DISCOVERY OF AN X-RAY–LUMINOUS GALAXY CLUSTER AT $z = 1.4^{+1}_{-2}$

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ABSTRACT

We report the discovery of a massive, X-ray–luminous cluster of galaxies at $z = 1.393$, the most distant X-ray–selected cluster found to date. XMMU J2235.3–2557 was serendipitously detected as an extended X-ray source in an archival XMM-Newton observation of NGC 7314. VLT FORS2 R- and $z$-band snapshot imaging reveals an overdensity of red galaxies in both angular and color spaces. The galaxy enhancement is coincident in the sky with the X-ray emission; the cluster red sequence at $R-z = 2.1$ identifies it as a high-redshift candidate. Subsequent FORS2 multiobject spectroscopy unambiguously confirms the presence of a massive cluster based on 12 concordant redshifts in the interval $1.38 < z < 1.40$. The preliminary cluster velocity dispersion is $762 \pm 265$ km s$^{-1}$. VLT ISAAC $K_s$- and $J$-band images underscore the rich distribution of red galaxies associated with the cluster. Based on a 45 ks XMM-Newton observation, we find that the cluster has an aperture-corrected unabsorbed X-ray flux of $f_x = (3.6 \pm 0.3) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, a rest-frame X-ray luminosity of $L_x = (3.0 \pm 0.2) \times 10^{44} h_{70}^{-2}$ ergs s$^{-1}$ (0.5–2.0 keV), and a temperature of $kT = 6.0^{+1.2}_{-1.0}$ keV. Though XMMU J2235.3–2557 is likely the first confirmed $z > 1$ cluster found with XMM-Newton, the relative ease and efficiency of discovery demonstrates that it should be possible to build large samples of $z > 1$ clusters through the joint use of X-ray and large ground-based telescopes.

Subject headings: galaxies: clusters: general — X-rays: general

1. INTRODUCTION

There is a strong impetus in astronomy to discover and investigate objects at ever-increasing redshifts in order to probe the state of the universe at increasingly earlier stages of cosmic history. Such observations allow us to construct evolutionary sequences that ultimately reveal the underlying mechanisms and parameters that define the universe. The high-redshift push is acutely applicable to the study of galaxy clusters. Their density evolution and distribution on large scales are very sensitive to the cosmological framework. Furthermore, clusters play a key role in tracking the formation and evolution of massive early-type galaxies. It is important to recognize that the leverage on both the derived cosmological parameters and the efficacy of evolutionary studies is greatly enhanced as we probe to higher redshifts.

X-ray selection is currently the optimal technique for constructing large, well-defined samples of distant clusters (see review by Rosati et al. 2002). However, infrared large-area surveys may well become a complementary approach (e.g., Eisenhardt et al. 2004). The present status of X-ray cluster samples is due in large part to numerous ROSAT-based surveys. We now have definitive local samples ($z \approx 0.3$) totaling ~1000 clusters (e.g., REFLEX; Böhringer et al. 2004) and high-redshift samples totaling a few hundred clusters (e.g., 160SD; Vikhlinin et al. 1998; Mullis et al. 2003). Galaxy clusters are routinely discovered at $z > 0.5$, and occasionally at $z > 0.8$. However, the $z > 1$ domain has been largely unexplored. Only five X-ray–emitting clusters are known here (Stanford et al. 1997; Rosati et al. 1999; Stanford et al. 2002; Rosati et al. 2004; Hashimoto et al. 2004), four of which are from the ROSAT Deep Cluster Survey of Rosati et al. (1998).

It is now possible to redress the lack of knowledge of galaxy clusters at $z > 1$ using XMM-Newton, which features unprecedented sensitivity, high angular resolution, and wide-field coverage. Several general surveys are under way (e.g., Romer et al. 2001; Pierre et al. 2004; Schwope et al. 2004). We briefly describe here the first high-redshift discovery resulting from our pilot program, which is specifically focused on the identification of $z > 1$ galaxy clusters using XMM-Newton.

