiple emission features or else robust absorption lines (z_MOSFIRE_ZQUAL = 7). There is no overlap between the selected MOSDEF redshifts and the zCOSMOS redshifts.

Masters et al. (2017): The Complete Calibration of the Color–Redshift Relation (C3R2) Survey is a deep redshift survey that aims to calibrate the color–redshift relation of galaxies to the Euclid depth. Masters et al. (2017) presented Data Release (DR) 1 including redshifts of COSMOS galaxies measured from Keck spectroscopy. We obtain 940 redshifts from DR1; only 12 of them overlap with zCOSMOS measurements.

---

**Table 2**

| R.A.    | Decl. | z       | z error |
|---------|-------|---------|---------|
| 149.556005 | 2.362138 | 0.37433 | 0.00019 |
| 149.914532 | 2.450852 | 0.44304 | 0.00003 |
| 150.640850 | 2.466479 | 0.61610 | 0.00006 |
| 150.683432 | 2.224703 | 0.41087 | 0.00013 |
| 149.538039 | 2.073853 | 0.20916 | 0.00006 |

**Note.** The entire table is available in machine-readable form in the online journal. (This table is available in its entirety in machine-readable form.)

Tasca et al. (2017): The VIMOS Ultra Deep Survey (Le Fèvre et al. 2015) includes 384 redshifts in the COSMOS field from VLT/VIMOS observations. We compile 367 redshifts from DR1 (Tasca et al. 2017) with the quality flag zconf = 3 or 4.

Straatman et al. (2018): The Large Early Galaxy Astrophysics Census (LEGA-C) Data Release 2 provided redshifts from VLT/VIMOS observations. LEGA-C includes 1809 redshifts for objects in the COSMOS galaxy catalog: 544 objects also have redshifts from zCOSMOS. The LEGA-C redshifts show a small systematic offset compared to the zCOSMOS redshift of 11 ± 4 km s⁻¹.

### 2.2.2. Observations

We carried out new Hectospec observations for the COSMOS field in 2018 December. Following the hCOSMOS survey, we used the 270 line mm−1 Hectospec grating, which yields a 6.2 Å spectral resolution over the wavelength range 3800–9100 Å. The exposure time for the Hectospec observations is an hour.

The Hectospec data were reduced with the IDL HSRED v2.0 package. We measure redshifts with RVSAO (Kurtz & Mink 1998), which cross-correlates observed spectra with a set of redshift templates. We visually inspected the cross-correlation results and classified them into three groups: Q for high-quality fits, ? for ambiguous cases, and X for poor fits. We use 277 redshifts derived from high-quality fits with a typical uncertainty of ~36 km s⁻¹; 52 of them are X-ray system members.

### 2.3. The COSMOS Spectroscopic Sample

Based on the COSMOS galaxy catalog, we compile spectroscopic redshift measurements from a wide variety of surveys in the literature. In addition, we obtain new redshifts from MMT/Hectospec observations. As a result, we have 22,667 redshifts for objects in the COSMOS galaxy catalog regardless of the brightness of the galaxies. This COSMOS galaxy catalog includes 7600 galaxies with Pmem > 0, where Pmem indicates the membership probability (George et al. 2011; see details in Section 2.4). Our compilation includes 1805 (~24%) spectroscopic redshifts for X-ray system member candidates.

We compare the spectroscopic redshifts with the photometric redshifts from the COSMOS galaxy catalog (George et al. 2011). These photometric redshifts were originally derived by Ilbert et al. (2009), who compared spectral energy distributions (SEDs) from over 30 bands of ultraviolet, optical, and infrared...
data with a set of galaxy templates with stellar population synthesis models. The photometric redshifts from George et al. (2011) were updated with $H$-band data and with improved template fitting techniques. The uncertainty in the photometric redshift measurement is $\Delta z \sim 0.008$.

Figure 1(a) compares photometric and spectroscopic redshifts for the COSMOS objects. In Figure 1(b), we display the difference between the photometric and spectroscopic redshifts normalized by the spectroscopic redshift. The median difference (the red dotted line) over this redshift range is $-560 \pm 120 \text{ km s}^{-1}$, smaller than the typical uncertainty in the photometric redshift. It is interesting that there is a systematic offset between photometric and spectroscopic redshifts. This large difference suggests that membership identification for groups and clusters based on photometric redshifts may be incorrect.

We also estimate the stellar mass of the galaxies with spectroscopic redshifts based on the technique used in Damjanov et al. (2018). We use the Le Phare fitting code (Arnouts et al. 1999; Ilbert et al. 2006) to derive a mass-to-light ratio by comparing observed magnitudes with an SED model. We use optical $ugri$ band magnitudes of individual galaxies. For comparison, we generate a set of synthetic SED models based on the stellar population synthesis model from Bruzual & Charlot (2003) and a Chabrier (2003) initial mass function. We assume exponentially declining star-forming histories with e-folding timescales of $\tau = 0.1, 0.3, 1, 2, 3, 5, 10, 15, \text{ and } 30 \text{ Gyr and three metallicities } (Z = 0.004, 0.008, \text{ and } 0.02)$. We also take into account the variation of the stellar population age in the range 0.01 to 13 Gyr. We account for foreground extinction using the Calzetti et al. (2000) extinction law with an $E(B - V)$ range of 0.0 to 0.6. We obtain the median value of the stellar mass from the probability distribution function for the stellar mass.

2.4. COSMOS X-Ray Systems and Their Members

We use the COSMOS X-ray group catalog from George et al. (2011). This catalog is the second version of the catalog of X-ray systems in the COSMOS field updated from Finoguenov et al. (2007) and was followed by Gozaliasl et al. (2019). We use the catalog from George et al. (2011) because they included a catalog of X-ray system candidate member galaxies along with the catalog of X-ray systems. This member candidate catalog is critical for determining the spectroscopic membership based on spectroscopic survey data.

The first catalog of X-ray clusters in the COSMOS field is from Finoguenov et al. (2007). They use the first 36 XMM-Newton observations. The X-ray flux limit of this survey is $\sim 1 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}$ within the 0.5–2.0 keV band. They provide the physical properties of the X-ray systems including X-ray luminosity, temperature, and characteristic mass ($M_{500}$) based on X-ray scaling relations.

George et al. (2011) extended the search for X-ray systems based on 54 XMM-Newton pointings. They identify 72 X-ray cluster candidates with extended X-ray emission associated with concentrations of galaxies in photometric redshift space. The X-ray survey reaches a flux limit of $3 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}$ within the 0.5–2.0 keV band. They detect $\sim 150$ extended sources. To identify the optical counterparts of the extended X-ray sources, George et al. (2011) apply a red-sequence finder to galaxies within a projected distance of 0.5 Mpc from the X-ray center. The X-ray system catalog from George et al. (2011) includes 165 X-ray groups and clusters with optical counterparts and 18 extended X-ray sources with ambiguous optical counterparts.

The X-ray group membership catalog is a primary asset of the COSMOS X-ray system survey. They employ a Bayesian approach to assign membership for galaxies associated with extended X-ray emission. The selection algorithm determines the membership probability ($P_{\text{mem}}$) based on the position, the photometric redshift, and the stellar mass of the galaxy. The COSMOS galaxy catalog includes 7600 galaxies with $P_{\text{mem}} > 0$ (4623 galaxies with $P_{\text{mem}} > 0.5$) regardless of the magnitude.

