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# 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 over-density 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 $R - z \simeq 2.1$ identifies it as a high-redshift candidate. Subsequent VLT-FORS2 multi-object 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 $Ks$ 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 the cluster has an aperture-corrected, unabsorbed X-ray flux of $f_{\rm X} = (3.6 \pm 0.3) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, a rest-frame X-ray luminosity of $L_{\rm X} = (3.0 \pm 0.2) \times 10^{44}\ h_{70}^{-2}$ ergs s$^{-1}$ (0.5–2.0 keV), and a temperature of $kT = 6.0^{+2.5}_{-1.8}$ 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 which 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, Borgani, & Norman 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 ($z \lesssim 0.3$) totaling $\sim$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 were 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 RDCS 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 underway (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 >20 ks. Our ultimate objective is to construct an X-ray flux-limited sample of tens of galaxy clusters at $z \gtrsim 1$. 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 is 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 2 May 2001 (obsid 0111790101). As demonstrated by the X-ray flux contours in Figure 1, this source is extended on arcminute scales and is clearly resolved in comparison to the prominent X-ray point source to the north-west and 2.3′ further off-axis. The X-ray centroid of XMMU J2235.3–2557 in equatorial coordinates

[1] Based on observations obtained with *XMM-Newton*, an ESA mission with contributions from NASA

[2] Based on observations obtained at the European Southern Observatory using the ESO Very Large Telescope on Cerro Paranal (ESO programs 72.A-0706, 73.A-0737, 74.A-0023 and 274.A-5024)

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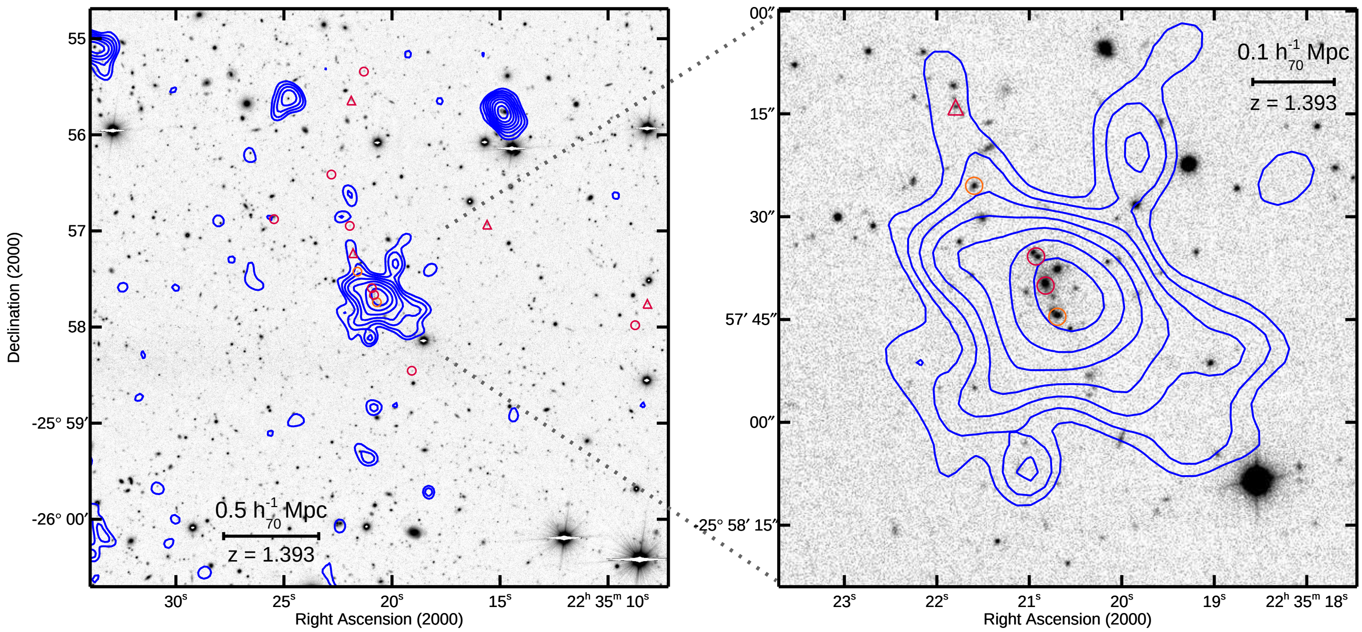


FIG. 1.— Galaxy cluster XMMU J2235.3–2557 at $z = 1.393$ — *Left:* VLT-FORS2 $R$-band image (1140s) overlaid with X-ray contours from a 45 ks *XMM-Newton* observation. The 0.5–2.0 keV X-ray image from the EPIC M1+M2 detectors has been smoothed with a 4″ Gaussian kernel; eight logarithmically-spaced contours are drawn between 0.2 and 1 count per 2″ pixel. The prominent X-ray point source north-west and 2.3′ further off-axis than the cluster is a Seyfert 2 galaxy at $z = 0.4060$. *Right:* VLT-ISAAC $Ks$ image (3600s) 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 cases circles indicate absorption line galaxies and triangles indicate emission line galaxies.

