The XMM Cluster Survey: Optical analysis methodology and the first data release

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1 INTRODUCTION

Clusters of galaxies provide an opportunity to explore the underlying cosmological model and the processes governing structure formation (see [Voit 2005] [Allen et al. 2011] for reviews) and so several large-area surveys for clusters are currently underway. In this paper we present the XMM Cluster Survey (XCS), a search for serendipitous galaxy clusters in archival XMM–Newton (XMM hereafter) data, using the signature of X-ray extent. The original XCS concept was described in [Romer et al. 2001]. The main goals of the survey are to (i) measure cosmological parameters, (ii) measure the evolution of the X-ray luminosity–temperature scaling relation (L_X – T_X relation, hereafter), (iii) study galaxy properties in clusters to high redshift, and (iv) provide the community with a high quality, homogeneously selected, X-ray cluster sample. XCS highlights to date include the detection, and subsequent multi-wavelength follow-up, of a z = 1.46 cluster (XMMXCS J2215.9–1738; Stanford et al. 2006 [Hilton et al. 2007, 2009, 2010], studies of galaxy evolution in high-redshift clusters (Collins et al. 2009 [Stott et al. 2010]), and forecasts of the performance of XCS for cosmological parameter estimation and cluster scaling relations (Sahlen et al. 2009 [S09] hereafter). In a companion paper, (Lloyd-Davies et al. 2010) we describe the corresponding optical data analysis strategy and present the first XCS data release (XCS-DR1 hereafter). A schematic of the XCS methodology is reproduced (from LD10) in Fig. 4. The components indicated with solid outlines were discussed in LD10. Those with dashed outlines are discussed herein: Redshift Follow-up (New Observations) in Section 2; Redshift Follow-up (Archive) in Section 3; Quality Control in Section 4 and Compile Cluster Catalogue in Section 5. Summaries and discussions are presented in Section 6. Brief conclusions are made in Section 7.

In this paper we have relied heavily on the red-sequence, or colour–magnitude relation (CMR), technique to derive photometric redshifts using one colour (r – z) CCD imaging ([Ostrander et al. 1998] [Gladders & Yee 2000] [López-Cruz et al. 2004]). This technique takes advantage of the fact that cluster cores are populated with passively-evolving elliptical galaxies that dominate the bright end of the luminosity function. The mass–metallicity relation of these ellipticals, when expressed in colour–magnitude space, has only a small intrinsic scatter ([Sandage & Visvanathan 1978] [Bower et al. 1992] [Kodama & Arimoto 1997] [Stanford et al. 1998] [López-Cruz et al. 2004] and has become known as the E/S0 ridge-line or the cluster red-sequence. The red-sequence has been found to be remarkably homogeneous between clusters at the same redshift and has been detected to z > 1 ([Lidman et al. 2008] [Mei et al. 2009] [Hilton et al. 2009] [Papovich et al. 2010], meaning it can be used as a tool for cluster detection out to high redshifts (e.g. [Gladders & Yee 2000] [Gladders & Yee 2005] [Wilson et al. 2009] [Muzzin et al. 2009] [Demarco et al. 2010] [Papovich et al. 2010]). The red-sequence can also be used to measure cluster redshifts because, by using appropriately placed filters, one can track the migration of the 4000A break feature in the spectrum of passive ellipticals. It is this redshift application that we make use of in XCS.

We note that, in the following, we have used the following terms in an XCS-specific manner; count, ObsID,
candidate, candidate$^{300}$, and cluster$^{300}$. 'Count' is used as a shortening of the phrase 'background-subtracted (0.5–2.0 keV) photon count as determined by XAPA'. As explained in LD10, these count values have not been corrected for photons falling outside the XAPA defined aperture (that is done during an additional spatial fitting step once the cluster redshifts are known). The count values pertain to the number of photons gathered from a single ObsID, where 'ObsID' is used herein to refer to each of the complex sets of XMM exposures and calibration files that comprise the 5,776 XMM observations processed so far by XCS. If a candidate was detected in multiple ObsIDs, then the highest recorded count is used. 'Candidate' is used with reference to the LD10 definition of an XCS cluster candidate, i.e. a XAPA-detected XMM source, detected with 50 or more counts, that has been classified – without warning flags – as being more extended than the instrument point spread function (PSF). Moreover, candidates must not lie in the Galactic plane or near the Magellanic Clouds. Candidates must have also passed the target filters, i.e. are genuine serendipitous detections (as far as we can tell using automated methods). To date, we have selected a total of 3,675 candidates (LD10). A subset of 993, the ‘candidates$^{300}$’, are of particular importance, as these were detected with 300 or more counts (see below). Similarly, ‘clusters$^{300}$’ are candidates$^{300}$ that have been optically confirmed as clusters.

The significance of the 300 count threshold mentioned above is twofold. First, and most importantly – because we require temperature measurements for most of our key scientific goals – we have determined (LD10) that XAPA will detect most (> 70 per cent) of the clusters$^{300}$ that lie within the field of view of an ObsID.

Throughout, we assume a concordance cosmology ($\Omega_m = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) and error bounds are quoted by their 1$\sigma$ limits. XCS reduced X-ray images and optical images (colour-composite and greyscale) of the XCS-DR1 clusters mentioned in the text can be viewed at http://xcs-home.org/datareleases (see Section 5).

2 REDSHIFT FOLLOW-UP (NEW OBSERVATIONS)

We have carried out several observing campaigns in order to measure redshifts for XCS clusters. We describe our photometric follow-up in Section 2.1, the derivation of redshifts from that photometric follow-up in Section 2.2 and our spectroscopic follow-up in Section 2.3.

2.1 The NOAO–XMM Cluster Survey

The NOAO–XMM Cluster Survey, or NXS, was a two-band imaging survey that gathered data across the Northern and Southern Celestial hemispheres to $r \approx 24$ over 38 nights. It was carried out at the National Optical Astronomy Observatory (NOAO) 4-m facilities at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO) during six observing campaigns between November 2005 and April 2008. Slightly more time (by two nights) was allocated to the Southern hemisphere due to larger optical archival coverage in the North. During the NXS, both the KPNO and CTIO 4-m telescopes were equipped with wide-field MOSAIC CCD cameras. The KPNO MOSAIC I and CTIO MOSAIC II cameras consist of a $4 \times 2$ array...
of 2048 × 4096 pixel CCDs. These CCDs are separated by
gaps of 35 pixels between columns and 50 pixels between
rows. Both cameras are controlled by four ARCON CCD con-
trollers that read out eight amplifiers for MOSAIC I (one
per chip) and 16 amplifiers for MOSAIC II (two per chip).
The similarity of the two MOSAIC instruments has allowed
the NXS to produce a homogeneous data set across the sky.
The MOSAIC I and II pixel scale of 0.26 arcsec/pixel and
0.27 arcsec/pixel respectively, provides a total imaging area
of 0.36 deg² and 0.38 deg² on the sky. By comparison, the
XMM field of view is circular with a diameter of 30 arcmin.
Thus, each NXS image encompasses one XMM image. Since
each ObsID typically contains multiple candidates, we opted
to centre the MOSAIC camera near the aim-point of the Ob-
siD, rather than on a specific candidate. With several thou-
sand candidates to choose from, and only a limited number
of nights at our disposal, emphasis was placed on imaging
candidates^000 when possible.

The primary aim of the NXS was to efficiently provide
photometric redshifts for candidates to z ≃ 1. Therefore,
the Sloan Digital Sky Survey (SDSS[7] York et al. 2000) r-
band and z-band filters were chosen for the survey, because
these straddle the 4000Å break over the approximate red-
shift range 0.3 < z < 0.6. This enhances the magnitude
contrast of elliptical red-sequence galaxies detected in both
bands at z ∼ 0.5, and enables the estimation of red-sequence
redshifts to z > 1 (Gladders & Yee 2000). MOSAIC obser-
vations were made in a typical sequence of 2 × 600 s r-band
and 3 × 750 s z-band exposures. Hereafter the set of NXS
observations towards an ObsID will be referred to as an
NXS field, where the NXS fieldID (see Table 1) is set to the
respective ObsID name. Exposures were offset by 30 arcsec
in R.A. and Dec. to eliminate MOSAIC chip gaps and aid
the removal of cosmic rays and satellite trails in the final
stacked images. If the original sequence of exposures was not
taken under photometric conditions, then additional, short
exposures were obtained (when possible) under photomet-
ric conditions at a later date, for calibration purposes.
Over the course of the NXS project, 154 NXS fields, containing
a total of 415 candidates, were observed. All of the raw data
are publicly available at the NOAO Archive by searching
the NOAO Portal[2] (Miller et al. 2007) for the Program ID:
2005B-0045. The total uncompressed data volume taken as
part of the NXS survey is just over 500GB. This includes
1589 science exposures and another ~2000 calibration im-
age. A summary of the NXS observations is presented in
Table 1. Examples of NXS images of XCS-DR1 clusters are
shown in Fig. 2.

