Groups of Galaxies at Intermediate Redshift

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Abstract

Galaxy groups are key tracers of galaxy evolution, cluster evolution, and structure formation, yet they are difficult to study at even moderate redshift. We have undertaken a project to observe a flux-limited sample of intermediate-redshift ($0.1 < z < 0.5$) group candidates identified by the XBootes Chandra survey. When complete, this project will nearly triple the current number of groups with measured temperatures in this redshift range. Here we present deep Suzaku/XIS and Chandra/ACIS follow-up observations of the first 10 targets in this project; all are confirmed sources of diffuse, thermal emission with derived temperatures and luminosities indicative of rich groups/poor clusters. By exploiting the multi-wavelength coverage of the XBootes/NOAO Deep Wide Field Survey (NDWFS) field, we aim to (1) constrain non-gravitational effects that alter the energetics of the intragroup medium, and (2) understand the physical connection between the X-ray and optical properties of groups. We discuss the properties of the current group sample in the context of observed cluster scaling relations and group and cluster evolution and outline the future plans for this project.

Key words: galaxies: clusters — X-rays: galaxies: clusters — surveys

1. Motivation

Galaxy groups are vital to our understanding of structure formation, cluster evolution, and galaxy evolution. In the local universe, 50%–70% of all galaxies are found in groups (Tully 1987). Under the standard picture of hierarchical structure formation, groups merge to form clusters. Since group masses are relatively low, they are ideal sites in which to observe non-gravitational processes that affect the energetics of the plasma in both groups and clusters (e.g. Balogh 2006). Interactions among group galaxies, as well as interactions between individual galaxies and the group gravitational potential and intragroup medium (IGM), can alter galaxy properties substantially (Mulchaey 2000, Rasmussen et al. 2006).

Groups are difficult to study at even moderate redshifts ($z > 0.1$) because the galaxy overdensity is low and because X-ray luminosities are modest ($L_X \sim 10^{41}$–10^{43} erg s^{-1}). The XBootes Chandra survey (Murray et al. 2005) provides a powerful opportunity for systematic study of more distant groups. The 9.3 deg^2 survey region is almost fully covered by deep optical and near-IR imaging from the NOAO Deep Wide-Field survey (NDWFS; Jannuzi & Dey 1999), by the Spitzer/IRAC Shallow Survey (Eisenhardt et al. 2004), and by optical spectroscopy of over 20,000 galaxies from the AGN and Galaxy Evolution Survey (AGES) and ongoing MMT observations.

We have undertaken a project to observe a flux-limited sample of intermediate-redshift ($0.1 < z < 0.5$) group candidates identified by the XBootes Chandra survey (Kenter et al. 2005). By exploiting the multi-wavelength coverage of the XBootes/NDWFS field, we aim to constrain non-gravitational effects that alter the energetics of the IGM, and to understand the connection between the X-ray and optical properties of groups. Here we present deep Suzaku/XIS and Chandra/ACIS follow-up observations of the first targets in this project.

2. Sample Selection

Of the 43 extended X-ray sources identified by the XBootes survey (see Figure 1), 27 exceed our flux threshold of 2×10^{-14} erg s^{-1} cm^{-2}. For 17 of these sources, we have confirmed the presence of a bound group of galaxies with MMT spectroscopy. The brightest 13 targets of the total sample have been observed (10 groups) or awarded time (3 groups) with either Suzaku or Chandra, depending on the presence of contaminating X-ray point sources. These targets are listed in Table 1. We continue to obtain redshift information for the remaining sample, and additional groups will be proposed for observation in future cycles of Suzaku and Chandra.

Table 1. Group target list and observations

Group	XBootes ID	z	S^a_{14}	Telescope	Date Obs.	ksec
1	CXOXB J143449.0+354301	0.151	4.2	Suzaku	Dec 2007	42
7	CXOXB J143109.1+350609	0.194	4.7	Suzaku	June 2007	42
30	CXOXB J143747.6+333110	0.222	4.1	Suzaku	June 2007	39
2	CXOXB J142900.6+353734	0.234	6.9	Chandra	May 2007	38
26	CXOXB J143615.4+334650	0.342	4.5	Suzaku	June 2007	44
14	CXOXB J143156.1+343806	0.350	4.2	Chandra	Sept 2008	50
24	CXOXB J142916.1+335929	0.131	9.7	Chandra	Nov 2008	25
10	CXOXB J143508.8+350349	0.280	3.3	Chandra	Nov 2008	45
37	CXOXB J142532.9+325644	0.215	2.3	Suzaku	July 2008	40
32	CXOXB J142955.8+331711	0.420	2.7	Suzaku	Feb 2009	40
33	CXOXB J142709.3+331510	0.242	6.3	Chandra	AO10 (awarded)	30
23	CXOXB J142657.9+341201	0.130	22.1	Chandra	AO10 (awarded)	20
39	CXOXB J143113.8+323225	0.278	11.2	Chandra	AO10 (awarded)	50