Gozaliasl et al. (2019) is the most recent update for the COSMOS X-ray system survey. They use even deeper XMM-Newton and Chandra observations and reach an X-ray flux limit of $3 \times 10^{-16} \text{ erg cm}^{-2} \text{s}^{-1}$, an order of magnitude deeper than George et al. (2011). They identify 247 X-ray groups in the redshift range $0.08 < z < 1.3$. The major update from the previous catalogs is identification of higher redshift systems. For systems at $z < 1.0$, the X-ray luminosities of the systems included in both George et al. (2011) and Gozaliasl et al. (2019) are essentially identical. We use the properties of X-ray systems from George et al. (2011) because we are limited by the spectroscopy to $z < 1$ and because Gozaliasl et al. (2019) do not provide a candidate member catalog.
Figure 2. X-ray luminosity of COSMOS X-ray systems (red circles) as a function of redshift. Gray crosses and pentagons show X-ray samples from Mahdavi et al. (2000) and Popesso et al. (2007), respectively. Black pluses, diamonds, and triangles show the CIRS (Rines et al. 2003), HeCS (Rines et al. 2013), and HeCS-SZ (Rines et al. 2016) samples, respectively. Blue circles show X-ray clusters in HectoMAP (Sohn et al. 2018a).

The final catalog we use includes 180 X-ray systems at \( z < 1 \) among 183 X-ray systems listed in George et al. (2011). We exclude three systems because they have no member candidates \( (P_{\text{mem}} > 0) \) in the COSMOS galaxy catalog. George et al. (2011) offer a quality flag \( (Q_X) \) for the X-ray systems: 1 indicates a well-defined X-ray system, 2 indicates a well-detected X-ray system with an ambiguous X-ray center, and 3 indicates suspicious X-ray systems that require checking with spectroscopic data. The three systems we exclude are \( Q_X = 2 \) systems. There are 62 systems with \( Q_X = 1 \), 100 systems with \( Q_X = 2 \), and 18 systems with \( Q_X = 3 \). We begin by examining all of the systems with some members regardless of the quality flag.

Figure 2 shows the X-ray luminosity as a function of redshift for all of the candidate COSMOS X-ray systems. For comparison, we plot X-ray clusters with spectroscopy from the literature (Mahdavi et al. 2000; Rines et al. 2003, 2013, 2016; Popesso et al. 2007; Sohn et al. 2018a). The COSMOS X-ray systems cover a wider redshift range than previous samples. More importantly, the COSMOS systems include very low luminosity X-ray systems at a given redshift as a result of the very deep X-ray data. In particular, at \( z < 0.4 \), the COSMOS X-ray sample offers a unique chance to study systems with very low luminosity with \( \log L_X < 42.5 \).

3. Spectroscopic Survey Completeness

Figure 3 shows the projected spatial distribution of the COSMOS X-ray systems. The background density map displays the completeness of the combined spectroscopic surveys to \( r = 21.3 \). Yellow circles show the location of the X-ray systems. The largest symbols indicate a high X-ray confidence flag \( (Q_X = 1) \); the smallest symbols indicate \( Q_X = 3 \). Most of the X-ray systems are located in the area where the spectroscopic survey is complete. We also mark the location of galaxy cluster candidates based on red-sequence detection; magenta crosses indicate redMaPPer systems (Rykoff et al. 2016), and green pluses display CAMIRA clusters (Oguri 2014). We describe these systems in the Appendix.

Figure 4(a) shows the spectroscopic survey completeness for the X-ray system member candidates with \( P_{\text{mem}} > 0 \). We plot the \( r \)-band magnitude distribution of all member candidates along with the member candidates with spectroscopic redshifts. To \( r \sim 20.6 \), the hCOSMOS survey limit, 91% of the member candidates have spectroscopic redshifts. The dashed line in Figure 4(a) displays the spectroscopic completeness as a function of \( r \)-band magnitude; the completeness decreases rapidly for \( r > 20.6 \).

We compute the spectroscopic completeness for individual X-ray systems within \( R_{\text{proj}} < R_{200,X} \), where \( R_{\text{proj}} \) is the projected distance and \( R_{200,X} \) is the characteristic radius of the X-ray system where the mean density is 200 times the critical density of the universe at the mean redshift of the system. Figure 4(b) displays the completeness for galaxies brighter than \( r = 21.3 \) (the hCOSMOS limit) in each X-ray system. The spectroscopic survey is more than 75% complete for 97 (54%) of the COSMOS X-ray systems and more than 50% complete for 169 (90%) systems.

4. Spectroscopic Catalogs of Cosmos X-Ray Systems

We identify spectroscopic members of COSMOS X-ray systems based on the compilation of spectroscopic redshifts. These spectroscopic members are the basis for studying the properties of the X-ray systems. We describe the identification of spectroscopic members in Section 4.1 and show some example X-ray systems in Section 4.2. We describe the final
spectroscopic sample of COSMOS X-ray systems and the spectroscopic catalog of members in the COSMOS X-ray systems in Section 4.3. In Section 4.4, we define the refined sample based on X-ray flags and the number of spectroscopic members that we use to study the $L_X - \sigma_v$ relation. In Section 4.5, we identify the brightest group galaxies (BGGs) in the X-ray systems.

4.1. Identification of Spectroscopic Members

We examine the distribution of X-ray system member candidates based on the classic R–v diagram: the rest-frame group-centric velocity as a function of projected distance from the X-ray center. Figure 5 shows R–v diagrams of some well-sampled COSMOS X-ray systems: these systems are the brightest X-ray sources with more than 10 spectroscopic members at $z < 0.4$. All of these example systems are used to study the $L_X - \sigma_v$ scaling relation (Section 4.4). The black open circles in Figure 5 show galaxies with spectroscopic redshifts around each X-ray system. We also display the Subaru/Hyper Suprime Cam (HSC) gri image of each X-ray system within a 500 kpc × 500 kpc field of view. The HSC images show that there are galaxy overdensities accompanying a dominant bright galaxy near the X-ray center. Sometimes, the dominant bright galaxy is offset from the X-ray center.

In the R–v diagram, member candidates with $P_{\text{mem}} > 0.5$ (red circles) show a strong concentration around the center of each X-ray system. In contrast, we note that a large fraction of the galaxies with $0 < P_{\text{mem}} < 0.5$ (orange circles) are line-of-sight interlopers. They are barely distinguishable from cluster members based on photometric redshifts.

We identify spectroscopic members of the X-ray systems within $R_{\text{proj}} < R_{200,X}$. George et al. (2011) estimated the $R_{200,X}$ based on the $L_X - M_{200}$ scaling relation calibrated based on the weak lensing mass (Leauthaud et al. 2010). We use the $R_{200,X}$ measurement because the membership probabilities from George et al. (2011) are assigned to galaxies within this radius.

We also apply a generous $|\Delta c(z_{\text{member}} - z_{cl})|/(1 + z_{cl}) < 1000$ km s$^{-1}$ criterion to identify spectroscopic members. Here the central redshift of the X-ray system ($z_{cl}$) is determined by iteration. We first identify spectroscopic member candidates based on a wide window: $R_{\text{proj}} < R_{200,X}$ and $|\Delta c(z_{\text{member}} - z_{cl})|/(1 + z_{cl}) < 3000$ km s$^{-1}$. We then we identify the spectroscopic members with the narrower window of $R_{\text{proj}} < R_{200,X}$ and $|\Delta c(z_{\text{member}} - z_{cl})|/(1 + z_{cl}) < 1000$ km s$^{-1}$. The number of spectroscopic members changes little when we use a larger velocity difference limit of 1500 or 2000 km s$^{-1}$.