2.1.1 NXS data reduction

Images were reduced using the MSCRED package (Valdes 1998)
written for the IRAF environment. MSCRED is specifically writ-
ten to reduce data taken by the NOAO MOSAIC I and
MOSAIC II cameras. We briefly summarize the reduction
procedures below.

After correction for cross-talk between amplifiers, and
overscan trimming, the images were bias and dome flat-
field corrected. Next, artifacts were corrected by generating
a fringe frame and pupil-ghost frame from science images
and subtracting these templates from each individual sci-
ence image (MOSAIC I and II z-band images both suffer
from interference fringing, and MOSAIC I z-band images
also suffer from a pupil ghost). A further flat-field correc-
tion was then applied using a sky-flat. Usually this was gen-
erated by combining suitable science images taken under
similar conditions, but for the March 2008 observing cam-
paign (due to the low number of NXS fields observed), it was
necessary to make use of a sky-flat generated by the NOAO
MOSAIC reduction pipeline. Cosmic rays, bad pixels and
bleed trails were automatically identified and added to bad-
pixel masks. Satellite trails were identified and masked by
eye. An astrometric solution for each image was generated
from the USNO-A2.0 catalogue using the automated task
msccmatch. This solution was then used to rebin the image
to a constant pixel scale to compensate for distortions across
the MOSAIC field of view. The large-scale sky gradient was
then removed from each image. Individual images of a par-
ticular field were then stacked by matching the background
sky levels and excluding bad pixels.

Source detection and photometric measurements were
performed on the stacked images using SExtractor (Bertin
& Arnouts 1996) operated in dual-image mode. In this mode,
source positions and apertures were identified in z-band im-
ages and then the photometry was performed in both r and z
bands simultaneously to produce matched object catalogues.
To facilitate dual-image mode, the r and z band images were
registered to pixel-level accuracy to allow matched aperture
photometry across both bands. To avoid introducing erro-
neous colour estimates in the resulting galaxy catalogues,
regions near bright stars were excluded in the NXS images
prior to source detection. Such regions were identified in
NXS images by performing an initial run of SExtractor
using a high detection threshold to locate large extended
sources (> 3000 connected pixels) that also contained satu-
rated pixels. The corresponding regions were then masked
in the NXS exposure maps. The final object catalogues were
then produced, using a second run of SExtractor, utilising
these updated NXS exposure maps. We adopt Kron magni-
tudes (MAGAUTO) to estimate galaxy magnitudes and isopho-
tal magnitudes (MAGISO) to calculate galaxy colours.

Photometric calibration was achieved predominantly
through the use of NXS fields that happened to lie within
the survey regions of the SDSS Sixth Data Release (DR6,
Adelman-McCarthy et al. 2008), because SDSS sources have
photometric calibration in both r and z bands accurate to
within 3 per cent. Where this was not possible, observa-
tions were made of regions that contained either Southern
Standard stars (Smith et al. 2002) or Landolt stars (Landolt
1992) measured in the SDSS photometric system. In addi-

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[2] Information and a Data Handbook which describes how to ac-
cess NOAO archival data and use the NOAO Portal is available
at this URL: http://www.noao.edu/sdm/help.php

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[3] The pipeline implements a Master sky-flat generated from ev-
ery science frame taken at the CTIO 4-m telescope and produces
pre-stacked, sky-flattened, WCS (World Coordinate System) cor-
corrected images.

[4] Satellite trails were masked using the script sat-b-gon.pl written
by Matthew Hunt, available from www.ifa.hawaii.edu.
Figure 2. A selection of optically confirmed XCS clusters as imaged by the NOAO-XMM Cluster Survey (NXS) and classified as gold in ZooNXS. These clusters have corresponding redshifts and X-ray temperature measurements, and none of them have been previously catalogued in the literature. False colour-composite images are 3 × 3 arcmin with X-ray contours overlaid in blue. From left to right and top to bottom, the compilation displays the clusters: XMMXCS J130649.9−233128.5 at \( z = 0.21 \); XMMXCS J232221.3+193855.0 at \( z = 0.23 \); XMMXCS J205405.9−154736.5 at \( z = 0.27 \); XMMXCS J223852.3−202612.2 at \( z = 0.35 \); XMMXCS J011140.3−453908.0 at \( z = 0.367 \); XMMXCS J075427.8+220950.9 at \( z = 0.40 \); XMMXCS J233212.6+119514.8 at \( z = 0.40 \); XMMXCS J063945.9+821847.3 at \( z = 0.41 \); XMMXCS J003439.4−120715.8 at \( z = 0.44 \); XMMXCS J011624.2+325717.0 at \( z = 0.45 \); XMMXCS J092545.7+305856.9 at \( z = 0.52 \); XMMXCS J212748.7−450515.9 at \( z = 0.56 \); XMMXCS J011023.8+330544.1 at \( z = 0.60 \); XMMXCS J011632.1+330325.0 at \( z = 0.64 \); XMMXCS J001115.5+250611.5 at \( z = 0.763 \); and XMMXCS J025006.4−310400.8 at \( z = 0.91 \).
tion, two NXS fields imaged during the second observing campaign were also used to calibrate subsequent runs.

For NXS fields with SDSS DR6 overlap, standard star catalogues were generated by extracting MODEL magnitudes from the SDSS DR6 PHOTOObj table for stars containing standard flags for clean photometry in the r and z band, respectively. The positions of these SDSS stars were then cross-matched with sources in the NXS object catalogues, using 1 arcsec matching radii, to produce a matched catalogue of stars with both instrumental and corresponding standard magnitudes. Similarly, Southern Standard star positions, as well as the positions of calibrated objects in the two designated NXS calibration fields, were cross-matched with the NXS object catalogues using a 1 arcsec matching radius. In the case of Landolt stars, these were identified and photometered using the aperture photometry tool in GAIA.

Using the IRAF task FITPARAMS, the resulting catalogues of instrumental and corresponding standard magnitudes were compared in order to fit for a single zeropoint for each night, or partial night, that was deemed to be photometric. If multiple NXS fields containing calibration stars were observed over the course of a night, then the matched catalogues of instrumental and standard stars of each field were combined to fit for a single zeropoint. These updated zeropoints were then applied to the appropriate NXS object catalogues. Galactic extinction corrections were subsequently applied to NXS object magnitudes based on the dust maps and software of Schlegel et al. (1998).

Star–galaxy separation was determined for each NXS image using the method presented in Metcalfe et al. (1991), based on identifying the locus of stars in the concentration–magnitude plane. A concentration parameter was computed using aperture magnitudes measured within four and twelve pixels (∼1 and ∼3 arcsec) in diameter. Star–galaxy separation was performed in the r-band and results in a clear separation of stars from galaxies at magnitudes typically brighter than r ∼ 22. At fainter magnitudes, we classified all objects to be galaxies, regardless of their concentration parameter.

The 90 NXS fields taken under photometric conditions have a typical seeing of 1.39 and 1.23 arcsec in the r and z-band, respectively. For an additional 11 NXS fields, it was possible to calibrate them a posteriori using short integrations taken on subsequent photometric nights. Observations of another 30 NXS fields were taken under non-photometric conditions, but the images were still of sufficient quality that they could be used for the optical identification work described in Section 4.1. The mean depth of the calibrated NXS fields, as given by the 5σ point source detection limit, are r = 25.0 and z = 23.8. Based on the Bruzual & Charlot (2003) population synthesis models and the assumption that the bulk of the signal in detecting a cluster comes from the galaxies brighter than about 0.5 magnitudes below L∗, these limits should be sufficient to detect clusters, and measure CMR-redshifts, to z ≃ 1. In total, 366 candidates are contained within photometrically-calibrated NXS fields.

