LETTER TO THE EDITOR

Discovery of the X-ray selected galaxy cluster XMMU J0338.8+0021 at z = 1.49*

Indications for a young system with a forming brightest galaxy

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ABSTRACT

We report on the discovery of a galaxy cluster at z = 1.490 originally selected as an extended X-ray source in the XMM-Newton Distant Cluster Project. Further observations carried out with the VLT-FORS2 spectrograph allowed the spectroscopic confirmation of seven secure cluster members, providing a median system redshift of z = 1.490±0.009. The color magnitude diagram of XMMU J0338.8+0021 reveals the presence of a well populated red sequence with z − H ≈ 3, albeit with an apparent significant scatter in color. Since we do not detect indications for strong star formation activity in any of the objects, the color spread could indicate different stellar ages of the member galaxies. In addition, we found the brightest cluster galaxy in a very active dynamical state, with an interacting, merging companion located at a physical projected distance of d ≈ 20 kpc. From the X-ray luminosity we estimate a cluster mass of M(200) ≈ 1.2 × 10^{14} M_\odot. The data seem to suggest a scenario in which XMMU J0338.8+0021 is a young system, possibly caught in a moment of active ongoing mass assembly.

Key words. galaxies: clusters: general – X-rays: general

1. Introduction

The search for distant (z > 0.8) galaxy clusters has experienced a remarkable boost recently. By means of various selection methods, several clusters have been found in the redshift desert, at z ≥ 1.5. [Papovich et al. 2010] and [Tanaka et al. 2010] independently reported on a new IRAC selected cluster at z = 1.62, characterized by a well populated and tight red sequence.

Further multi-band analysis revealed that the star formation activity in this cluster increases with the environment density, with star forming galaxies being mainly localized in the center of the system [Tran et al. 2010]. An analogous trend has been observed in three other X-ray selected galaxy clusters, two newly confirmed at z = 1.56 [Fassbender et al. 2011] and z = 1.58 [Santos et al. 2011] and one at z = 1.46 [Hilton et al. 2009, 2010]. For these systems, however, the galaxy red sequence is not fully established yet, revealing that the members are still building their stellar mass via star formation activity. The situation is different in clusters found so far at z < 1.4, where active star forming galaxies preferentially reside in the cluster outskirts (e.g. Bolagh et al. 2004, Lidman et al. 2008, Patel et al. 2009). However, it is expected that more distant galaxy clusters exhibit a larger number of star forming galaxies in their central regions (e.g. Hopkins et al. 2008, Rettura et al. 2010). In addition, early-type galaxies (ETG) in clusters are known to have completed the formation of their stellar populations much faster with respect to ETG in the field and the red sequence is expected to fade by z ≈ 2 [Gobat et al. 2008]. The latter prediction is consistent with the recent results in [Gobat et al. 2011], where the discovery of the most distant cluster known to date, at z = 2.07, is reported. In this system the population of passive galaxies shows a very large intrinsic scatter in the Y − K_s colour, with an apparent absence of an established red sequence. This suggests that observations are now approaching the early stages of galaxy formation in the densest environments.

All these new findings highlight the importance to detect new distant galaxy cluster study targets for a syste-
mantic investigation of those processes which drive galaxy evolution in different environments.

In this Letter we report on the discovery of an X-ray selected, spectroscopically confirmed galaxy cluster at $z=1.490$, found within the XMM-Newton Distant Cluster Project (XDCP). We first present the X-ray data (§2.1) followed by a discussion of the near-infrared (NIR) imaging observations (§2.2) and the optical spectroscopy results (§2.3). In Section 3 we will discuss the dynamical state of the system and its galaxy population. Finally, a summary and conclusions are reported in §4.

For this paper, we assume a concordance ΛCDM cosmology, with $H_0 = 70$ km/s, $\Omega_M = 0.7$, $\Omega_{\Lambda} = 0.3$ and $w = -1$. For the given cluster redshift, the angular scale is 8.46 kpc/″. Magnitudes are given in the Vega system.