Figure 6 shows the number of spectroscopic members of X-ray systems as a function of redshift. We identify at least one spectroscopic member in 176 COSMOS X-ray systems. There are 146 spectroscopically identified groups (76%) with three or more spectroscopic members. The median number of spectroscopic members is five, comparable with the XXL survey (~5) combined with the SDSS, GAMA, and VLT spectroscopic surveys (Pacaud et al. 2016). The systems where we do not identify any spectroscopic members are mostly (9/10) at high redshift ($z > 0.65$).

4.2. Examples of Clean and Overlapping X-Ray Systems

We explore two individual X-ray systems to illustrate their very different photometric member distributions. Figure 7(a) shows an X-ray system (ID from George et al. 2011: 29) at $z = 0.34$. This X-ray system is an unambiguous, isolated system with no other X-ray system within 3'. Filled circles in Figure 7(a) indicate the 119 photometrically identified members, and open circles are galaxies with $|\Delta c(z_{\text{galaxy}} - z_{\text{system}})/(1 + z_{\text{system}})| < 1000$ km s$^{-1}$. Figure 7(b) displays the R–v diagram of this system; red filled circles are the member candidates with $P_{\text{mem}} > 0$, and black open circles are the galaxies with spectroscopic redshifts. We identify 14 spectroscopic members of this system and calculate the velocity dispersion of the system. This X-ray system lies on the X-ray luminosity–velocity dispersion scaling relation of the massive clusters (Section 5.1).

Figure 7(c) and (d) demonstrate an ambiguous case where several X-ray systems overlap. The complexity of this region was highlighted in Knobel et al. (2009). Figure 7(c) shows the spatial distribution of galaxies around four X-ray systems (IDs from George et al. 2011: 191, 193, 201, 321). These four X-ray systems are essentially at the same redshift of $z = 0.22$. We display the photometrically identified members ($P_{\text{mem}} > 0$) color coded by membership in the individual clusters. Although the membership determination algorithm assigns membership within the individual X-ray systems, the spatial distributions of the photometrically identified members overlap significantly on the sky.

In Figure 7, we show the R–v diagram for the photometrically identified members (filled circles) of these four X-ray systems. We have spectroscopic redshifts for 69 galaxies among the 160 member candidates. Among these 69 galaxies, 47 are within $|\Delta c(z_{\text{galaxy}} - z_{\text{system}})/(1 + z_{\text{system}})| < 1000$ km s$^{-1}$, where $z_{\text{system}} = 0.22$. These spectroscopically identified members are all well within the $R_{200,X}$ values of the X-ray systems.

Figure 7(d) plots the R–v diagram of galaxies in the four overlapping systems based on the X-ray center of the system ID 193. Because the redshifts of the four X-ray systems are...
essentially identical, separation of the members in the individual clusters is ambiguous even with spectroscopic redshifts. This plot suggests that there may be a single cluster at \( z \approx 0.22 \) and with four separate X-ray peaks. In this field, there is a weak excess of galaxies at \( z \approx 0.35 \) and \( \sim 0.74 \), but these galaxies do not show a strong overdensity on the sky. Thus, we cannot tell whether the X-ray emission has some optical counterparts at greater redshift. We note that we do not use this sample to study the \( L_X - \sigma_t \) scaling relation because this system is removed by the X-ray flags (see Section 4.4).

4.3. Total Catalog of COSMOS X-Ray Systems

Our final sample of COSMOS X-ray systems includes 146 spectroscopic groups with three or more spectroscopic members; we exclude 30 systems with only one or two spectroscopic members. Spectroscopic groups span the redshift range \( 0.07 < z < 0.99 \) and the X-ray luminosity range \( 41.3 < \log L_X < 43.9 \).

Table 3 compares the COSMOS X-ray system sample and the other recent X-ray-selected system catalogs. AEGIS yields an X-ray group catalog covering similar redshift and X-ray luminosity ranges over a \( \sim 0.67 \text{ deg}^2 \) field of view (Erfanianfar et al. 2013). The typical number of spectroscopic members of these AEGIS groups is six, comparable with COSMOS X-ray systems. There are 49 AEGIS groups, three times smaller than the number of COSMOS X-ray systems, approximately as expected given the relative area covered by the two surveys.

We also compare the XMM-XXL survey (Pacaud et al. 2016; Adami et al. 2018) covering two \( 25 \text{ deg}^2 \) fields. Adami et al. (2018) identify 365 X-ray systems including 260 spectroscopically
Figure 6. Number of spectroscopic members of COSMOS X-ray systems as a function of redshift; 76% of the X-ray systems are spectroscopically identified groups with three or more members.

Figure 7. (a) Spatial distribution of galaxies around the well-defined X-ray system (ID 029). Gray dots are the galaxies in the field. Filled circles are the photometrically identified members (George et al. 2011), and the open circles are 14 galaxies within \( |\Delta z_{\text{galaxy}} - z_{\text{system}}| / (1 + z_{\text{system}}) < 1000 \text{ km s}^{-1} \). The large circle is \( R_{200,X} \). (b) \( R - v \) diagram for galaxies around the system shown in (a). Filled circles are the member candidates with \( P_{\text{mem}} > 0 \), and open circles are galaxies with spectroscopic redshifts. (c) Same as (a), but for an overlapping set of four X-ray systems at \( z \sim 0.22 \). Blue symbols are the members of X-ray system ID 321, red for ID 191, green for ID 193, and magenta for ID 201. Open circles are the spectroscopically identified members with \( |\Delta z_{\text{galaxy}} - z_{\text{system}}| / (1 + z_{\text{system}}) < 1000 \text{ km s}^{-1} \). (d) Same as (b), but for the overlapping four X-ray systems. Filled circles are the member candidates in each X-ray system; color coding is the same as (c). The member candidates of the four apparent X-ray peaks are mixed together in the \( R - v \) diagram.

identified groups with three or more spectroscopic members within the redshift range \( 0.0 < z < 1.2 \). The XXL groups cover an X-ray luminosity range similar to the COSMOS X-ray systems. Because the XXL survey flux limit is a few times brighter than the COSMOS and AEGIS X-ray surveys, the XXL survey yields a lower X-ray system surface number density. Table 4 lists the COSMOS X-ray group members with spectroscopic redshifts in the 176 systems. We include 1805 X-ray system member candidates with \( P_{\text{mem}} > 0 \) and with a spectroscopic redshift. We also list the 391 spectroscopic members without \( P_{\text{mem}} \). The total number of spectroscopic members is 2196. This catalog includes the X-ray system ID from George et al. (2011), R.A., decl., spectroscopic redshifts, \( r \)-band magnitude, \( P_{\text{mem}} \), spectroscopic membership flag, BGG flag, and the flag for the sample we use to derive the scaling relation (Section 5).

4.4. Refined COSMOS X-Ray Systems for the \( L_X - \sigma_v \) Scaling Relation

We investigate the \( L_X - \sigma_v \) scaling relation using the COSMOS X-ray systems (Section 5). To explore this relation, we construct a cleaner sample based on X-ray flags from George et al. (2011). The total sample of COSMOS X-ray systems (Section 4.3) includes some X-ray systems with uncertain X-ray luminosity, due to overlapping X-ray systems or to imaging defects. Moreover, the spectroscopy is not complete for some systems in the total sample.