2.2 Photometric redshifts

We have applied the CMR-redshift technique to single-colour (r − z) photometric images of candidates. The photometry has either come from the NXS project (Section 2.1) or from the SDSS (Section 3.1). Our redshift algorithm is based on that presented in Gladders & Yee (2000), in that it identifies overdensities of galaxies exhibiting a red-sequence and assigns a redshift based on the red-sequence colour. However it differs from Gladders & Yee (2000) in that it assumes the cluster centre is defined by the X-ray centroid of the corresponding XCS candidate (rather than by the centroid of a galaxy overdensity).

For each candidate, potential cluster galaxies are extracted from within twice the X-ray extent as measured by the XAPA algorithm. The colour distribution of these galaxies is then compared to that of an assumed field galaxy sample (normalised to the cluster area) to identify potential overdensities of red-sequence galaxies. For NXS, a local field sample was generated separately for each NXS field. This involved masking out all extended X-ray sources in that field using a fixed circular aperture of radius 0.15 deg. We note that this mask aperture was always larger than that used to extract cluster galaxies.

We then constructed a matched-filter to detect red-sequences via a maximum-likelihood fit. According to convention (e.g. Postman et al. 1996; Koester et al. 2007b), we refer to the likelihood of there being a cluster red-sequence at a particular redshift, and with a certain number of galaxy members, as the ridgeline likelihood. We chose to maximise

| NXS FieldID | R.A. (J2000) | Dec. (J2000) | No. Exposures | Integration Time | Seeing | Depth | Run |
|-------------|-------------|-------------|---------------|-----------------|--------|-------|-----|
| 0002940101  | 13:07:04.7  | −23:38:51.3 | 2/3           | 1200/1500       | 1.2/1.0 | 24.1/23.4 | 4   |
| 0010620101  | 05:15:45.0  | +01:03:14.6 | 2/2           | 1200/1000       | 1.1/1.9 | 24.4/23.8 | 1   |
| 0012440301  | 22:05:04.3  | −01:54:19.1 | 2/3           | 1200/1500       | 1.4/1.4 | 24.5/23.2 | 4   |
| 0021540101  | 15:06:27.4  | +01:37:55.2 | 2/3           | 1200/1500       | 1.4/1.1 | 25.3/23.6 | 4   |
| 0025540301  | 08:38:25.5  | +25:43:40.0 | 2/2           | 1200/1500       | 2.0/1.5 | 25.0/23.7 | 3   |
| 0025514601  | 01:24:49.6  | +03:46:30.7 | 2/3           | 1200/1500       | 1.0/1.1 | 25.3/22.5 | 1   |
| 0029340101  | 06:41:43.3  | +02:14:31.4 | 2/2           | 1200/1000       | 1.4/0.9 | 25.1/23.9 | 1   |
| 0032114201  | 13:05:11.8  | +10:19:22.0 | 2/3           | 1200/1500       | 1.1/1.0 | 24.6/23.5 | 4   |
| 0037980301  | 02:25:25.7  | +03:50:59.2 | 2/3           | 1200/1500       | 1.3/1.0 | 25.6/23.0 | 5   |
| 0037981601  | 02:23:14.3  | −02:48:56.3 | 2/3           | 1200/1500       | 1.8/1.8 | 25.0/23.8 | 2   |

Table 1. A summary of reduced observations taken by the NOAO-XMM Cluster Survey. r and z refer to exposures taken in the SDSS r and z-band filters, respectively. A full version of Table 1 is provided in electronic format in the online version of the article. These tables are ordered by increasing NXS FieldID number.
our likelihood using the Cash statistic (Cash 1979) adapted to the form shown in Eq. [1], because the number of extracted red-sequence galaxies is often low compared to the local field sample. This likelihood is evaluated for each potential cluster galaxy, \( x \), and summed over the candidate as a whole, as follows:

\[
\mathcal{L} = \sum_{x=D}^{x=0} \left[ \ln(b(z) + \Lambda_N M(z)) \right] - D,
\]

where \( \mathcal{L} \) is the negative log likelihood; \( z \) is the cluster redshift; \( b(z) \) is the background distribution, given by the colour distribution of the local field sample; \( \Lambda_N \) is a measure of cluster richness and corresponds to the total number of cluster galaxies above the background distribution; \( M(z) \) is our red-sequence cluster model; and \( D \) is the total number of galaxies within twice the X-ray extent. The red-sequence cluster model we adopt is a Gaussian distribution in colour (Koester et al. 2007b):

\[
M(z) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left(\frac{(x_{r,z} - RS_{col})^2}{2\sigma^2}\right),
\]

\[
\sigma = \sqrt{\sigma^2_{r,z} + RS^2_{\text{width}}},
\]

where \( \sigma^2 \) is the variance of the cluster model red-sequence; \( x_{r,z} \) is the colour of a sampled galaxy; \( RS_{col} \) is the assumed red-sequence colour at the cluster redshift being evaluated; \( \sigma_{r,z} \) is the uncertainty in the colour \( x_{r,z} \); and \( RS_{\text{width}} \) is the intrinsic width of the red sequence, assumed to be 0.05 in colour (López-Cruz et al. 2004) and constant with redshift.

The maximum ridgeline likelihood is found by considering a grid of red-sequence colours at redshifts 0.1 \( \leq z \leq 1.0 \) and richness 0 \( \leq \Lambda_N \leq 50 \) in discrete steps of \( \Delta \lambda = 0.01 \) and \( \Delta \Lambda_N = 1 \) respectively. Each model redshift is converted into a red-sequence colour using a theoretical map of red-sequence colour relations with redshift. This map is based on the slope of the composite red-sequence of 73 clusters at \( z \sim 0.1 \) detected by the SDSS-C4 survey (Miller et al. 2005), which is then evolved with redshift using the Bruzual & Charlot (2003) population synthesis models assuming a single-burst Salpeter IMF with a formation redshift of \( z_f = 2.5 \) (Gladders & Yee 2005).

In addition, a simultaneous estimate of the cluster richness (\( \Lambda_N \)) is produced together with an estimate of the cluster redshift. We note that the \( \Lambda_N \) richness can be considered to be a lower limit to the true richness. This is because the adopted search radius (of twice the X-ray radius extent) is typically less than \( R_{200} \) (an approximation to the virial radius, defined as the radius at which the overdensity has fallen to 200 times that of the critical density). Moreover, the entire \( R_{200} \) region is not always contained within an XNS field (the fields are centred on the ObsID aim point rather than on a specific candidate).

The best-fitting redshift, or CMR-redshift, will have an associated error that depends on a range of factors including the true redshift, the sensitivity of the image, the accuracy of the photometric calibration, the quality of the local field sample, and the appropriateness of the red-sequence model. The error on an individual CMR-redshift can only be determined once spectroscopic follow-up has taken place, but the typical error on a CMR-redshift can be externally determined via comparisons with measured spectroscopic redshifts (see Section 5.3). That said, we do calculate \( \chi^2 \) error estimates for the individual redshift measurements and these \( \chi^2 \) errors are used as an indication of the quality of the individual fits.

We deemed a CMR-redshift fit to be unreliable if the \( \chi^2 \) error was too high (\( \sigma_\chi > 0.1 \)), or if the richness was too low (\( \Lambda_N < 5 \)), or if the NXS images were taken under non-photometric conditions. Excluding these unreliable fits, a total of 224 CMR-redshift measurements were made using NXS data. We note that the drop in number between the 203 candidates contained within photometrically calibrated NXS fields (see above) to the 224 with reliable CMR-redshifts, is primarily due to the \( \Lambda_N < 5 \) cut. We assess the accuracy of NXS CMR-redshifts in Section 5.3.