[a] XBootes survey flux (0.5–2 keV) in units of 10^{-14} erg s^{-1} cm^{-2}

Due to the size and depth of the XBootes survey, this sample of groups fills a niche not covered by other surveys. In general, our groups are poorer/cooler than the clusters found in the larger but shallower ROSAT 400d survey (Burenin et al. 2007). They should be richer than those detected with XMM in the COSMOS survey (Finoguenov et al. 2007). When complete, this project will triple the current number of intermediate-redshift groups with measured temperatures.

3. Observations and Spectral Modeling

We detect extended soft X-ray emission from all 10 observed targets, with 0.5–2 keV fluxes ranging from 3–21 $\times 10^{-14}$ erg s^{-1} cm^{-2}. For some sources this is nearly five times the measured XBootes snapshot flux (given in Table 1), although this is expected from the deeper exposures. Sample images from Suzaku and Chandra are shown in Figures 2 and 3, with the exposure-corrected X-ray emission overlaid on a combined SDSS b, i and Spitzer/IRAC 3.6 μm image. The Suzaku image in Figure 2 contains X-ray point sources; the Chandra image in Figure 3 has been smoothed after point source removal.

The Suzaku/XIS group spectra were extracted from circular apertures of 1 Mpc radius at the group redshift. Point sources brighter than 10^{-14} erg s^{-1} cm^{-2} were masked out. Due to vignetting and non-uniform OBF contamination, the X-ray background was fit simultaneously to a region outside the group aperture. Detector background was corrected using the accumulated Suzaku night Earth background data. The Chandra/ACIS spectra were extracted from a similar aperture, with a nearby region used as the background. Point sources were masked by hand.

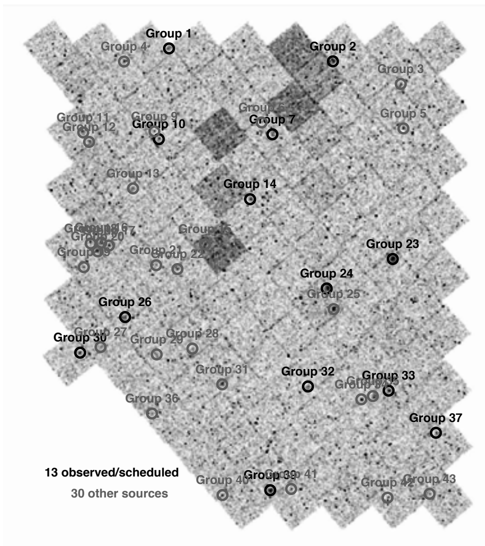

Fig. 1. Counts image mosaic of the original 5 ksec XBootes Chandra snapshot (Kenter et al. 2005). The 13 confirmed groups in our current sample are identified in black, the remaining 30 extended X-ray sources are circled in gray. The image has been smoothed, so some bright point sources appear extended. A handful of fields suffered from high background, leading to the patchy appearance.

The diffuse group emission was modeled using the APEC plasma code with variable temperature and abundance. For all groups, the best-fit kT ranges from 0.7–2.5 keV with abundances of 0.1–0.7 solar. The range of temperatures is illustrated in Figure 4.

4. Initial Results: The L_X-T_X Relation

Scaling relations identify divergence from self-similarity due to non-gravitational effects (pre-collapse heating,