We select systems with X-ray flags (\( \text{FLAG} \_\text{MERGER} \) and \( \text{FLAG} \_\text{MASK} \)) equal to zero. \( \text{FLAG} \_\text{MERGER} = 0 \) indicates no overlap with other X-ray systems, and \( \text{FLAG} \_\text{MASK} = 0 \) indicates that less than 10% of the area in the optical imaging of the X-ray system is affected by image defects, including saturated stars or the edge of the imaging. We also require that the systems have at least three spectroscopic members to derive the velocity dispersion.

A total of 125 COSMOS X-ray systems satisfy these criteria (Table 3). These refined COSMOS X-ray systems span the redshift range \( 0.1 < z < 0.98 \). The refined COSMOS X-ray sample is a factor of eight larger than the sample of AEGIS X-ray groups used to derive the \( L_X - \sigma_v \) scaling relation (Erfanianfar et al. 2013) and slightly larger than the sample compiled (83 systems) in Erfanianfar et al. (2014).

Figure 8 shows the X-ray flux distribution of COSMOS X-ray systems and the refined sample. For comparison, we show the X-ray flux distribution of all of the AEGIS X-ray systems (Erfanianfar et al. 2013). Most of the systems in the refined sample have an X-ray flux exceeding the COSMOS X-ray survey flux limit (4σ detection at \( 1.0 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \)). COSMOS X-ray systems with X-ray fluxes near the limit are excluded by the selection process. The refined

---

**Table 3**

| Survey     | FoV | \( \log L_X \) range | \( z \) range | \( N_{\text{spec, group}} \) |
|------------|-----|-----------------------|---------------|-----------------------------|
| COSMOS\(^b\) | 1.65 | [41.3, 43.9] | [0.07, 0.99] | 146 |
| refined COSMOS\(^b\) | 1.65 | [41.3, 43.9] | [0.10, 0.98] | 125 |
| AEGIS\(^c\) | 0.67 | [41.7, 43.9] | [0.06, 1.55] | 47 |
| XXL\(^d\) | 50.0 | [41.4, 44.4] | [0.00, 1.20] | 260 |

Notes.

\(^a\) Total number of spectroscopically identified groups with three or more spectroscopic redshifts.

\(^b\) This study.

\(^c\) Erfanianfar et al. (2013).

\(^d\) Adami et al. (2018).
COSMOS X-ray systems have an X-ray flux distribution similar to that for AEGIS X-ray systems.

4.5. BGGs

Based on the spectroscopy, we identify the brightest galaxy in each X-ray system. Hereafter, we refer to these brightest galaxies as BGGs. Identification of the BGGs is important for investigating the cluster dynamics. The BGG often sits at the bottom of a local potential well (e.g., Beers & Geller 1983; Newman et al. 2013).

Previous studies of COSMOS X-ray systems define the BGG as the galaxy with the largest stellar mass among member candidates within $R_{200}$ of the X-ray center (George et al. 2011; Gozaliasl et al. 2019). We refer to these galaxies with the largest stellar mass as the most massive galaxies hereafter. However, in some cases, the most massive galaxy is not the brightest galaxy in the system in the $r$-band. Furthermore, a large fraction ($\sim 30\%$) of the most massive galaxies are member candidates identified based only on photometric redshifts (Gozaliasl et al. 2019).

We identify the BGGs of 160 COSMOS X-ray systems based on their $r$-band luminosity following the conventional definition of the brightest cluster (group) galaxy (e.g., Lauer et al. 2014). These 160 COSMOS X-ray systems all contain at least one spectroscopic member within $R_{\text{proj}} < 0.5 R_{200}$, where $R_{\text{proj}}$ is the projected distance from the X-ray peak (Gozaliasl et al. 2019). When we test the BCG identification within $R_{\text{proj}} < R_{200}$, even brighter galaxies located at large projected distance $0.5 < R_{\text{proj}}/R_{200} < 1.0$ are identified as BGGs for 40 systems. The typical magnitude difference between the BGG and brighter galaxies in the outskirts is $\sim 0.4$ mag. However, the connection between these bright galaxies in the system outskirts and the X-ray emission is unclear. We use the tight projected radius $R_{\text{proj}} < 0.5 R_{200}$ for BGG identification.

We compare these BGGs with the most massive galaxies identified based on our stellar mass estimates. There are 30 X-ray systems where the BGG is apparently not the most massive galaxy among the spectroscopic members. We lack a stellar mass estimate for the BGG of three X-ray systems (ID: 11, 196, 264). George et al. (2011) identified these BGGs as the most massive galaxies based on their stellar mass estimates with photometric redshifts (George et al. 2011). In 17 systems, the BGGs are located closer to the X-ray center than the most massive galaxies, suggesting that the BGGs we identify are closer to the bottom of the potential well. For the remaining 10 systems, the most massive galaxies are closer to the X-ray center than the BGGs. Large uncertainty in the stellar mass estimate may contribute to the confusion. In total, the BGGs are also the most massive galaxies in 130 X-ray systems ($\sim 81\%$ of a total 160 COSMOS X-ray systems).

We next examine the BGG offset from the X-ray center. Gozaliasl et al. (2019) studied the offset between the most massive galaxies and the X-ray center of the COSMOS X-ray systems. They investigated several relations between the BGG offset and other group properties, including group redshift, X-ray flux, and the magnitude gap between the first and second brightest galaxies. Here, we limit our investigation to the offset between the X-ray centers and the BGGs identified based on the luminosity. We use this indicator as a verification for the refined sample of X-ray systems.

Figure 9(a) shows the distribution of projected distances between BGGs and the X-ray center normalized by $R_{200}$ of the individual system; the red histogram shows the distribution for the 125 refined COSMOS X-ray systems. For the refined catalog, their BGGs are more concentrated toward the X-ray center.

The BGGs show a larger offset from the X-ray center than BCGs in massive systems. Lavoie et al. (2016) examined the BCG offset from the X-ray centers based on XXL clusters with a typical mass of $10^{14} M_{\odot}$, a factor of four larger than the typical mass of COSMOS X-ray systems. They show that $\sim 80\%$ of the BCGs in the XXL clusters lie within $R_{\text{proj}} < 0.05 R_{200} \sim 0.035 R_{300}$ of the X-ray centers. However, only 21% of BGGs in COSMOS X-ray systems are located within $R_{\text{proj}} < 0.035 R_{200}$.
5. The $L_X$–$\sigma_v$ Scaling Relation

The deep X-ray and large spectroscopic data sets for the COSMOS X-ray systems enable exploration of the X-ray scaling relation to systems with very low X-ray luminosity. We examine the $L_X$–$\sigma_v$ scaling relation of COSMOS X-ray systems in Section 5.1. We discuss the redshift evolution of the scaling relation in Section 5.2.

5.1. The $L_X$–$\sigma_v$ Scaling Relation of COSMOS X-Ray Systems

We investigate the $L_X$–$\sigma_v$ scaling relation based on the refined COSMOS X-ray systems (Section 4.4) covering the redshift range $0.1 < z < 0.97$. For these 125 X-ray systems, we calculate the rest-frame radial velocity differences between the spectroscopic members within $R_{200}$ and the BGGs of the individual clusters. We use the biweight recipe (Beers et al. 1990) to compute the velocity dispersions, following Popesso et al. (2007), a comparison sample. We discuss the effect of the velocity dispersion determination on deriving the scaling relation in Section 6.1. We note that, according to previous studies, the $L_X$–$\sigma_v$ scaling relation in this redshift range shows little or no evolution (e.g., Girardi & Mezzetti 2001; see Section 5.2).