2. Observations, data analysis, and results

The cluster XMMU J0338.8+0021 (hereafter X0338) was discovered within the XMM-Newton Distant Cluster Project (XDCP), a serendipitous archival X-ray survey focussed on the identification of X-ray luminous systems at $z > 0.8$ (e.g. Mullis et al. 2005; Böhringer et al. 2005; Fassbender 2007; Fassbender et al. 2011).

2.1. X-ray selection with XMM-Newton

The X-ray source associated with the cluster X0338 was initially observed in 2002, in the XMM-Newton field with observation identification number (OBSID) 0036540101 targeting the quasar SDSS033829.31+002156 ($z = 5.02$) with a nominal exposure time of 22.9 ksec. It was detected as weak source with SAS v6.5 at an off-axis angle of 5.6′, with a source significance of about 5σ and an extent significance of about 2.5σ.

We have reprocessed the field with SAS v10.0 for a more accurate source characterization. After applying a strict two-step flare cleaning process for the removal of high background periods, a clean net exposure time of 16.4/15.9 ksec remained for the two EMOS cameras and 7.8 ksec for the PN instrument. Figure 1 shows log-spaced X-ray contours (blue/cyan) of the cluster environment with significance levels of 2-16σ derived from the adaptively smoothed combined images. For the flux measurement we applied the growth curve analysis (GCA) method of Böhringer et al. (2000) in the soft 0.5-2 keV band and measured $L_{X,500} \sim (3.0 \pm 1.8) \times 10^{45}$ erg/s in a 30″ ($\simeq R_{500}$) aperture. At the cluster redshift, this translates into a 0.5-2 keV X-ray luminosity of $L_{X,500} \sim (4.1 \pm 2.4) \times 10^{44}$ erg/s. Owing to the faintness of the source at the limit of detectability, with $\sim 33$ net counts within an aperture of 24″, the determination of additional structural or spectral parameters is currently not feasible and the extended nature of the source is tentative. However, based on the $M-L_X$ scaling relation in Pratt et al. (2009), with a modified redshift evolution (Fassbender et al. 2011; Reichert et al., submitted), a first rough estimate of the expected temperature ($T_X^{est}$) and mass ($M_{500}$) can be obtained, with $T_X^{est} \sim 2.5$ keV and $M_{500} \sim 2.7 \times 10^{14} M_{\odot}$.


2.2. Near-infrared follow-up imaging

X0338 was photometrically confirmed as a significant overdensity of very red galaxies coincident with the X-ray position using the wide-field (15.4′×15.4′) near-infrared (NIR) camera OMEGA2000 at the Calar Alto 3.5m telescope (Bailer-Jones et al. 2000). We obtained medium-deep H-band (50 min) and z-band (53 min) images of the X0338 field on January 5, 2006 under good, but non-photometric, conditions with a seeing of 1.2″. A single MXU exposure (5 min) on December 2009 (program ID:84.A-0844) with seeing 0.7″−1.1″ was observed with the FORS2-VLT spectrograph on December 2009 (program ID:84.A-0844) with seeing conditions varying between 0.7″and 1.1″. A single MXU exposure on January 5, 2006 under good, but non-photometric, conditions varying between 0.7″−1.1″ was observed with the FORS2-VLT spectrograph.

3. Spectroscopic analysis

3.1. Data reduction

X0338 was observed with the FORS2-VLT spectrograph on December 2009 (program ID:84.A-0844) with seeing conditions varying between 0.7″and 1.1″. A single MXU exposure on January 5, 2006 under good, but non-photometric, conditions varying between 0.7″−1.1″ was observed with the FORS2-VLT spectrograph.