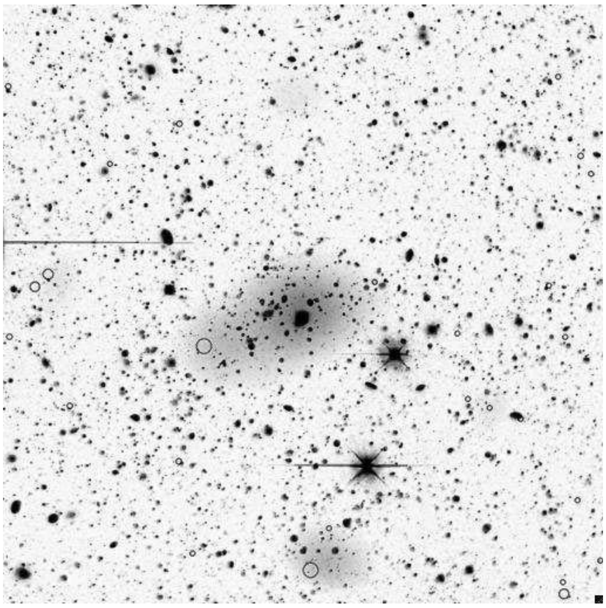

Fig. 2. Image of Group 1 ($z = 0.151$, $kT = 0.67$ keV) showing the SDSS b, i and Spitzer/IRAC 3.6 μm combined image. The Suzaku/XIS X-ray emission is shown as diffuse grayscale. XBootes point sources are identified by open circles; the diffuse group X-ray emission appears extended to the east due to a nearby point source. North is up, and the image is 10 arcmin $\sim$ 1.6 Mpc on a side.

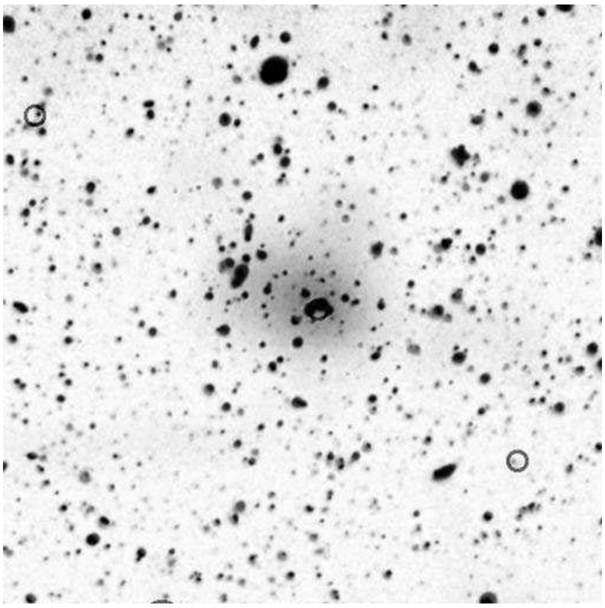

Fig. 3. Image of Group 14 ($z = 0.352$, $kt = 1.45$ keV) showing the SDSS b, i and Spitzer/IRAC 3.6 μm combined image. The Chandra/ACIS X-ray emission is shown as diffuse grayscale. XBootes point sources are identified by open circles; all X-ray point sources have been excluded. North is up, and the image is 5 arcmin $\sim$ 1.5 Mpc on a side.

galactic/AGN feedback, radiative cooling). Evolution in scaling relations at group (rather than cluster) scales is a powerful diagnostic because these non-gravitational effects are more important at smaller mass scales. A small number of groups have been observed at intermediate redshift with XMM-Newton (Willis et al. 2005, Jeltema et al. 2006), and they show little if any evolution in the L_X-T_X scaling relation (see Figure 4). A number of other groups at $z > 0.15$ have measured T_X (Bauer et al. 2002, Grant et al. 2004, Fassnacht et al. 2007), bringing the total to 16, excluding this work. The large intrinsic scatter in the L_X-T_X relation requires a large sample of groups to distinguish between various models. Our full sample will triple the number of groups with measured T_X in this redshift range. The first 10 groups have properties consistent with the observed L_X-T_X relation at $z \sim 0$ (see Figure 4). They lie in a region on the faint end of the cluster population and bright end of the typical group population, similar to the XMM-Newton group samples.

The XBootes group L_X-T_X relation shows a hint of flattening at the low kT end, however systematic effects prevent us from concluding this at the present. No spatial analysis has been completed to extrapolate the group X-ray fluxes out to r_{500}. We expect the aperture correction to be less than 50%, and this will increase the L_X systematically. On the other hand, the Suzaku data suffer from AGN contamination due to the poor spatial resolution. This correction will decrease L_X for the six groups observed with Suzaku.