2. X-RAY SELECTION AND ANALYSIS

We have initiated a search for distant, X-ray–luminous clusters through the serendipitous detection of extended X-ray emission in archival XMM-Newton observations with exposure times greater than 20 ks. Our ultimate objective is to construct an X-ray–flux–limited sample of tens of galaxy clusters at $z \geq 1$. A more immediate goal has been to develop a rapid and efficient observational strategy to identify the most distant systems ($z > 1$). One of the noteworthy objects identified in our initial test fields is XMMU J2235.3–2557, which was detected in a 45 ks XMM-Newton observation of the Seyfert 1.9 galaxy NGC 7314. The source is located at 7:7 off-axis in the observation, recorded on 2001 May 2 (observation ID 0111790104). As demonstrated by the X-ray flux contours in Figure 1, this source is extended on arcminute scales and is clearly resolved in comparison with the prominent X-ray point source to the northwest and 2:3 farther off-axis. The X-ray centroid of XMMU J2235.3–2557 in J2000 equatorial coordinates is $\alpha = 22^h 35^m 20^s.6, \delta = -25^\circ 57' 42",$ which corresponds to a Galactic latitude of $b = -59^\circ 6'$. Extended X-ray sources at high Galactic latitudes are almost exclusively galaxy clusters.

Our X-ray analysis is restricted to the two EPIC MOS detectors, since the EPIC pn detector was operated in small-
Fig. 1.—Galaxy cluster XMMU J2235.3–2557, at $z = 1.393$. Left: VLT FORS2 $R$-band image (1140 s) overlaid with X-ray contours from a 45 ks XMM-Newton observation. The 0.5–2.0 keV X-ray image from the EPIC M1+M2 detectors has been smoothed with a 4$''$ Gaussian kernel; eight logarithmically spaced contours are drawn between 0.2 counts and 1 count per 2$''$ pixel. The prominent X-ray point source northwest and 2.3 farther off-axis than the cluster is a Seyfert 2 galaxy at $z = 0.4060$. Right: VLT ISAAC $K_s$ image (3600 s) overlaid with the same X-ray contours. Spectroscopically confirmed members ($1.38 < z < 1.40$) are marked in red. Two galaxies at $1.37 < z < 1.38$ are marked in orange. In both panels, circles indicate absorption-line galaxies and triangles indicate emission-line galaxies.

Fig. 2.—Color image of XMMU J2235.3–2557 overlaid with the same X-ray contours as in Fig. 1. The red channel is an ISAAC $K_s$-band image (3600 s), the green channel is a FORS2 $z$-band image (480 s), and the blue channel is a FORS2 $R$-band image (1140 s).
window mode to avoid pileup from NGC 7314 and thus did not image the location of XMMU J2235.3−2557. The available data are equivalent to a ∼22.5 ks observation with all three detectors. An effective integration time of 38 ks remains after screening periods of high background. Counts were extracted from a 50′′ radius circular region centered on the source; the background was estimated locally using three source-free circular apertures (r = 60′′−120′′) flanking XMMU J2235.3−2557. There are 280 net source counts in the 0.3–4.5 keV band for the combined MOS detectors (M1 + M2). This corresponds to an unabsorbed aperture flux of (2.6 ± 0.2) × 10^{-14} ergs cm^{-2} s^{-1} in the 0.5–2.0 keV energy band, modeling the source with a 6 keV thermal spectrum (details in § 4). Measurement errors are given at the 68% confidence interval (1σ) throughout.

XMMU J2235.3−2557 was also serendipitously detected in a ROSAT Position Sensitive Proportional Counter observation (1WGA J2235.3−2557; White et al. 1994). The ROSAT flux of (2.4 ± 0.4) × 10^{-14} ergs cm^{-2} s^{-1} (0.5–2.0 keV) is in excellent agreement with our XMM-Newton result. This source was not followed up by the ROSAT-era cluster surveys, because its extent is poorly constrained by ROSAT data and its flux is fainter than most survey flux limits.

3. OPTICAL FOLLOW-UP OBSERVATIONS

To reject the possibility of a relatively low redshift cluster (z ≲ 0.4–0.5), we examined the location of XMMU J2235.3−2557 in the second-epoch Digitized Sky Survey and found the region to be devoid of any galaxy overdensity. To further constrain the redshift in an efficient manner, we acquired relatively short exposure images in the R (1140 s) and z (480 s) bands using VLT FORS2 on 2003 October 2. These images, combined with a subsequently obtained deep VLT ISAAC Ks-band image (3600 s, 2004 December 9–11), are shown as a 2.5′ × 2.5′ color composite in Figure 2. The Rz discovery imaging reveals a significant overdensity of faint, very red galaxies spatially coincident with the extended X-ray emission. Note that the brightest cluster galaxy (BCG) has an extended surface brightness profile typical of massive cluster cD galaxies.