### 2.3 Spectroscopic redshifts

Table 2 lists the mean spectroscopic cluster redshifts obtained by members of the XCS team for 35 candidates. Of the objects in the table, only the spectroscopic redshift of XMMXCS J2215.9–1738 (\( z = 1.46 \)) has previously been published (Stanford et al. 2006, Hilton et al. 2007, 2009, 2010). At the start of our spectroscopic programme, candidates were selected for follow-up either to fill R.A. gaps during the follow-up of the Sloan Digital Sky Survey-II Supernova Survey (¨Ostman et al. 2011; Frieman et al. 2008), or because they were judged by eye to be potential \( z > 1 \) clusters (and hence suitable for Keck or Gemini follow-up). However, as the project matured, the target selection was informed by X-ray redshift estimates (see LD10), thus allowing us to design a follow-up programme that both sampled the \( L_X - T_X(z) \) relation and allowed us to determine the accuracy of the CMR-redshifts (Section 5.3).

The spectroscopic observations were performed over several years at a number of different observatories with a variety of instruments, as summarised in Table 2. Data taken with the DEep Imaging and Multi-Object Spectrograph (DEIMOS, Faber et al. 2003) at the Keck observatory were processed with version 1.1.4 of spec2d, the pipeline developed for the DEEP2 galaxy redshift survey (Davis et al. 2003). All Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2003) observations were obtained in nod-and-shuffle mode, and reduced in a manner similar to that described in Hilton et al. (2010). An example cluster spectroscopically confirmed in one of the GMOS observing programmes is shown in Fig. 3. The ESO Multi-Mode Instrument (EMMI; Dekker et al. 1986) and ESO Faint Object Spectrograph and Camera (EFOSC2; Buzzoni et al. 1984; Snodgrass et al. 2008) at the NTT were used to obtain long-slit spectroscopy of likely (as judged by eye) Brightest Cluster Galaxies (BCGs). Multi-object spectroscopic observations were also obtained for some clusters using EFOSC2. All of the data obtained at ESO were reduced using IRAF in the standard manner.

Redshifts were measured either from visually identified spectral features or using the cross-correlation method implemented in the rvsao IRAF package (Kurtz & Mink 1998). Table 2 lists the number of secure concordant redshifts obtained for each cluster. A number of clusters listed in Table 2 have only one redshift measurement; in these cases, the quoted redshift is that of the likely BCG.

We highlight here two clusters from Table 2. First, a
Table 2. Spectroscopic follow-up by XCS team members. The \(N(z)\) column lists the number of concordant redshifts obtained for each cluster. For clusters with only one spectroscopic redshift, the \(z\) column gives the redshift of the suspected BCG; otherwise the \(z\) column gives the mean galaxy redshift. The rightmost column lists the date(s) of observation, the observing programme number (for ESO or Gemini), or references, as appropriate. Uncertainties on the spectroscopic redshift values are not presented but are assumed to be at the level of the cluster velocity dispersion, i.e. \(\sigma_v < 2000 \text{ km s}^{-1}\). (Note that many more spectroscopic cluster redshifts are presented in XCS-DR1, but these were obtained from archives or from the literature.)

| XCS ID           | \(z\)  | \(N(z)\) | Telescope/Instrument | Comments                                      |
|------------------|--------|----------|----------------------|-----------------------------------------------|
| XMMXCS J003548.2-432322.4 | 0.633  | 12       | GMOS/Gemini          | GS2010B-Q-46                                  |
| XMMXCS J011140.3-453908.0 | 0.367  | 11       | NTT/EFOSC2           | 28, 30-31 Jul 2008 (Program ID: 081.A-0843(A)) |
| XMMXCS J012400.0+035110.8 | 0.883  | 7        | Keck/DEIMOS          | 21 Sep 2006                                   |
| XMMXCS J015241.1-133855.9 | 0.825  | 10       | Keck/DEIMOS          | 2 Sep 2005, 21 Sep 2006                       |
| XMMXCS J023346.0-085048.5 | 0.25   | 1        | NTT/EMMI             | 15 Sep 2006 (Program ID: 077.A-0437(A))       |
| XMMXCS J025006.4-310400.8 | 0.908  | 6        | Gemini/GMOS          | GS2010B-Q-46                                  |
| XMMXCS J030145.5+000335.8 | 0.694  | 3        | Gemini/GMOS          | GS-2010B-Q-46                                 |
| XMMXCS J030317.4+001238.4 | 0.594  | 1        | NTT/EMMI             | 15 Sep 2006 (Program ID: 077.A-0437(A))       |
| XMMXCS J032553.3-061719.9 | 0.322  | 2        | NTT/EMMI             | 9 Dec 2007 (Program ID: 080.A-0024(C))        |
| XMMXCS J035417.0-001066.6 | 0.214  | 2        | NTT/EMMI             | 9 Dec 2007 (Program ID: 080.A-0024(C))        |
| XMMXCS J041944.6+134901.5 | 0.196  | 2        | NTT/EMMI             | 17 Oct 2006 (Program ID: 078.A-0325(C))       |
| XMMXCS J045506.3-532343.8 | 0.410  | 1        | NTT/EMMI             | 13 Dec 2006 (Program ID: 078.A-0325(A))       |
| XMMXCS J051610.0+010954.0 | 0.318  | 2        | NTT/EMMI             | 7 Dec 2007 (Program ID: 080.A-0024(C))        |
| XMMXCS J060806.6+152309.0 | 0.41   | 1        | WHT/ISIS             | 1-3 Dec 2007 (Program ID: P53)                |
| XMMXCS J091821.9+211446.0 | 1.007  | 16       | Gemini/GMOS          | GN-2010B-Q-65                                 |
| XMMXCS J095105.7+391742.9 | 0.47   | 1        | WHT/ISIS             | 1-3 Dec 2007 (Program ID: P53)                |
| XMMXCS J095940.8+023111.3 | 0.720  | 14       | Gemini/GMOS          | GS2010B-Q-46                                  |
| XMMXCS J100201.7+021332.8 | 0.41   | 2        | Gemini/GMOS          | GN-2010B-Q-65                                 |
| XMMXCS J100201.7+021332.8 | 0.83   | 6        | Gemini/GMOS          | GN2009B-Q-80                                  |
| XMMXCS J101236.9+125643.2 | 0.325  | 1        | NTT/EMMI             | 14 Dec 2006 (Program ID: 078.A-0325(C))       |
| XMMXCS J104422.2+213025.2 | 0.510  | 7        | Gemini/GMOS          | GN-2010B-Q-65                                 |
| XMMXCS J105040.6+573741.4 | 0.689  | 12       | Gemini/GMOS          | GN-2010B-Q-65                                 |
| XMMXCS J111645.5+180047.7 | 0.662  | 7        | Gemini/GMOS          | GN2005B-Q-66                                  |
| XMMXCS J111726.0+074327.7 | 0.482  | 15       | Gemini/GMOS          | GS2010B-Q-46                                  |
| XMMXCS J112349.3+052506.8 | 0.652  | 11       | Gemini/GMOS          | GS2010B-Q-46                                  |
| XMMXCS J130001.4+180145.9 | 0.93   | 3        | Keck/LRIS            | 10 Feb 2005                                   |
| XMMXCS J150059.9+014242.8 | 0.655  | 2        | NTT/EFOSC2           | 29 Jul 2008 (Program ID: 081.A-0843(A))       |
| XMMXCS J150653.3-141024.2 | 0.40   | 2        | NTT/EFOSC2           | 30 Jul 2008 (Program ID: 081.A-0843(A))       |
| XMMXCS J200703.1-443775.7 | 0.290  | 1        | NTT/EFOSC2           | 31 Jul 2008 (Program ID: 081.A-0843(A))       |
| XMMXCS J204134.7-350910.2 | 0.425  | 1        | NTT/EFOSC2           | 30 Jul 2008 (Program ID: 081.A-0843(A))       |
| XMMXCS J212807.6-445417.3 | 0.538  | 4        | NTT/EFOSC2           | 27-28, 30-31 Jul 2008 (Program ID: 081.A-0843(A)) |
| XMMXCS J215221.0-273022.6 | 0.826  | 9        | Gemini/GMOS          | GS2010B-Q-46                                  |
| XMMXCS J221559.6-173816.2 | 1.457  | 31       | Various              | See Stanford et al. (2006); Hilton et al. (2007, 2009, 2010) |
| XMMXCS J231852.3-423147.6 | 0.114  | 1        | NTT/EMMI             | 10 Dec 2007 (Program ID: 080.A-0024(C))       |
| XMMXCS J235708.6-241449.2 | 0.588  | 10       | NTT/EFOSC2           | 27, 29-31 Jul, 1 Aug 2008 (Program ID: 081.A-0843(A)) |

3 REDSHIFT FOLLOW-UP (ARCHIVE)

In addition to our own redshift follow-up work, we have been able to extract a large number of redshifts (both spectroscopic and photometric) for our candidates using data archives and from the literature. We describe the extraction of redshifts from the SDSS Seventh Data Release (DR7; Abazajian et al. 2009) in Sections 3.1 (photometric) and 3.2 (spectroscopic), and the extraction of redshifts from the literature in Section 3.3. We note that no XCS-determined X-ray redshifts are included in XCS-DR1. These redshifts have been shown to be reliable (at the \(\Delta_z < 0.1\) level) in 75 per cent of cases (LD10) and so, in principle, we could have used them for XCS-DR1. However, in practice, there were only 42 overlaps between the sample of candidates with X-ray redshifts and the XCS-DR1 list, and all of these have other redshift determinations of higher quality.