Figure 10 displays the $L_X$–$\sigma_v$ relation for individual COSMOS X-ray systems (red circles). Gray squares show the 137 Abell clusters from Popesso et al. (2007) with X-ray luminosities measured within the energy band 0.1–2.4 keV and galaxy velocity dispersions estimated based on SDSS spectroscopic data. Gray crosses display the 59 low X-ray systems from Mahdavi et al. (2000); the X-ray luminosities of these systems are measured within the same energy band. The solid line is the scaling relation derived from Popesso et al. (2005). The COSMOS X-ray systems overlap both the sample of Popesso et al. (2005) and of Mahdavi et al. (2000). The scatter for the COSMOS system scaling relation is very large for $\log L_X < 42.5$ with an extended tail toward low velocity dispersion. Several previous studies show similar behavior, including the extension to low velocity dispersion for low X-ray luminosity systems (Xue & Wu 2000; Osmond & Ponman 2004).

Measuring the scaling relation for the X-ray luminosity range $41.5 < \log L_X < 42.5$ is challenging. Mahdavi et al. (2000) suggest that X-ray systems in this X-ray luminosity range with $\sigma_v < 340$ km s$^{-1}$ fit a shallow scaling relation $L_X \propto \sigma_v^{0.37}$ (dashed lines in Figure 10). At first glance, the COSMOS X-ray systems in this X-ray luminosity range also appear to fit this shallow scaling relation. However, the shallow scaling relation depends on a small number of systems with $\sigma_v > 125$ km s$^{-1}$: two systems from Mahdavi et al. (2000) and 14 systems from the COSMOS X-ray sample. The systems with $\sigma_v > 125$ km s$^{-1}$ are scattered around the standard steeper scaling relation that fits more massive systems.

We next compute the more robust median velocity dispersion of the COSMOS X-ray systems as a function of their X-ray luminosity. We divide the set of 125 COSMOS X-ray systems into seven bins according to X-ray luminosity; each bin includes $\sim$17 X-ray systems. The median velocity dispersion of the COSMOS X-ray systems (large blue circles in Figure 10) is consistent with the velocity dispersion expected from the extrapolation of the scaling relation for the high X-ray luminosity systems at a given X-ray luminosity; the overall slope of the relation (fitted to the median dispersion from...
5.2. Redshift Evolution of $L_X$–$\sigma_v$ Relation

The COSMOS X-ray systems we use to study the scaling relation are distributed over the redshift range $0.1 < z < 0.97$. Galaxy systems evolve significantly over this wide redshift range. For example, N-body simulations show that galaxy systems increase their mass by a factor of 2–3 (e.g., Fakhouri et al. 2010). This mass growth increases the velocity dispersion. On simple theoretical grounds, the X-ray luminosity and temperature are physically related to the velocity dispersion. Thus, both the X-ray luminosity and the velocity dispersion should continue to reflect the depth of the underlying potential well (Bryan & Norman 1998), and the predicted relation between the two measurements should continue to hold.

Previous studies show that indeed there is no significant evolution in the $L_X$–$\sigma_v$ scaling relations for galaxy clusters. Borgani et al. (1999) measured the velocity dispersion of 16 galaxy clusters at 0.17 $< z < 0.55$ and showed that the $L_X$–$\sigma_v$ scaling relation of these systems is consistent with that for local clusters. Similarly, Girardi & Mezzetti (2001) compared the $L_X$–$\sigma_v$ and $T_X$–$\sigma_v$ scaling relations of local clusters at $z < 0.15$ and higher redshift clusters within the range $0.15 < z < 0.9$ and a mean redshift of 0.3. They found no evidence of redshift evolution of these scaling relations. Ruel et al. (2014) show that there is no evolution in the $T_X$–$\sigma_v$ relation for $\sim$30 South Pole Telescope clusters at $z < 1.3$.

We also find no evidence of redshift evolution in the $L_X$–$\sigma_v$ scaling relation for the COSMOS X-ray systems. Following previous studies, we divide the COSMOS systems into two redshift bins $(0.1 < z < 0.4$ and $0.4 < z < 0.7)$ and compare the $L_X$–$\sigma_v$ relations. The X-ray systems in the two redshift bins show no significant difference in the scaling relation, but the scatter is large. This result is insensitive to the redshift limit where we divide the sample.

We also compare the distribution of X-ray systems within narrow redshift bins $(\Delta z = 0.1)$. The higher redshift X-ray systems appear at higher X-ray luminosity because the sample is X-ray flux limited. The X-ray systems in each redshift bin show a broad velocity dispersion distribution within a narrow X-ray luminosity range. In effect, the scaling relation derived based on the median velocity dispersion (blue squares in Figure 10) is sorted by redshift; the higher X-ray luminosity sample is a higher redshift sample. Thus, the consistency in the scaling relations of the COSMOS X-ray systems in various redshift ranges and the local systems indicates that the scaling between X-ray luminosity and velocity dispersion reflects the underlying cluster physics in a way that is independent of redshift in this range.

6. Discussion

We explore the $L_X$–$\sigma_v$ scaling relation based on COSMOS X-ray systems with a clean X-ray luminosity measurement and with complete spectroscopic coverage. Although we use well-defined X-ray systems, measuring a robust scaling relation is challenging because of large uncertainties in the measurements, particularly for low X-ray luminosity systems. Here, we discuss challenges in the estimation of the velocity dispersion of the systems (Section 6.1) and other ambiguities in deriving the $L_X$–$\sigma_v$ scaling relation for systems with $41.4 < \log L_X < 42.5$ (Section 6.2).

6.1. Challenges in Deriving $\sigma_v$

In Figure 10, we show the $L_X$–$\sigma_v$ scaling relation based on the unique sample of 125 X-ray luminosity systems in the COSMOS field within $41.4 < \log L_X < 43.3$. The median velocity dispersion for all of the COSMOS X-ray systems fits the relation derived from luminous X-ray clusters. However, systems with X-ray luminosity of log $L_X$ $\sim$ 42 have velocity dispersions within the wide range of 50 to 500 km s$^{-1}$.

Here, we explore several issues that affect the velocity dispersion of the systems and discuss their effect on the $L_X$–$\sigma_v$ scaling relation. We first investigate the effect of velocity dispersion measurement recipes. We use the velocity dispersion measured based on the biweight recipe (Beers et al. 1990) following measurements made previously. This recipe works well for estimating the velocity dispersion of systems with small numbers of members. However, this recipe does not account for uncertainties in the individual redshift measurements. We thus compare the biweight velocity dispersion measurements with measurements based on the recipe from Danese et al. (1980) that takes measurement error into account. The velocity dispersion measurements from these two recipes are consistent with one another, indicating that the velocity dispersion measurements are robust.

We also calculate the velocity dispersion using the “gapper” estimator method (Beers et al. 1990), another good velocity dispersion estimator for systems with small numbers of
members (Erfanianfar et al. 2013; Clerc et al. 2016). Figures 11 (a) and (b) compare the $L_X - \sigma$ relation based on velocity dispersion measurement using the biweight and gapper methods. The black solid line and the gray shaded area show the $L_X - \sigma$ scaling relation for massive clusters and the 95% confidence region (Popesso et al. 2005). Red circles in Figures 11 (a) and (b) show the median velocity dispersions for the refined COSMOS X-ray sample bins as in Figure 10. The error bars show the interquartile range for the velocity dispersion measurements. The gapper velocity dispersions are systematically larger than the biweight velocity dispersions only by $\sim 10\%$. This systematic difference is much smaller than the uncertainties in individual velocity dispersion measurements.