Table 1. Main properties of XMMU J0338.8+0021

| RA       | DEC      | z        |
|----------|----------|----------|
| 03:38:49.5 | +00:21:08.1 | 1.490±0.009 |
| \(f_X(0.5−2\text{keV})\) | (3.0±1.8)×10\(^{-14}\)erg s\(^{-1}\) cm\(^{-2}\) | |
| \(L_X(0.5−2\text{keV})\) | (4.1±2.4)×10\(^{43}\)erg s\(^{-1}\) | |
| \(T_X^\text{bol}\) | (1.1±0.6)×10\(^{44}\)erg s\(^{-1}\) | |
| \(M_X,200\) | \(1.2×10^{14}M_\odot\) | |
| \(R_{200}\) | \(590\text{kpc}\) | |
| \(T_X^\text{core}\) | \(2.5\text{keV}\) | |

Fig. 2. Top: Color-magnitude diagram of the cluster field. All galaxies with \(D_{\text{proj}} \leq 30''\) are displayed in red. The seven secure spectroscopic cluster members are marked by black squares (with blue dots for \(D_{\text{proj}} > 30''\)) and are all located within a color range \(2.6 \leq z − H \leq 3.5\) (green dotted lines), with an average color of \(z − H \sim 3\). The interlopers found in the above color cut are marked by black crosses. Two simple stellar population (SSP) models for \(z < 1\) were calculated and are displayed in Fig. 2 (bottom). The stars are shown in red while the black crosses indicate the apparent magnitude of passively evolving galaxies at \(z = 1\).5 with absolute magnitude of \(M^*+1.3\) in \(H\) and \(M^*\) in \(z\). Figure 2 (left) shows an H-band image of the cluster field (4.5″×4.5″), with overlaid X-ray contours (blue), density contours of color selected galaxies with \(2.6 \leq z − H \leq 3.5\) (red), and marked spectroscopic cluster members (small black circles). A zoom onto the core region is shown in Fig. 2 (right). The \(z − H\) versus \(H\) color magnitude diagram (CMD) of the field is shown in Fig. 2 (top).
Fig. 3. 1-D spectra of the seven confirmed members of XMMU J0338.8+0021, smoothed with a 7 pixel boxcar filter. For each spectrum, an identification label (ID) and the measured redshift is reported. For the brightest component of the BCG (ID:1-A) the same LRG spectrum template used in Fig. 2 (bottom) is overlaid in blue for comparison. In red, the sky features in absorption (top) and emission (bottom) are shown. The position of the main spectral features, shifted according to the corresponding redshift values, are marked by the vertical dashed lines.

Table 2. Properties of spectroscopic members of XMMU J0338.8+0021

| ID  | RA    | DEC    | z      | σz   | Projected Distance (arcsec) | Projected Distance (kpc) | H (Vega) | z−H (Vega) | Main spectral features                  |
|-----|-------|--------|--------|------|-----------------------------|--------------------------|----------|------------|----------------------------------------|
| 1-A | 03:38:48.048 | +00:21:38.06 | 1.5031 | 0.0006 | 20.8                        | 175.8                    | 18.25    | 3.30       | MgII, FeII, CaH/K                      |
| 5   | 03:38:49.159 | +00:21:32.77 | 1.5024 | 0.0005 | 24.9                        | 210.5                    | 20.19    | 2.97       | MgII, FeII, CaK                       |
| 7   | 03:38:50.483 | +00:21:55.65 | 1.4976 | 0.0007 | 49.8                        | 421.4                    | 19.17    | 2.81       | MgII, FeII (weak), [OII] (weak)        |
| 6   | 03:38:48.449 | +00:21:45.78 | 1.4899 | 0.0006 | 40.4                        | 341.9                    | 19.49    | 3.54       | FeII, CaH/K                           |
| 4   | 03:38:49.286 | +00:21:20.43 | 1.4788 | 0.0013 | 12.6                        | 106.7                    | 19.53    | 2.84       | CaH/K                                  |
| 11  | 03:38:52.357 | +00:22:43.76 | 1.4736 | 0.0005 | 104.9                       | 887.7                    | 19.04    | 2.94       | MgII, [OII] (weak), [NeIII], CaH/K     |
| 14  | 03:38:46.998 | +00:23:27.98 | 1.4730 | 0.0007 | 144.5                       | 1222.2                   | 19.66    | 3.33       | MgII, [OII] (weak), CaH/K             |

A total of 45 1-dimensional spectra were obtained, with a final calibration uncertainty of ~1 Å.