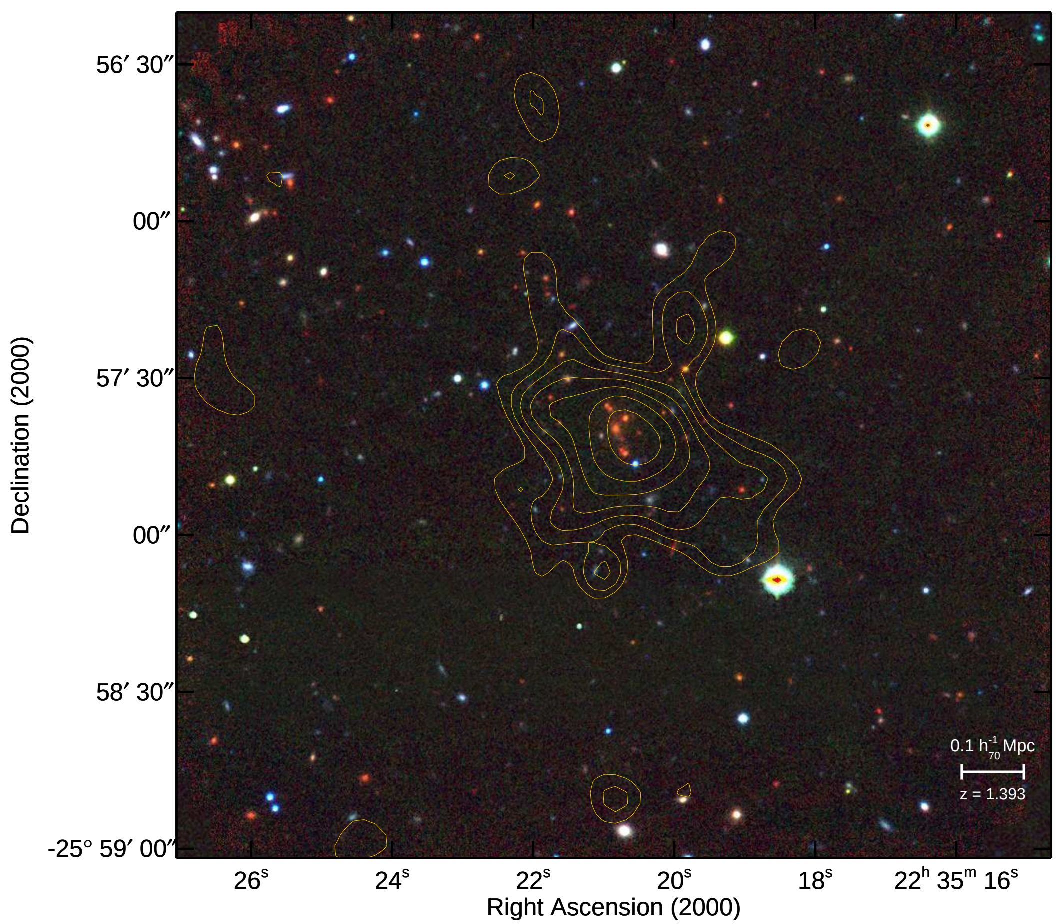


FIG. 2.— Color image of XMMU J2235.3–2557 overlaid with the same X-ray contours as Figure 1. The red channel is a VLT-ISAAC $Ks$ image (3600s); the green channel is a VLT-FORS2 $z$-band image (480s); the blue channel is a VLT-FORS2 $R$-band image (1140s).

is $\alpha_{\rm J2000.0} = 22^{\rm h}35^{\rm m}20.6^{\rm s}, \delta_{\rm J2000.0} = -25°57^{\rm m}42^{\rm s}$ which corresponds to a Galactic latitude of $b = -59.6°$. 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 window mode to avoid pile-up and to permit rapid variability observations of 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 $(2.6 \pm 0.2) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2.0 keV energy band modeling the source with a 6 keV thermal spectrum (details presented in § 4). Measurement errors are given at the 68% confidence interval ($1\sigma$) throughout.