3.1 Redshifts from SDSS (photometric)

The red-sequence redshift algorithm described above (Section 2.2) was also applied to each of the candidates that fall in the SDSS DR7 footprint. Included in SDSS DR7 is a 270 deg² co-added stripe, known as Stripe 82, and referred

\[6\] During the preparation of this manuscript, the SDSS Eighth Data Release was made public (DR8; Ahn et al. 2011). Im...
to as S82 hereafter, that reaches a depth ~2 magnitudes fainter than the regular survey. We have used both datasets to determine CMR-redshifts from SDSS DR7. At the time of writing (June 2011), 1,721 candidates lie within the SDSS DR7 footprint, of which 69 lie within the S82 footprint.

Galaxy samples were extracted from the GALAXY VIEW, which contains photometric information for all primary objects imaged by SDSS and subsequently classified as galaxies. We use the SDSS measurement MODELMAG to provide galaxy magnitudes and calculate colours for each galaxy, and apply the Galactic extinction corrections supplied by the SDSS based on the dust maps by [Schlegel et al. (1998)]. We specify that all galaxies must contain the standard flags for clean photometry in both the r and z bands. In this manner, potential cluster galaxy samples were generated by retrieving de-reddened model r and z magnitudes for all galaxies falling within twice the XPA extent of each candidate contained within the SDSS DR7 and S82 footprints, respectively.

As the SDSS is a large, homogeneous survey, a universal field sample could be constructed (rather than the field-by-field approach adopted for NXS, Section 2.2). For this, a random sample of 50 (20) ObsIDs within the SDSS DR7 (S82) footprint were selected as the basis for a field sample. Pointings with incomplete SDSS coverage, or those containing image defects or saturated objects, were not used. De-reddened model r-band and z-band magnitudes were retrieved for all galaxies with clean photometry across the regions covered by each of the 50 (20) ObsIDs.

To minimize contamination of the field sample by galaxies within clusters, areas that overlapped either with candidates or with known clusters (identified using NED) were masked from the field sample. In the case of XCS candidates, we do not a priori know their redshift or temperature, so a fixed radius of 0.15 degrees was used (as was the case for NXS). In the case of NED clusters, the redshifts are usually known, but the temperatures typically are not. So, to be conservative, we used an R_{200} radius for the masking that assumes a cluster temperature of T\_X = 4 keV (less than 30 per cent of XCS clusters are hotter than this). The R_{200} values were calculated according to the method outlined in Section 3.2 of S09. This process yielded a single combined field sample containing 52,660 (207,693) galaxies covering a combined total area of 18.10 deg\(^2\) (5.87 deg\(^2\)) derived from SDSS DR7 (S82).

Similar to the approach taken with NXS CMR-redshifts (Section 2.2), we deemed a SDSS DR7 (S82) CMR-redshift fit to be unreliable if the \(\chi^2\) error was too high (\(\sigma_{\chi^2} > 0.1\)), or if the richness was too low (\(\Lambda_N < 5\)). After excluding these unreliable fits, and candidates with less than 100 counts (DR7 only; see Section 4.1), a total of 574 and 51 CMR-redshift measurements were made using DR7 and S82 data, respectively. We assess the accuracy of DR7 and S82 CMR-redshifts in Section 5.3.

### 3.2 Redshifts from SDSS (spectroscopic)

Luminous Red Galaxies, or LRGs, have been targeted by SDSS for spectroscopic follow-up using colour and magnitude cuts designed to select luminous (\(L > 3L_\odot\)), intrinsically red, elliptical galaxies [Eisenstein et al. (2001)]. As LRGs predominantly reside in the central regions of dense cluster environments, we can make the assumption that an identified LRG coincident with an X-ray emitting cluster, is part of that cluster. The spectroscopic redshift of this LRG (or group of LRGs) can then be adopted as the cluster redshift.

Because the 4000Å break migrates with redshift, two colour cuts are necessary to select LRGs within SDSS imag-
ing: we use the low-redshift ($z < 0.45$) colour cuts of Eisenstein et al. (2001) and the high-redshift ($0.45 < z < 0.7$) cuts of Padmanabhan et al. (2003) and Collister et al. (2007). From the resulting combined sample, an LRG (and its spectroscopic redshift) is assigned to an XCS candidate if it lies within 175 kpc of the X-ray centroid (assuming the redshift of the LRG). This matching radius was chosen because it was both free from high-levels of contamination (the ratio of real-to-false matches was found to be 18 per cent when comparing the assigned LRG redshift to corresponding cluster redshifts in the 400d catalogue; Burenin et al. 2007), and because it was consistent with the results from Lin & Mohr (2004) who found that 70 per cent of BCGs are located within 5 per cent of the cluster virial radius ($R_{200}$) from the X-ray centroid. There are instances however where multiple LRGs are assigned to a given XCS candidate. Some of these will be groups of LRGs belonging the same cluster halo. These are identified by scanning in redshift intervals of $\Delta z = 0.05$ and counting the number of (assumed) Gaussian colour error distributions overlapping in segments of $\Delta z = 0.1$. A cluster redshift is then assigned from a given group of LRGs using the following hierarchy: if one distinct group of LRGs is found, then the weighted mean redshift and weighted error of that group is assigned to the XCS candidate; if more than one group of LRGs is found, the group with the larger number of LRGs is chosen; if the number of LRGs within two groups are identical, then the group with the redshift closest to the CMR-redshift determined from the deepest imaging data (Sections 2.2 and 3.1) is chosen.

It was found, using eye-ball inspection, that when low-redshift ($z < 0.08$) LRGs were associated with XCS candidates, the matches were typically erroneous. This is because the 175 kpc search radius subtends a large angle on the sky at low LRG redshifts. Therefore, only LRG redshifts at $z \geq 0.08$ were typically used for XCS-DR1. However, we did make exceptions if the candidate had a measured CMR-redshift pegged at the algorithm’s minimum value ($z = 0.1$). In this instance, the candidate was judged to be at low redshift and so could be safely associated with LRG redshifts below $z = 0.08$. There are 5 such cases in XCS-DR1: XMMXCS J010720.2+141604.2, XMMXCS J015315.0+010214.2, XMMXCS J115112.0+550655.5, XMMXCS J134326.9+554648.3, and XMMXCS J163015.6+243423.2. In summary, 265 candidates were associated with spectroscopic derived from SDSS LRGs.

### 3.3 Redshifts from the literature

All candidates have been cross matched using a simple automated NED query to determine whether they have been catalogued by an earlier cluster survey (Section 5). In addition, a more complex NED query has been used to determine which of the candidates can be associated with a published redshift. This search involves an iterative analysis of the XMM data, and the technical aspects have been described in LD10. To date 493 literature redshifts, or $z_{\text{lit}}$’s, have been extracted from NED using this process. The automated nature of the $z_{\text{lit}}$ collection means that not all of the extracted redshifts are correct. Therefore, for XCS-DR1 we have taken a conservative approach of only using literature redshifts if $z_{\text{lit}} \geq 0.08$. After applying this cut

\[345 \text{ } z_{\text{lit}} \text{ values remain.} \]

To these, we have added by hand 11 redshifts that were not in NED at the time when the automated $z_{\text{lit}}$ extraction was performed (4 taken from a recent data release by the XMM-LSS survey by Adami et al. 2010, three redshifts from a parallel study, Harrison et al. 2011, H11 hereafter, see Section 5.2, two redshifts taken from Suhada et al. 2011, a single redshift taken from Lamor et al. 2008, and a single redshift taken from Boehringer et al. 2005). In addition, we updated 8 redshifts in NED with improved values (6 XMM-LSS redshifts taken from Adami et al. 2010, the redshift for the cluster RX J105346.6+573517 taken from Hashimoto et al. 2005, and the redshift for the cluster XM-MXCS J2215.9−1738 taken from Stanford et al. 2006, see Table 2).