3.2. Redshift measurements

In order to assess the redshift for each extracted spectrum, the graphical VIPGI tools were initially used for a quick visual inspection. Then, the EZ software (Garilli et al. 2010) and the RVSAO/IRAF package were also used with a set of different galaxy spectra templates. The analysis confirmed the existence of seven galaxies with concordant redshifts in the range 1.473 ≤ z ≤ 1.503, six of which with a projected slit-mask (field of view 6.8′ × 6.8′) with a total of 42 1″ width slits was used. The chosen instrument setup with the 300I grism without blocking filter provides a wavelength coverage of 5800 – 10500 Å, with a resolution of R = 660. The total net integration time was 8.4k. Raw data were reduced with a new FORS2 adaption of the VIMOS Interactive Pipeline Graphical Interface (VIPGI, Scovell et al. 2003), which includes all the standard reduction steps: bias subtraction, flat-field corrections, image stacking and wavelength calibration by means of a Helium-Argon reference spectrum (Nastasi et al., in prep.).
distance from the X-ray emission peak \( D_{\text{proj}} < 2' \) and rest frame velocity offsets of \( |\Delta v| < 2000 \text{ km/s} \) with respect to the median redshift. For the BCG, we extracted the spectra of both components ID:1-A and ID:1-B (Fig. 3 right), distinguishable in the 0.86" seeing z-band preimage of Fig. 4 (left). For the second component (ID:1-B) only a tentative redshift measurement of \( z = 1.5001 \) can be obtained owing to its low signal-to-noise ratio. The extracted spectra and the main properties of the seven confirmed members are shown in Fig. 5 and reported in Table 2 respectively. Several spectral features are identifiable, albeit strong emission and absorption sky lines affect the quality of the individual spectra. This allows us to confirm the presence of a bound system of, at least, seven galaxies with a median redshift of \( z = 1.490 \pm 0.009 \). Using the biweight estimator (Beers et al. 1990) we obtain a crude velocity dispersion estimate of \( \sigma_v \approx 670 \text{ km/s} \) in the cluster rest frame, albeit with an associated large uncertainty owing to the poor statistics.

In order to enhance the faintest features, an average, noise-weighted composite spectrum of the seven members was created. The result is shown in Fig. 2 (bottom) and compared with an LRG template spectrum (red), derived for 726 luminous red galaxies at \( 0.47 < z < 0.55 \) by Eisenstein et al. (2003).

4. A young cluster in formation?

From the CMD in Fig. 2 (top) we note that the red sequence of X0338 appears well populated. The 11 red galaxies, with colors \( 2.6 \leq z - H \leq 3.5 \) and brighter than the completeness limit, have a median (average) color of \( z - H = 2.9 \text{ mag} \) (3.0 mag), which is consistent with the model prediction of \( z - H \approx 3.0 \) mag for a stellar formation redshift of \( z_f = 3 \), which implies an evolved red sequence population, as seen in other distant clusters (XMMUJ1229, Santos et al. 2009; XMMUJ2235, Strazzullo et al. 2010). From the observed color spread of \( \delta_{z-H} \approx 0.25 \text{ mag} \), with an assumed flat slope and a Monte-Carlo estimated contribution of the photometric errors of \( 0.16 \pm 0.04 \text{ mag} \), we obtain a first order estimate of the intrinsic red sequence scatter of \( \delta_{z-H} \sim 0.19 \pm 0.04 \text{ mag} \). This is significantly larger than in the above cases, e.g. 0.08 for XMMUJ2235, but consistent with the findings of Hilton et al. (2009) for their z = 1.46 cluster. The estimate for the above intrinsic scatter does not change if a non-flat slope (e.g. the one of XMMUJ2235 given by Strazzullo et al. 2010) for the fit is used. This larger scatter can be explained with stellar formation age differences of the bright end of the red galaxy population of the order of 0.5–1 Gyr, as discussed in Hilton et al. (2009). The seven spectroscopic members show weak or no signs of ongoing star formation activity, with a measured equivalent width of the [OII] line in their spectra of \( |EW_{[OII]}| \leq 5\AA \). Assuming the above spectral feature as a proxy of their star formation rate, the measured values for \( EW_{[OII]} \) indicate a very moderate intensity for such activity. The existence of a real, albeit weak, [OII] emission activity in the X0338 members is confirmed by the presence of such a spectral feature in the composite spectrum of Fig. 2 bottom.