We also compare velocity dispersion measurements based on different centers. We assume that the BGGs are located at the center of the gravitational potential of the system. To test the effect of possible center misidentification, we compute the velocity dispersions centered on the most massive galaxy and on the mean redshift of cluster members.

A comparison between the velocity dispersion measurements based on the BGG and the mean redshift of group members shows no systematic difference. The 1\sigma standard deviation of the ratio between these two velocity dispersion measurements is $\sim 0.24$. Figure 11 (c) shows the $L_X - \sigma$ scaling relation based on the velocity dispersion measurement centered on the mean redshift of group members.

We finally examine the effect of the radial velocity limit for identifying spectroscopic members. The radial velocity limit separates cluster members and LOS interlopers. If the radial velocity limit is too large, interlopers with large relative radial velocity can be identified as members and inflate the velocity dispersion, and vice versa. The caustic method (Diaferio & Geller 1997; Diaferio 1999; Serra & Diaferio 2013) is often used to identify cluster members to minimize the contamination by interlopers. However, we cannot apply the caustic technique because the typical number of spectroscopic members in COSMOS X-ray systems is too small.

We test the sensitivity of the velocity dispersions of the COSMOS X-ray systems by changing the radial velocity limit ($|\Delta v| = |(1 + z_{sys})|/|\Delta z_{sys}|$) from 500 to 2000 km s$^{-1}$. Figure 11 (d) displays the $L_X - \sigma$ scaling relation based on velocity dispersion measurements with a tight radial velocity limit of 500 km s$^{-1}$. The velocity dispersions of systems with $\sigma > 300$ km s$^{-1}$ are reduced significantly. The tight radial velocity limit only affects systems with high velocity dispersion by excluding possible member candidates with a large radial velocity difference. The velocity dispersion measurements change little with generous radial velocity limits $> 700$ km s$^{-1}$.

Interestingly, the entire $L_X - \sigma$ scaling relation derived based on the massive clusters and the less massive COSMOS sample is insensitive to the radial velocity limits we use. The variation in radial velocity limit affects only the systems with a large velocity dispersion. However, the $L_X - \sigma$ scaling relation of COSMOS X-ray systems based on the reduced velocity dispersions with a tight radial velocity limit still lie on the scaling relation defined by massive clusters. For the systems with low velocity dispersion ($\sigma < 300$ km s$^{-1}$), the velocity dispersion measurement is insensitive to the radial velocity limits. Erfanianfar et al. (2013) show the same effects for the smaller but similarly defined AEGIS sample.

In summary, we test the $L_X - \sigma$ scaling relation for COSMOS X-ray systems based on velocity dispersions measured with various approaches. These variations affect individual systems and contribute to the scatter in the scaling relation. However, the global $L_X - \sigma$ scaling relation remains within the 95% confidence range determined from other samples.

Measuring the velocity dispersion is fundamentally challenging for systems with low velocity dispersion. All of the COSMOS X-ray systems are embedded in the surrounding large-scale structure (see Figure 5). For example, we plot a stacked R–v diagram for galaxies around 21 X-ray systems we used to derive the $L_X - \sigma$ scaling relation within the X-ray luminosity range $42.0 < \log L_X < 42.25$ (Figure 12). Galaxies with $R_{proj} \gtrsim 0.6$ Mpc (open circles) inhabit the surrounding large-scale structure.

In the R–v diagram, the radial velocity distribution of the X-ray system members is undistinguishable from that of nonmember galaxies in the outskirts. Massive clusters or groups tend to show a larger extension in the radial velocity direction (a finger) toward the cluster center (e.g., see the R–v diagram of the massive cluster A2029 in Sohn et al. 2019). For a typical low X-ray luminosity system (Figure 12), the width of the radial velocity distribution for galaxies with $0.6 < R_{proj} < 1.0$ Mpc is $\sim 350$ km s$^{-1}$, which is comparable to or
is no clear difference between the velocity dispersion of X-ray system members and the surrounding large-scale structure. In effect, the effective velocity dispersion of the surrounding large-scale structure sets a velocity-dispersion system. Including these extreme systems. Indeed, the 14 COSMOS systems (~16%) with very low velocity dispersion appear to fit the shallow scaling relation.

The physical origin of these extremely low velocity dispersion systems is unclear. Mamon (2000) argued that the minimum velocity dispersion of a virialized galaxy system should be larger than the sum of the masses of its member galaxies. Surprisingly, the velocity dispersions of outliers in the COSMOS X-ray sample are sometimes smaller than the stellar velocity dispersion of their BGGs (J. Sohn et al. 2019, in preparation). Helsdon et al. (2005) suggested three possible explanations for reduced velocity dispersions: (1) the dynamical fraction reduces the orbital velocities, (2) tidal interaction reduces the orbital velocities of the galaxies, and (3) the line-of-sight velocity dispersion appears reduced as a result of velocity or spatial anisotropy. The low-velocity-dispersion systems in the COSMOS field may result from one or more of these mechanisms. Additionally, poor sampling can still result in artificially low velocity dispersions.

Furthermore, the X-ray source may be misidentified. ID 278 provides a case in point (we note that Gozaliasl et al. 2019 exclude this system, but it is a kind of prototype for potential problems in the system identification). Figure 13 shows a Subaru/HSC image of this system. George et al. (2011) identify the apparent red sequence of a galaxy group at $z = 0.306$ associated with X-ray emission. However, a foreground galaxy with an impressive shell structure ($z = 0.079$) is probably the X-ray source. In fact, the $z = 0.306$ apparent system is offset from the center of the X-ray emission, and the shell galaxy is coincident with it. We also suggest below that this source is an example of X-ray emission from an individual galaxy. This unique system demonstrates the importance of the dense spectroscopic survey for identifying an X-ray source and for studying the X-ray scaling relation.

Another ambiguity in deriving the $L_X-\sigma_v$ scaling relation for a system with low X-ray luminosity is that clusters with high X-ray luminosity are associated with an individual galaxy that may be either (1) a system member or (2) a galaxy that is not the X-ray source. In fact, the $z = 0.306$ apparent system is offset from the center of the X-ray emission, and the shell galaxy is coincident with it. We also suggest below that this source is an example of X-ray emission from an individual galaxy. This unique system demonstrates the importance of the dense spectroscopic survey for identifying an X-ray source and for studying the X-ray scaling relation.

Figure 12. Stacked R–v diagram of the 15 systems with the lowest X-ray luminosity in the COSMOS sample. Red filled circles are spectroscopic members, and the open circles are galaxies with spectroscopic redshifts. There is no clear difference between the velocity dispersion of X-ray system members and the radial extent of the surrounding large-scale structure.