The NED-based $z_{\text{lit}}$ collection method cannot discern automatically whether individual redshifts were spectroscopic or photometric. However, this information is important to XCS, both to assess the reliability of derived quantities (especially X-ray luminosities) and to determine the typical error on XCS photometric redshifts (Section 5.3).

Therefore, we have made a manual check of the respective publication(s) for each of the 229 XCS-DR1 clusters with associated $z_{\text{lit}}$ values (210 coming from the automatic NED search, the remainder coming from the sources described above).

### 4 QUALITY CONTROL

A quality control step is necessary for XCS-DR1 because candidates are selected in a fully automated fashion (Fig. 1). Whilst automation is important to XCS – for both efficiency and to maintain statistical robustness – it can result in contamination of the candidate list by: (i) non-extended X-ray sources (e.g. low-redshift galaxies); (ii) non-extended X-ray sources (e.g. blended point sources); and (iii) contamination of the candidate list by: (i) non-extended X-ray sources; and (ii) clusters that were the intended target of the respective ObsID (or physically associated with it). Therefore, some quality control must be applied before releasing a confirmed cluster catalogue based on a given input candidate list. This has been carried out for XCS-DR1 using one or more of the following: an XCS-Zoo (Section 4.1); information from the literature (Section 4.2); our own spectroscopy (Section 4.3); and checks of the ObsID headers (Section 4.3).

#### 4.1 Candidate identification using XCS-Zoo

Both the name and the methodology of XCS-Zoo were inspired by the SDSS Galaxy Zoo project (Lintott et al. 2008). The Galaxy Zoo project took advantage of community input to morphologically classify SDSS galaxies over the web. The XCS-Zoo project is similar, in that it draws on a team of volunteers – either members of XCS or astronomers at affiliated universities – to classify XCS cluster candidates, and this classification is done using eye-ball inspection via

\[7\] In principle, as was the case for the LRG redshifts (Section 3.2), we would have been prepared to assign $z_{\text{lit}} < 0.08$ values to clusters if the measured CMR-redshift pegged at the algorithm’s minimum value ($z = 0.1$). However, in practice there were no such candidates.
a web interface. However, XCS-Zoo is on a much smaller scale than Galaxy Zoo. Moreover, unlike the hundreds of thousands of Galaxy Zoo volunteers, all 23 XCS-Zoo participants are co-authors of this paper.

The XCS-Zoo allowed us to establish, by consensus, whether a candidate had an obvious optical cluster counterpart. Candidates were included in XCS-Zoo if optical CCD imaging was available from the NXS (Section 2.1) or SDSS DR7 (both the regular survey and S82). A separate XCS-Zoo was undertaken for each of the three imaging surveys, and hereafter we refer to these as Zoo$^{\text{NXS}}$, Zoo$^{\text{DR7}}$, and Zoo$^{\text{S82}}$, respectively. Each candidate was classified at least five times per Zoo, even if they were covered by multiple imaging surveys. The number of candidates that could potentially have been classified by Zoo$^{\text{DR7}}$ was much larger (1,721) than the other two Zoos (484 in total), and so we set a minimum X-ray count ($> 100$) threshold for Zoo$^{\text{DR7}}$. This reduced the number of candidates included in Zoo$^{\text{DR7}}$ to a more manageable 1,151.

The inspected candidates were classified into one of the following categories of cluster: gold, silver, and bronze. A fourth category (other) was used for any remaining candidates (Section 4.1.1). The XCS-Zoo categorisation of each source was based upon the following information: a series of X-ray images (3 × 3, 6 × 6, 12 × 12 arcmin), highlighting X-ray contours and the region enclosed by the XAPA X-ray extent; a corresponding series of colour-composite optical images (with and without X-ray contours overlaid); and an image highlighting the location of the candidate within the ObsID.

To be assigned a classification of gold, a candidate must have an unambiguous overdensity of galaxies coincident (i.e. within the extent of the XAPA defined source ellipse) with an unambiguous extended X-ray source (Fig. 3). Candidates classified as silver must have either an unambiguous overdensity of galaxies associated with an acceptable extended X-ray source, or an unambiguous extended X-ray source associated with a suspected galaxy overdensity and/or BCG (Fig. 5). Candidates classified as bronze were judged likely to be clusters, but could not be confirmed as such using only the information available in XCS-Zoo (Fig. 6).

Each category was allocated an integer (from 1 to 4), with 4 for gold through to 1 for other. The average value (after rounding down) was adopted for a particular candidate, based on the five (or more) classifications available per XCS-Zoo. If a candidate was included in more than one XCS-Zoo, and had gained different average categorisations, then the category with the highest numerical score was adopted.

Excluding duplicates, the number of candidates classified as gold, silver, bronze and other via XCS-Zoo was 82, 310, 330, and 766, respectively. Including duplicates, 415, 1,151, and 69 candidates were classified by Zoo$^{\text{NXS}}$, Zoo$^{\text{DR7}}$, and Zoo$^{\text{S82}}$, respectively. For the purposes of XCS-DR1, we have decided to include all candidates with gold and silver classifications, because we judge those to have been confirmed as clusters. By contrast, only a subset of those with bronze classifications are included in XCS-DR1 because, based on XCS-Zoo alone, we cannot be sure they are clusters (even if they have measured CMR-redshifts). Therefore, only the 19 bronze candidates that have been confirmed as being clusters by some other (to XCS-Zoo) method, are included (Section 4.2). Once deeper optical imaging, and/or multi-object spectroscopy, is available, we expect that many of the 330 candidates in the bronze category will be confirmed as clusters. This has already been demonstrated in 17 cases where candidates that were categorised as bronze in Zoo$^{\text{DR7}}$ were silver or gold in the Zoo$^{\text{NXS}}$ or Zoo$^{\text{S82}}$ (Fig. 8).

In summary, excluding duplicates, 81, 306, and 19 candidates classified as gold, silver, and bronze (and none of those classified as other, Section 4.1.1) appear in XCS-DR1 as confirmed clusters.

In principle, we would like to include all the remaining clusters that fall within the NXS, DR7 and S82 footprints in future data releases. These comprise of 311 bronze clusters and 766 other objects. In practice, this is too many to follow-up individually, so we have decided to concentrate our efforts on the candidates$^{10}$. Applying the count threshold reduces the numbers of candidates requiring follow-up by roughly two thirds. Moreover, we have found (see Section 4.1.1) that 75 per cent of the other candidates$^{30}$ do not require additional follow-up, but can rather be removed immediately (as contaminants) without impacting the completeness of a final cluster catalogue. Thus only 43 other, in addition to the 95 bronze, candidates$^{30}$ require additional follow-up. This process has recently begun based on imaging campaigns at the WHT and SALT telescopes.$^{11}$

The identities, and redshifts, of the candidates with fewer counts are likely to remain unknown until more sensitive large-area imaging surveys are publicly available (e.g. from the Dark Energy Survey, LSST, or Pan-Starrs$^4$).

### 4.1.1 Candidates not classified as clusters

The XCS-Zoo exercise was primarily designed to pick out the obvious clusters in the candidate list; these clusters can be used in the short term for a variety of scientific applications (Section 6.5) and in the longer term can be used to inform improvements to both the optical and X-ray methodology used by XCS. Therefore, anything that wasn’t obviously a cluster ended up in the other category. On the completion of XCS-Zoo, we reviewed all the candidates$^{30}$ in the other category and found they could be sub-divided into the following classes:

(i) Masking or reduction issues ($\simeq 50\%$ per cent): Before running the XAPA software on a given ObsID, the XCS generated image is examined by eye. Any sub-regions unsuitable for cluster searching are saved into a mask file, and

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8. In principle, useful information related to candidate identification could be derived from a wide range of observations, including radio and infra-red, but to date (June 2011) we have only had optical data.