\[ \text{[NeII]} \lambda 3870 \text{ line for the ID:11 galaxy, however, suggests the presence of an obscured AGN for it.} \]
On the red sequence we find a magnitude gap between the BCG and the second ranked member of $\Delta m_{12} \approx 0.8$ mag. From the study of Smith et al. (2010) in the local universe, this points towards a dynamically evolved cluster, while the apparent offset of the BCG with respect to the center of X-ray emission ($D_{proj} \approx 175$ kpc) is a typical sign of a dynamically young clusters (Haarsma et al. 2010). This is in line with the fact that the cluster shows indications of asymmetric X-ray emission with a low central surface brightness. A close-up look at the BCG, shown in Fig. 4 (left), shows a double-object morphology, indicating an active mass assembly process via a merger event (implying that the relatively large magnitude gap is a very recent feature). Because of the lack of detectable emission lines in ID:1-A and 1-B spectra, we can state that this confluence is likely a dry merger. The overall color and magnitude of the BCG are consistent with the ones found in red, passive, brightest galaxies residing in low-redshift clusters. The case of X0338 seems to suggest that we may be finally witnessing the active mass assembly epoch of BCGs, in contrast to the evolved counterparts observed at $z \lesssim 1.4$ (e.g. Whiley et al. 2008; Collins et al. 2009). Our observations support the hierarchical assembly scenario of BCGs, albeit at significantly earlier epoch than predicted from the cosmological simulation results of De Lucia & Blaizot (2007).

The large scatter of the red sequence, the X-ray morphology and the spatial distribution of color-selected red galaxies point towards a younger cluster compared to e.g. XMMUJ2235, a scenario that will be critically tested by planned deeper observations.

5. Summary and conclusion

We summarize our results as follows:

- We reported on the study of a newly discovered galaxy cluster XMMU J0338.8+0021 at $z = 1.490$. This system was selected as an extended X-ray source serendipitously detected within the XDCP.
- By means of spectroscopic follow-up we can confirm seven cluster members, six of which with $D_{proj} < 1$ Mpc and a rest frame velocity offset of $|\Delta v| < 2000$ km/s from the median redshift.
- The H-z band data reveal the presence of a well populated, albeit quite spread, red sequence in the CMD, with a median color of $z-H = 2.9$ mag and an intrinsic color scatter of $\sigma_{z-H} \sim 0.19$. Comparisons with SSP models suggest that the stellar populations of red sequence galaxies span the formation epochs in the redshift range $3 \lesssim z \lesssim 5$.
- A BCG is clearly identifiable on the red sequence and found in an active mass assembly phase, likely via a dry merging process.
- Our data overall suggest that X0338 is a young galaxy cluster not yet fully evolved, as the faint X-ray emission appears to be morphologically disturbed and the large area over which its galaxies are found possibly indicates the presence of infalling structures.

Currently, the present evidence for X0338 suggests partly an evolved cluster scenario and at the same time signs of a dynamically young system. More detailed studies are needed for a more complete characterization of this intriguing system and its components.

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