6.2. Ambiguity in Determining $L_X-\sigma_v$ Scaling Relation for Low-mass Systems

The $L_X-\sigma_v$ relation at low X-ray luminosity presents a puzzle. There are two very different slopes of the scaling relation for low X-ray luminosity systems in the literature so far: (1) a slope ($\alpha \sim 4-5$) similar to that for clusters with high X-ray luminosity versus (2) a shallower slope ($\alpha \sim 0.4-2$). Early on, Ponman et al. (1996) showed that the $L_X-\sigma_v$ relation for 22 Hickson compact groups with $41.0 < \log L_X < 43.0$ has a slope ($\alpha = 4.9$) similar to that for high X-ray luminosity clusters. Based on a similar-sized sample with similar X-ray luminosity, Mulchaey & Zabludoff (1998) and Helsdon & Ponman (2000) show that the scaling relation of poor X-ray groups is consistent with that for galaxy clusters with large scatter. Erfanianfar et al. (2013) also showed that the scaling relation for X-ray groups in the AEGIS survey scatters around the scaling relation for X-ray luminous clusters.

In contrast, Mahdavi et al. (2000) suggest that a broken power law is the best fit to the $L_X-\sigma_v$ relation of low X-ray luminosity systems (see also dall’Antonio et al. 1994). They derived a much shallower scaling relation ($L_X \propto \sigma_v^{\alpha}$) for systems with $\alpha < 340 \text{ km s}^{-1}$. Other studies based on the larger number of galaxy groups also report a shallower scaling relation ($\alpha = 2.3-3.3$; Xue & Wu 2000; Osmond & Ponman 2004; Brough et al. 2006; Khosroshahi et al. 2007).

The discrepancies result from a small number of low X-ray luminosity systems with extremely low velocity dispersion ($\sigma \lesssim 125 \text{ km s}^{-1}$). The shallow scaling relations reported in previous studies are derived based on X-ray samples that include these extreme systems. Indeed, the 14 COSMOS systems (~16%) with very low velocity dispersion appear to fit the shallow scaling relation.

Another ambiguity in deriving the $L_X-\sigma_v$ scaling relation is that for low X-ray luminosity systems in the literature so far: (1) a slope ($\alpha \sim 4-5$) similar to that for clusters with high X-ray luminosity versus (2) a shallower slope ($\alpha \sim 0.4-2$). Early on, Ponman et al. (1996) showed that the $L_X-\sigma_v$ relation for 22 Hickson compact groups with $41.0 < \log L_X < 43.0$ has a slope ($\alpha = 4.9$) similar to that for high X-ray luminosity clusters. Based on a similar-sized sample with similar X-ray luminosity, Mulchaey & Zabludoff (1998) and Helsdon & Ponman (2000) show that the scaling relation of poor X-ray groups is consistent with that for galaxy clusters with large scatter. Erfanianfar et al. (2013) also showed that the scaling relation for X-ray groups in the AEGIS survey scatters around the scaling relation for X-ray luminous clusters.

In contrast, Mahdavi et al. (2000) suggest that a broken power law is the best fit to the $L_X-\sigma_v$ relation of low X-ray luminosity systems (see also dall’Antonio et al. 1994). They derived a much shallower scaling relation ($L_X \propto \sigma_v^{\alpha}$) for systems with $\alpha < 340 \text{ km s}^{-1}$. Other studies based on the larger number of galaxy groups also report a shallower scaling relation ($\alpha = 2.3-3.3$; Xue & Wu 2000; Osmond & Ponman 2004; Brough et al. 2006; Khosroshahi et al. 2007).

The discrepancies result from a small number of low X-ray luminosity systems with extremely low velocity dispersion ($\sigma \lesssim 125 \text{ km s}^{-1}$). The shallow scaling relations reported in previous studies are derived based on X-ray samples that include these extreme systems. Indeed, the 14 COSMOS systems (~16%) with very low velocity dispersion appear to fit the shallow scaling relation.
The central redshift of the system suggested by George et al. (2011) is 0.079. The X-ray center position, critical to identifying optical counterparts. Furthermore, deep and dense spectroscopic surveys with the Subaru/Prime Focus Spectrograph (Takada et al. 2014) and 4MOST (Finoguenov et al. 2019) will yield more robust velocity dispersion measurements of low X-ray luminosity systems.

Figure 13. HSC image of the X-ray system ID 278. The image is centered on the X-ray center from George et al. (2011). Yellow circles are member candidates with $P_{mem} > 0$, and cyan circles are spectroscopic members around the central redshift of the system suggested by George et al. (2011). The magenta circle highlights a foreground galaxy with a remarkable shell structure, the likely X-ray source.

Figure 14. $L_X - \sigma_v$ scaling relation of X-ray systems and early-type galaxies with X-ray emission. The lines and symbols are the same as in Figure 10. Blue triangles are early-type galaxies from Babyk et al. (2018); the velocity dispersions are the central stellar velocity dispersions within 1 kpc. The green star symbol is the location of the X-ray system in Figure 13 based on the $z = 0.306$ system velocity dispersion. The magenta star symbol is the source position if the X-ray emission is associated with the shell galaxy.

individual galaxies based on the central velocity dispersion of the shell galaxy from the SDSS DR14 spectroscopy catalog. This remarkable ambiguity highlights the difficulty in understanding the physical nature of these X-ray sources.

7. Conclusion

COSMOS X-ray systems are a unique flux-limited sample spanning the redshift range $0.06 < z < 0.99$ and the X-ray luminosity range $41.3 < \log L_X < 43.9$. The COSMOS X-ray system catalog constructed by George et al. (2011) we examine here includes X-ray systems with X-ray fluxes $> 1.0 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, an order of magnitude deeper than the future survey with e-ROSITA (Merloni et al. 2012). The rich data set obtained from multiwavelength photometric and spectroscopic observations enables investigation of the properties of systems with low X-ray luminosity. These COSMOS systems with low X-ray luminosity demonstrate the complexity that should be unraveled by e-ROSITA.

We identify 2196 spectroscopic members in 176 COSMOS X-ray systems. This large spectroscopic sample combines all available spectroscopic data for galaxies in the COSMOS field. A total of 146 (~81%) systems contain at least three spectroscopic members within $R_{200}$. The typical number of spectroscopic members per cluster is ~5. We also explore five redMaPPer systems and 13 CAMIRA systems in the COSMOS field.

We identify the BGGs among the spectroscopic members. For ~22% of the systems, the BGG is not the galaxy with the largest stellar mass in the system. The typical offset between the BGG and the X-ray peak is $R_{proj} \sim 0.14 R_{200}$, larger than the typical offset between BCGs and the cluster X-ray peak ($R_{proj} \sim 0.05 R_{200}$). The $L_X - \sigma_v$ scaling relation for a refined subset including 125 COSMOS X-ray systems is consistent with the relation derived from high X-ray luminosity systems ($L_X \propto \sigma^4_v$), but the error and the scatter are large. The scaling relation based on robust velocity dispersion measurements from the median velocity dispersion of the sample with similar X-ray luminosity lies on the extrapolation of the scaling relation for massive clusters.

We explore several effects on the velocity dispersion measurement, including the measurement recipes, misidentification of the central redshift of the system, and the radial velocity limits for identifying spectroscopic members. None of these significantly affect the global slope of the scaling relation. Variation in the velocity dispersion measurements only increases the random uncertainties in the scaling relation.
We discuss the fundamental difficulty in deriving the $L_X-\sigma_v$ relation at low $L_X$ and low $\sigma_v$ due to the nature of low X-ray luminosity systems. At low X-ray luminosity, poor groups and extended emission associated with individual quiescent galaxies overlap. The morphology of the distribution of extended X-ray sources in the $L_X-\sigma_v$ plane appears complex, with a tail that includes poor groups and extends toward low velocity dispersion. In contrast, quiescent galaxies populate a locus steeper than the relation for massive clusters (Babyk et al. 2018).