9. All XCS candidates are extended in a statistical sense, but only the high signal-to-noise sources stand out to the human eye as being unambiguously extended and without blend contamination.

10. The slight decrease compared to the numbers mentioned in the paragraph above is a result of the removal of some clusters that were either ObsID targets or associated with ObsID targets, Section 4.2.

11. www.mgi.iac.es, www.salt.ac.za

12. darkenergysurvey.org; lsst.org; pan-starrs.ifa.hawaii.edu
Figure 4. The first four clusters presented in Table 3 classified as gold in Zoo^{DR7} (Section 4.1). False colour-composite images are $3 \times 3$ arcmin with X-ray contours overlaid in blue. Corresponding X-ray images are shown below each optical image (lighter regions show areas of increased X-ray flux). The shape of the XAPA-detected extended (point) source ellipses are highlighted in green (red).

From left to right, the clusters are: XMMXCS J001737.4−205235.4 at $z = 0.21$; XMMXCS J010858.7+132557.7 at $z = 0.15$; XMMXCS J083454.8+553420.9 at $z = 0.24$; and XMMXCS J092018.9+370617.7 at $z = 0.21$.

Figure 5. Four XCS-DR1 clusters that have been classified as silver in Zoo^{DR7} (Section 4.1). False colour-composite images are $3 \times 3$ arcmin with X-ray contours overlaid in blue. Corresponding X-ray images are shown below each optical image (lighter regions show areas of increased X-ray flux). The shape of the XAPA-detected extended source ellipses are highlighted in green. The right-most cluster is an example where the classification (as silver) was based predominantly on the X-ray data, the other three are examples where the classification (as silver) was based predominantly on the galaxy overdensity (these three represent the first silver entries in Table 3).

From left to right, the clusters are: XMMXCS J004231.6+005119.9 at $z = 0.15$; XMMXCS J004252.6+004303.1 at $z = 0.27$; XMMXCS J004333.7+010109.6 at $z = 0.20$; and XMMXCS J122658.1+333250.9 at $z = 0.89$. 
Figure 6. The first four clusters in Table 3 classified as bronze in Zoo^{DR7} (Section 4.1), all four have been optically confirmed using information in the literature (Section 4.2). False colour-composite images are \(3 \times 3\) arcmin with X-ray contours overlaid in blue. Corresponding X-ray images are shown below each optical image (lighter regions show areas of increased X-ray flux). The shape of the XAPA-detected extended (point) source ellipses are highlighted in green (red). From left to right, the clusters are: XMMXCS J092111.0+302758.2 at \(z = 0.43\); XMMXCS J095951.4+014052.1 at \(z = 0.37\); XMMXCS J101056.3+555711.5 at \(z = 0.17\); and XMMXCS J103100.1+305134.9 at \(z = 0.14\).

some files are removed from the pipeline entirely. The removed files include those with atypically high backgrounds (this can occur if one of the XMM cameras was behaving abnormally during the exposure). The masked regions include those covered by large extended objects, such as low-redshift clusters, or those with out-of-time bleed trails (see LD10). The purpose of these eye-ball checks is to correct the XCS survey area for regions where serendipitous clusters could not have been found. However, XCS-Zoo has shown that several high background files had not been excluded. Moreover, some of the image masks were not large enough and, as a result, XAPA was either mistaking discontinuities at the mask edges as ‘sources’ (e.g. Fig. 7, far left panel), or detecting multiple portions of a large cluster as separate sources (because the largest XAPA wavelet was too small to encompass the whole object). Both these problems can be solved by improving the checks of reduced images before they are passed to XAPA. In future the checks will be made independently by at least two experienced XCS members (rather than relying on student volunteers, as was done previously). We are confident, therefore, that future generations of the candidate list will not be similarly contaminated by masking or reduction issues.

(ii) Require additional follow-up: a) identity unknown (\(\simeq 13\) per cent): In these cases, the identity of the candidate will not be established until more data is available. If any of these candidates are distant clusters, then they will be revealed using deeper optical (or IR) imaging (as was the case for the examples shown in Fig. 8). However, if any of them are blends or other artefacts (see items v and vi), then additional X-ray imaging might be required, e.g. using the Chandra X-ray observatory\(^{13}\) because it has much higher spatial resolution than XMM.

(iii) Require additional follow-up: b) clusters (\(\simeq 12\) per cent): The XCS-Zoo categories were set by rounding down the average value. So it was inevitable that some candidates judged likely to be clusters by some classifiers would end up in the other category, rather than bronze. We note that in one case (XMMXCS J074528.1+280011.3\(^{1}\)), the candidate could have been classed as silver because it is an ‘unambiguous extended X-ray source associated with a suspected galaxy overdensity’. However, the overdensity was only revealed after extra (to XCS-Zoo) manipulation of the SDSS data; the location of the X-ray source falls under a bright star diffraction spike in the SDSS image. This cluster was detected with 1690 counts and so would easily yield a \(T_{X}\) value, if the redshift were known.

(iv) Non-cluster X-ray source: a) extended but not a cluster (\(\simeq 11\) per cent): The XAPA software is designed to pick up extended objects, rather than clusters specifically, so contamination of the candidate list by non-cluster extended sources is to be expected. Fortunately, clusters are the only type of extended X-ray source outside of the Solar-System\(^{14}\) that are bright enough to be detected at high-red-
Figure 7. A selection of XCS sources classified as *other* in Zoo*DR7* (Section 4.1). None of these objects are included in XCS-DR1†. False colour-composite images are $3 \times 3$ arcmin with X-ray contours overlaid in blue. Corresponding X-ray images are shown below each optical image (lighter regions show areas of increased X-ray flux). The shape of the XAPA-detected extended (point) source ellipse is highlighted in green (red). Reasons for a classification as *other* include artifacts at the edge of ObsID masks (far left); extended X-ray sources not associated with a galaxy cluster, such as a low-redshift galaxy (mid left); cases where neighbouring X-ray point sources have been blended by XAPA into an erroneous extended source (mid right); and finally, cases of point sources misclassified as extended (because the point spread function model at the edge of the XMM field-of-view is inadequate; far right).

Figure 8. Four examples of XCS-DR1 clusters in classified as *bronze* in Zoo*DR7* (Section 4.1) that were subsequently classified as *gold* or *silver* in Zoo*NXS* or Zoo*S82*. False colour-composite images are $3 \times 3$ arcmin with X-ray contours overlaid in blue. Images from SDSS DR7 are shown above the corresponding deeper image (Stripe 82 on far and mid left, NXS on far and mid right). From left to right the clusters are: XMMXCS J030205.1−000003.6 at $z = 0.65$; XMMXCS J030317.4+001238.4 at $z = 0.59$; XMMXCS J083115.0+523453.9 at $z = 0.52$ and XMMXCS J083025.9+524128.4 at $z = 0.99$. 
shift, so any other types of extended sources, such as low-redshift galaxies, supernovae remnants or star-formation regions (e.g. Fig. 7 mid-left panel), are straightforward to identify using XCS-Zoo. We are improving our automated NED checks in order to remove more of this type of contaminating object from the candidate lists in future.

(v) Non-cluster X-ray source: b) blend (≈ 8 per cent): Despite using multi-scale wavelet detections, XAPA sometimes confuses emission from two or more neighbouring point sources as being the extended emission from a single object. Several obvious cases of blended emission were identified using XCS-Zoo, either from the X-ray data directly, and/or with reference to optical images (e.g. Fig. 7 mid-right panel). Blends will continue to affect our candidate lists in future, due to the limited spatial resolution of XMM, and the most effective way to remove them will be to continue to use an exercise like XCS-Zoo.

(vi) Non-cluster X-ray source: c) bow-tie-shaped point source (≈ 6 per cent): XAPA uses an XMM-supplied circularly-symmetric PSF model to distinguish between point-like and extended sources. It is well-known that this model fails to describe the bow-tie-shaped nature of point source images at large off-axis angles. Such sources can be erroneously classified as extended by XAPA and several examples were identified using XCS-Zoo (e.g. Fig. 7 far right panel). It is possible that an improved PSF model would help prevent these objects contaminating future candidate lists. If not, they can continue to be excluded at the XCS-Zoo stage.