We plot in the top panel of Figure 3 the optical/near-IR color-magnitude diagram of the galaxies detected in the 7′ × 7′ z-band image. The central cluster galaxies clearly delineate the bright end of the cluster red sequence at a color of R−z = 2.1. Given a realistic galaxy model, we can use the location of the red sequence as a reliable distance indicator (see, e.g., Kodama & Arimoto 1997; Gladders & Yee 2000). Assuming that cluster ellipticals form by means of monolithic collapse at z ≈ 3 and then passively evolve to the observed redshift (e.g., Daddi et al. 2000), we derive a color-redshift transformation, indicated on the right axis of the color-magnitude diagram. Thus the observed red-sequence color of XMMU J2235.3−2557 corresponds to a redshift of z ∼ 1.4.

To confirm this very high redshift estimate, we obtained spectroscopic data from two FORS2 MXU multiobject slit masks observed on 2004 October 11 and 15. The result of a 4 hr integration on the BCG is shown in the middle panel of Figure 3. We measure 12 secure redshifts in the range 1.38 < z < 1.40, with ⟨z⟩ = 1.393 and a preliminary velocity dispersion of 762 ± 265 km s^{-1}, corrected for cosmological expansion (see Fig. 3, bottom). These spectroscopically confirmed cluster members are marked in red in Figures 1 and 3.

4. DISCUSSION

Here we address a few fundamental characteristics of XMMU J2235.3−2557 based on the discovery data sets. Be-
suggest that XMMU J2235.3 (Fig. 3). Note that there are two galaxies at ,1.37
corridor. However, the alignment of the BCG–X-ray offset line with the
deep X-ray data and additional spectroscopy are available. We must be cautious with our interpretation until
southeast line. We must be cautious with our interpretation until
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Note that this asymmetry is exaggerated in the confirmed mem-
bers because of the bias inherent to the design of the spec-
troscopy slit masks, which were based on the relatively shallow
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XMMU J2235.3 2557 is fairly isolated in redshift space (Fig. 3). Note that there are two galaxies at 1.37 < z < 1.38,
shown in orange in Figures 1 and 3. One of these (z = 1.379)
just outside the formal 3σ velocity boundary defining cluster membership (1.38 < z < 1.40). Both galaxies are close in pro-
jection to the cluster core and likely part of the local structure
field immediately surrounding the main cluster. The five gal-
exes at 1.35 < z < 1.37 are roughly situated along a decli-
nation band 2:5 south of the cluster. Four of these fall within a 1.7 diameter circle, but there is no significant X-ray emission
in this region.

5. CONCLUSIONS

XMMU J2235.3 2557 (z = 1.393) is the most distant
X-ray–selected cluster thus far discovered. Based on its high
X-ray luminosity, ICM temperature, and optical/near-IR rich-
ness, this galaxy cluster is very likely the most distant and most
massive (z > 1) structure known to date. It provides an un-
precedented opportunity to test models of the evolution and
formation of the most massive galaxies and clusters in high-
density environments at the largest look-back time currently
accessible. Fundamental to this pursuit are high-quality data
sets including wide infrared coverage, high-resolution imaging
from space, optical spectroscopy, and dedicated X-ray follow-
up.

A remarkable and exciting aspect of the discovery of XMMU
J2235.3 2557 is the overall efficiency of telescope use from
first detection to spectroscopic confirmation. Our experience
demonstrates that (1) a massive, z = 1.4 cluster is easily de-
tectable in a typical XMM-Newton observation of 20 ks and
(2) the red cluster sequence provides a reliable distance indi-
cator (out to at least z = 1.4) that can be measured in less than
30 minutes with a red-sensitive CCD on an 8 m class telescope.
In the search for z > 1 clusters, the second point is crucial for
rejecting the large number of foreground clusters and econo-
mizing the costly optical follow-up. Given the relative ease of
discovery, we predict that the detection of z > 1 clusters will
become routine in the near future.

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