XMMU J2235.3–2557 was also serendipitously detected in a *ROSAT* PSPC observation (1WGA J2235.3-2557; White et al. 1994). The *ROSAT* flux of $(2.4 \pm 0.4) \times 10^{-14}$ 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 ($z \lesssim 0.4 - 0.5$), we examined the location of XMMU J2235.3–2557 in the second epoch Digitized Sky Survey and found the region devoid of any galaxy overdensity. To further constrain the redshift in an efficient manner, we acquired relatively short-exposure images in the $R$ (1140s) and $z$ (480s) bands using VLT-FORS2 on 2 October 2003. These images, combined with a subsequently obtained deep VLT-ISAAC $Ks$-band image (3600s, 9–11 December 2004), are shown as a $2.5' \times 2.5'$ color composite in Figure 2. The $Rz$ discovery imaging reveals a significant over-density of faint, very red galaxies spatially coincident with the peak of the extended X-ray emission. Note that the brightest cluster galaxy (BCG) has an extended surface brightness profile typical of massive cluster cDs.

We plot in the top panel of Figure 3 the optical/NIR color-magnitude diagram of the galaxies detected in the $7' \times 7'$ $z$-band image. The central cluster galaxies clearly delineate the bright end of the cluster red sequence at a color of $R - z \simeq 2.1$. Given a realistic galaxy model, we can use the location of the red sequence as a reliable distance indicator (e.g., Kodama & Arimoto 1997; Gladders & Yee 2000). Assuming cluster ellipticals form via monolithic collapse at $z \approx 3$ and then passively evolve to the observed redshift (e.g., Daddi, Cimatti, & Renzini 2000), we derive a color-redshift transformation indicated on the right-side ordinate of the color-magnitude diagram. Thus the observed red sequence color of XMMU J2235.3–2557 corresponds to a redshift of $z \sim 1.4$.

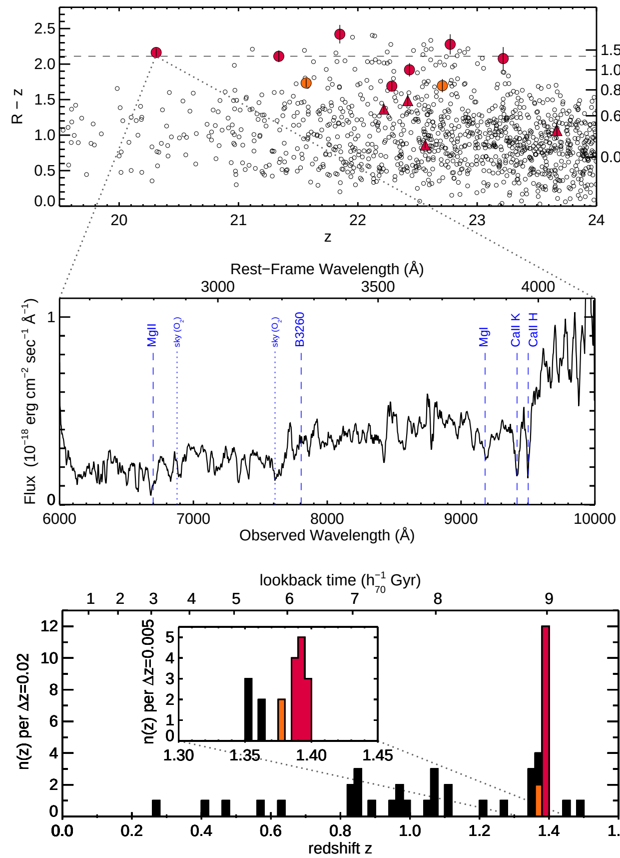


FIG. 3.— *Top:* Color-magnitude diagram of the $7' \times 7'$ field around XMMU J2235.3–2557. Spectroscopically confirmed cluster galaxies ($1.38 < z < 1.40$) are highlighted in red; two galaxies at $1.37 < z < 1.38$ in orange (circle: absorption line gal.; triangle: emission line gal.). The horizontal line indicates the predicted color of a $z = 1.393$ cluster elliptical. *Middle:* VLT-FORS2 spectrum of the brightest cluster galaxy ($z = 1.3943 \pm 0.0003$, 4 hr integration). *Bottom:* Histogram of galaxy redshifts measured in the VLT-FORS2 MXU observations of the $7' \times 7'$ region around XMMU J2235.3–2557 (same color scheme as above).