Interpretation of the group velocity dispersion measurement is challenging because of the effects of the surrounding large-scale structure and the poor sampling. Furthermore, identification of an X-ray source is difficult, and we demonstrate that, on the basis of extensive data, a source can move from the low dispersion tail to the locus for sources associated with individual galaxies.

The future survey with e-ROSITA will identify a large number of low X-ray luminosity systems from a large area on the sky with better spatial resolution and with temperature measurements (Finoguenov et al. 2019). Systems with low velocity dispersion ($\sigma < 150$ km s$^{-1}$) are abundant even in the SDSS spectroscopic sample (Sohn et al. 2016). The e-ROSITA survey will measure X-ray properties of these low-velocity-dispersion systems and will facilitate understanding of the morphology of the $L_X-\sigma_v$ distribution for poor groups and individual galaxies. Furthermore, deep and complete spectroscopy with the PFS and 4MOST surveys (Finoguenov et al. 2019) will enable better measurement of system velocity dispersions and the central velocity dispersions of individual galaxies. Combining these survey data will elucidate the scaling relations for systems and for individual galaxies and the relationship between them.

This paper uses data products produced by the OIR Telescope Data Center, supported by the Smithsonian Astrophysical Observatory. J.S. is supported by the CfA Fellowship. The Smithsonian Institution supported the research of M.J.G. H.J.Z. is supported by the Clay Postdoctoral Fellowship. This research has made use of NASA’s Astrophysics Data System Bibliographic Services. Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/. 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, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, 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, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, the Ohio State University, The 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.

**Appendix**

**Photometrically Identified Clusters in the COSMOS Field**

For completeness, we briefly explore photometrically identified cluster candidates (redMaPPer and CAMIRA systems) in the COSMOS field (see Figure 3) within the redshift range $0.21 < z < 0.58$. Detailed analyses of these systems, including determination of the spectroscopic redshift of the systems and the identification of spectroscopic members of the systems, are beyond the scope of this study. Our goal here is a simple comparison between these photometrically identified systems and COSMOS X-ray systems.

There are five redMaPPer systems (Rykoff et al. 2016) in the COSMOS field (Figure 3): RM 5652, RM 10096, RM 13718, RM 24235, and RM 52747 (IDs from Rykoff et al. 2016). These redMaPPer systems were identified based on a red-sequence detection technique applied to SDSS DR8 photometric data. RM 24235 corresponds to the X-ray system (G11–262) within $1'$. RM 52747 is located between two X-ray systems (G11–145 and G11–160), but the redshifts of the X-ray systems differ from the redshift reported by redMaPPer. The other three systems do not have X-ray counterparts from George et al. (2011) because they are outside of the area where George et al. (2011) identify the X-ray systems. With the larger search area, Gozaliasl et al. (2019) identify all of the redMaPPer systems except RM 52747. In summary, we identify X-ray counterparts for 80% of the redMaPPer systems, slightly lower than the result based on a larger X-ray cluster survey (86%, Sadibekova et al. 2014).

Figure 15 shows the R–v diagrams of the five redMaPPer systems. The redMaPPer member galaxy catalog (Rykoff et al. 2016) provides a photometric membership probability ($P_{mem}$) for each galaxy. We match the redMaPPer member galaxy catalog and the COSMOS galaxy catalog to obtain the redMaPPer membership probability of galaxies in the COSMOS galaxy catalog. The open circles in Figure 15 display the galaxies with spectroscopic redshifts, and the filled circles are the redMaPPer member candidates with $P_{mem} > 0.5$. We determine the central redshifts of the redMaPPer system as the median redshift of the redMaPPer member candidates with $P_{mem} > 0.5$. The dashed line is the system redshift ($z_s$) from the redMaPPer catalog.

There are galaxy overdensities at the redMaPPer centers. The central redshifts of the redMaPPer clusters are fairly well determined, except for one system (RM 52747), which is in a complex field. Similar to the X-ray cluster member candidates, several member candidates with high membership probabilities are not spectroscopic members of the systems. It is interesting that there are a number of spectroscopic members without membership probabilities. These galaxies may be excluded from the redMaPPer membership catalog because they are faint or blue.

The CAMIRA cluster catalog includes 13 candidate systems in the COSMOS field; six systems have X-ray counterparts from George et al. (2011). Gozaliasl et al. (2019) identify X-ray counterparts for eight CAMIRA systems in addition to the six systems with X-ray counterparts from George et al. (2011). Intriguingly, only three CAMIRA systems match redMaPPer systems, although both cluster catalogs were based on a
Figure 15. $R-v$ diagrams of the five redMaPPer systems in the COSMOS field. The labels indicate redMaPPer ID, richness ($\lambda$), the median redshift of the redMaPPer member candidates with $P_{\text{mem}}>0.5$, and the redshift from the redMaPPer catalog (dashed line). The system with a red label has an X-ray counterpart from George et al. (2011). Red filled circles indicate the redMaPPer member candidates with membership probabilities larger than 0.5. Black open circles are the galaxies with spectroscopic redshifts.

Figure 16. $R-v$ diagrams of the 13 CAMIRA candidate systems (Oguri 2014) in the COSMOS field. The labels indicate the central redshift and the corrected richness from the CAMIRA catalog. The systems with red labels have X-ray counterparts from George et al. (2011), and those with blue labels have X-ray counterparts from Gozaliasl et al. (2019). The systems with a redMaPPer ID have a redMaPPer counterpart. Black open circles indicate galaxies with spectroscopic redshifts.
red-sequence technique. The CAMIRA systems without red-
MaPPer counterparts are mostly (80%) systems with z > 0.3.
We examine the R−v diagrams of the 13 CAMIRA systems in Figure 16. Unlike the redMaPPer catalog, the CAMIRA catalog does not provide a membership probability. Thus, we simply use the central redshifts quoted in the CAMIRA catalog to plot the R−v diagram instead of the central redshifts determined based on spectroscopically identified members. The black open circles indicate galaxies with spectroscopic redshifts around the CAMIRA cluster center.

There are galaxy overdensities for some CAMIRA clusters, but the central redshifts from the catalog are often significantly offset from the overdensities in redshift space. We do not see a galaxy overdensity at the suggested cluster center for the systems at z = 0.379, 0.398, 0.554, and 0.574. These systems may be false positives, or the actual system is at a very different redshift.

Previous studies examine the relation between the X-ray luminosity and the richness of optically identified galaxy clusters: Oguri (2014) examine CAMIRA systems, and Hollwood et al. (2018) examine redMaPPer systems. Based on these relations, we expect that three X-ray systems (ID: 011, 120, 220) have a richness larger than 20, suggesting that they are in the photometric catalogs. However, these three systems are missing from the redMaPPer catalog, and only one system (ID 011) is included in the CAMIRA catalog. The two missing X-ray systems are perhaps missing from these catalogs because they are at high redshift (z > 0.72). The system ID 011 is a prominent cluster at z = 0.22, but the redMaPPer algorithm misses it. These differences among the catalogs highlight the challenge of constructing complete catalogs of galaxy systems, even for relatively massive systems.

ORCID iDs
Jubee Sohn https://orcid.org/0000-0002-9254-144X
Margaret J. Geller https://orcid.org/0000-0002-9146-4876
H. Jabran Zahid https://orcid.org/0000-0003-1672-8234