5. Future Work: Evolution of the Group X-Ray/Optical Connection

Most studies of the properties of groups beyond the local universe rely on X-ray selected samples, since finding the extended X-ray emission indicative of a virialized system is not difficult in surveys with sufficient depth. On cluster scales, it is clear that there are systematic differences in the X-ray properties depending on sample selection method (e.g. Donahue et al. 2001, Lubin et al. 2004, Barkhouse et al. 2006). On group scales ($kT < 3$ keV), only half of optically-selected groups at low redshift are seen to produce X-ray emission (Mulchaey 2000, Rasmussen et al. 2006). This could be due to incomplete gravitational collapse, a shallower potential (and lower X-ray temperature) than expected, or simply a lack of IGM gas, perhaps as a result of feedback from group galaxies to the IGM (Rasmussen et al. 2006). These differences likely result from the details of group formation and the interplay between galaxies and the IGM, but they have been very difficult to understand because we lack appropriate X-ray and optical data on representative group samples beyond the local universe.

We have begun an optical search for groups using AGES and additional MMT spectroscopic galaxy red-

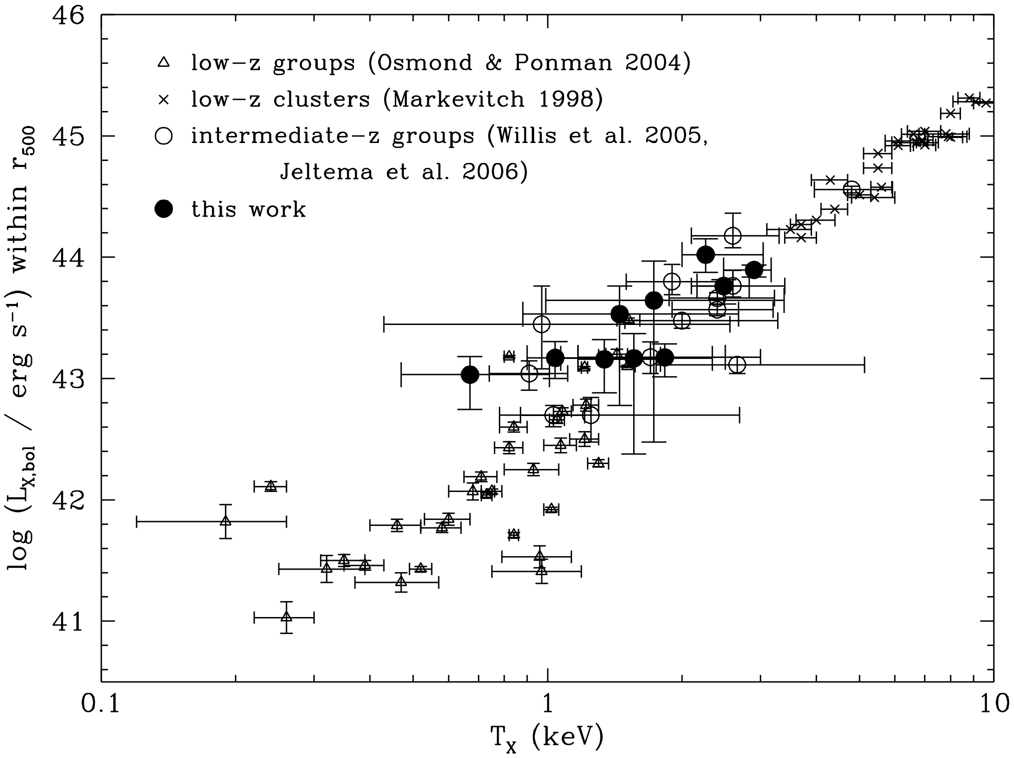

Fig. 4. L_X-T_X relation for our 10 groups, plotted with low-z group and cluster samples and a sample of 11 other intermediate-z groups with measured T_X. The XBootes systems lie in a region of rich groups and poor clusters. No aperture correction has been performed on the XBootes group emission, therefore an additional systematic error of $<$ 50% is possible in $L_{X,\rm bol}$.

shifts. With follow-up data of the full X-ray sample, we will directly compare the properties of optically-selected and X-ray-selected groups, and we will be able to directly compare groups at intermediate redshift to those at $z \sim 0$. This will enhance larger surveys such as the 400d cluster survey (Burenin et al. 2007), which is not sensitive to groups of this mass in this redshift range. It will also complement the deeper COSMOS survey (Finoguenov et al. 2007), which is sensitive to lower mass groups but due to its smaller field detects few groups in this mass range.

In addition to probing the X-ray properties of optically-selected groups, the multi-wavelength coverage of this Bootes field opens the door for additional studies. We will be able to constrain the group velocity dispersion and compare to X-ray mass estimators. With the existing deep, multi-band imaging, we will also investigate the role of environment (local galaxy density, early-type fraction, brightest group galaxy) in determining group X-ray properties (X-ray luminosity, gas temperature).

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