To confirm this very high redshift estimate, we obtained spectroscopic data from two VLT-FORS2 MXU multi-object slit-masks observed on 11 & 15 October 2004. The result of a four-hour 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 $762 \pm 265$ km s$^{-1}$, corrected for cosmological expansion (see histogram in bottom panel of Figure 3). These spectroscopically confirmed cluster members are marked in red in Figures 1 & 3.

## 4. DISCUSSION

Here we address a few fundamental characteristics of XMMU J2235.3–2557 based on the discovery datasets. Due to the space limitations of this Letter, we must defer a broad and in-depth discussion to a forthcoming paper. At $z = 1.393$ this cluster is the most distant bona-fide X-ray luminous cluster known to date, and it lies well beyond the redshift range ($z = 1.0 - 1.27$) of the only 5 previously known distant X-ray clusters (all from *ROSAT*).

Note that by advancing to $z = 1.4$, we can now look 0.5 Gyr further back compared to the previous limit. This is quite significant given the relevant formation time scales ($1-3$ Gyrs) for the stellar populations in massive cluster galaxies.

With the cluster redshift in hand, we can derive additional X-ray properties of XMMU J2235.3–2557. We estimate the temperature of the intra-cluster medium via a joint fit to the M1+M2 spectra over the 0.3–4.5 keV energy range. Assuming a thermal model (MEKAL) with a metallicity of 0.3 solar, a Galactic absorption column of $n_{\rm H} = 1.47 \times 10^{20}$ cm$^{-2}$ and fixing the cluster redshift at $z = 1.393$, we find $kT = 6.0^{+2.5}_{-1.8}$ keV. As noted in § 2, the cluster flux within a 50″ radius aperture based on this model is $(2.6 \pm 0.2) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–2.0 keV). At the cluster redshift this aperture corresponds to a physical radius of 421 $h_{70}^{-1}$ kpc. If the cluster emission profile follows the typical King profile with a slope of $\beta = 0.7$ and a core radius of 140 $h_{70}^{-1}$ kpc, then the photometry aperture encloses 74.9% of the flux. Thus the total flux is $(3.6 \pm 0.3) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ and the cluster rest-frame luminosity is $(3.0 \pm 0.2) \times 10^{44}$ $h_{70}^{-2}$ ergs s$^{-1}$ (0.5–2.0 keV). This high X-ray luminosity and the high rate of spectroscopic identification (high richness) suggest that XMMU J2235.3–2557 is likely more massive than RDCS1252–29 (previously the most massive, distant cluster known at $z = 1.24$).

Examining the projected distribution of red galaxies, those with colors similar to the spectroscopically confirmed cluster members, we see in general that there is a higher density of objects to the north of the cluster core versus to the south. Note this asymmetry is exaggerated in the confirmed members due to bias inherent to the design of the spectroscopy slitmasks which were based on the relatively shallow $Rz$ discovery images. For example, an ∼30″ band of right ascension beginning ∼15″ south of the X-ray peak was undersampled due to the dithering pattern required to fill the gap between the FORS2 CCDs. The BCG and X-ray centroid are offset by 3.7″, or 31 $h_{70}^{-1}$ kpc at the cluster redshift, along a northwest-southeast vector. We must be cautious with our interpretation until deeper X-ray data and additional spectroscopy are available. However, the alignment of the BCG–X-ray offset vector with the northwest/southeast spurs in the X-ray morphology and the filament of red galaxies leading out of the core to the northeast may indicate a recent subcluster merger along this corridor.

XMMU J2235.3–2557 is fairly isolated in redshift space (Figure 3). Note that there are two galaxies at $1.37 < z < 1.38$ shown in orange in Figures 1 & 3. One of these ($z = 1.379$) is just outside the formal $3\sigma$ velocity boundary defining cluster membership ($1.38 < z < 1.40$). Both galaxies are close in projection to the cluster core and likely part of the local structure field immediately surrounding the main cluster. The five galaxies at $1.35 < z < 1.37$ are roughly situated along a declination 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/NIR richness, this galaxy cluster is very likely the most distant and most massive ($z > 1$) structure known to date. It provides an unprecedented 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 datasets including wide infrared coverage, high-resolution imaging from space, optical spectroscopy & 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: 1) a massive, $z = 1.4$ cluster is easily detectable in a typical *XMM-Newton* observation of ∼20 ks, and 2) the red cluster sequence provides a reliable distance indicator (out to at least $z = 1.4$) which can be measured in less than 30 minutes with a red-sensitive CCD on an 8m-class telescope. In the search for $z > 1$ clusters, the second point is crucial for rejecting the large number of foreground clusters and economizing the costly optical follow-up. Given the relative ease of discovery, we predict the detection of $z > 1$ clusters will become routine in the near future.

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