4.2 Candidate identification using the literature or multi-object spectroscopy

In addition to using XCS-Zoo (Section 4.1), we have used information in the literature and our own multi-object spectroscopy to confirm candidates as clusters. To this end, we have examined candidates with associated redshifts that were either not part of XCS-Zoo at all, or that were classified by it as bronze. For those with redshifts from our spectroscopic follow-up campaign (Section 2.3), we have judged them to be confirmed as clusters if there are multiple concordant galaxy redshifts. There are 13 such cases. In addition, we confirmed one cluster, XMMXCS J231852.3−423147.6, despite it having a spectroscopic redshift based on only one galaxy, because it was associated with an obvious galaxy overdensity in the Digitised Sky Survey (DSS). For those with redshifts from the literature (zlit; Section 3.3), we have used published material, in combination with the DSS to confirm 103 candidates as clusters (see below for explanation and Fig. 6 for examples). XCS-DR1 clusters confirmed in either of these ways can be recognised because they either carry no indication of their XCS-Zoo classification (because they were not part of it), or are flagged as b for bronze (see Section 5.1).

For the zlit candidates, we used the following criteria as evidence for confirmation: (i) association with a galaxy overdensity that is obvious to the eye in the DSS (e.g. XMMXCS J000141.4−154031.3, z = 0.12, and XMMXCS J005603.0−373248.0, z = 0.17); and/or (ii) association with a galaxy overdensity that is obvious to the eye in published optical/IR images (e.g. XMMXCS J000141.4−154031.3, z = 0.12, and XMMXCS J005603.0−373248.0, z = 0.17); and/or (iii) zlit values based on multi-object spectroscopy (e.g. XMMXCS J010422.4−063004.5, z = 0.95, and XMMXCS J022738.5−031801.3, z = 0.84); and/or (iv) membership in an optical/IR cluster catalogue that was constructed using an objective galaxy-based technique (e.g. XMMXCS J022618.3−040000.1, z = 0.20, and XMMXCS J100053.2+022831.6, z = 0.3). Moreover, the XMM image of the candidate should be consistent with an extended X-ray source without blend contamination. We have been deliberately conservative with these 'literature confirmations'. As a consequence, several candidates with associated zlit values were not included in XCS-DR1 because they could not be confirmed using available resources, for example: XMMXCS J105251.8+573156.0† (z = 0.58).

4.3 Candidates that were not serendipitous detections

It is vital to the statistical integrity of XCS-derived cluster samples, that all the clusters are detected serendipitously by XMM. Therefore, filters are applied before the candidate list is generated to remove non-serendipitous or 'target' clusters (LD10). The filters are generally very effective, even when the telescope was positioned so that the target clusters were detected away from the aim-point. Target filtering works both when the respective ObsID is classified in the XMM database (and ObsID header) as having a cluster target, and when it does not. In the latter case, target clusters are identified by cross-checking the PI-supplied target names against NED. The NED cross-check can recognise most cluster names, but not when those names include atypical representations of cluster coordinates (see below for examples), so we can expect a small number of 'target' clusters to contaminate the candidate list. Therefore, during XCS-Zoo, we flagged up any candidates that might possibly be targets (based on their extent relative to their location in the ObsID) as a precautionary measure. We checked the ObsID headers for all of those so flagged individually. We also checked the headers for any remaining confirmed clusters with XAPA centroids that were separated by 3 arcmin or less from the ObsID aim-point.

Of those candidates that were checked, the majority were confirmed to be valid members of the candidate list, e.g. XMMXCS J100029.2+024137.4 (z = 0.35; Finoguenov et al. 2007), which was detected near the XMM aim-point, but was still a genuine serendipitous detection because that ObsID was part of a blind survey towards the COSMOS field (Scoville et al. 2007). Other examples include candidates that were indeed the target of the ObsID viewed during XCS-Zoo, but were also detected serendipitously in at least one other ObsID. In these instances, the ObsID with the target cluster was chosen by XAPA to represent the candidate because it contained the most detected counts. Examples of such candidates include XMMXCS J130832.6+534214.2 (z = 0.33) and XMMXCS J052215.4−362513.7 (z = 0.47). Only seven candidates flagged as being potential target
clusters by XCS-Zoo turned out to be so when individually checked. These have not been included in XCS-DR1. In these seven cases, the PI-supplied target name did not match any of those listed for that cluster in NED. Examples include XMMXCS J092021.2+303005.7, which is associated in NED with the literature cluster NSC J092017+303027 (Gal et al. 2003; \( z = 0.29 \)), but which had a target name of DLS09201+3029. Another example is XMMXCS J131914.6−005911.6, which is associated in NED with the literature cluster SDSS CE J199.807541−00.985108 (Goto et al. 2002; \( z = 0.09 \)), but which had a target name of 2PI0.084J1319.3−005.

It is also important to avoid including clusters in XCS samples that, despite not being the ObsID target, are physically associated with it; in these cases there is a better than random chance of the cluster entering the XCS survey volume. Therefore, a NED-based filter is run before the candidate list is drawn up to identify such cases (see LD10). However, this only works if the candidate’s redshift is available in NED, and in many cases it is not. Therefore, we ran a similar filter on an initial XCS-DR1 list to highlight clusters with similar redshifts to their respective ObsID target (whether that target is a cluster or not). We found one such case, XMMXCS J083057.0+655059.2, the cluster redshift was \( z = 0.21 \) and the target redshift was \( z = 0.18 \), and so this cluster was removed from XCS-DR1.

5 THE XCS-DR1 CLUSTER CATALOGUE

The first XCS data release (XCS-DR1) is presented in Tables [3] and [4]. It consists of 503 candidates that we have optically confirmed as being serendipitously detected X-ray clusters (Section [3]), 255 of which were detected with more than 300 counts. The contents of each of the columns in Tables [3] and [4] and the associated webpage, are explained in Section [5.1]. We describe the selection of redshifts for the clusters in Sections [5.2] and [5.3]. In Section [5.4], we discuss the errors on the CMR-redshifts derived from both our own observations and from archival data. In Section [5.5], we describe the selection of alternative names for the clusters.

5.1 The XCS-DR1 data table and webpage

The columns in Table [3] contain the following information:

1. The XCS name. Contained within the name are the positional coordinates (R.A. and Dec. in J2000) of the XAPA determined X-ray centroid.
2. The number of counts (0.5-2.0 keV) detected from each cluster (see Section [1] for a definition of ‘counts’).
3. The adopted cluster redshift (Section [5.2]).
4. The source of the redshift and, where applicable, the XCS-Zoo classification. Superscripts g, s, and b denote XCS-Zoo classifications of gold, silver and bronze respectively. If a cluster redshift is not presented in Column three, then Column four indicates which XCS-Zoo was used to provide the optical confirmation. In these cases, a superscript 1 refers to instances where the XNS images used for the optical confirmation were taken under non-photometric conditions, and a superscript 2 denotes cases where the CMR-redshift was considered to be unreliable (Section [2.2]).

Superscripts 3, 4 and 5 denote literature redshifts derived from spectroscopic, photometric and X-ray data respectively. The symbol ‘+’ denotes clusters that form part of a preliminary statistical subsample (Section [6.5.7]).

5. The measured X-ray temperature for each cluster, and the 1σ errors. Only clusters that have measured \( T_X \) values have \( L_X \) information (see LD10).
6. The adopted alternative cluster name taken from the literature (Section [5.4]).
7. The reference for the alternative name given in Column six, and, where applicable, a reference for the redshift in Column three.

The columns in Table [4] contain the following information:

1. The XCS name (i.e. as column 1 in Table [3]).
2. The bolometric (0.05 – 100 keV band) luminosity in units of \( 10^{44} \text{ erg s}^{-1} \) within a radius of \( R_{500} \), and the 1σ errors. Only clusters that have measured \( T_X \) values have \( L_X \) information (see LD10).
3. The \( R_{500} \) value used to derive the luminosity in Column 2.
4. The bolometric (0.05 – 100 keV band) luminosity in units of \( 10^{44} \text{ erg s}^{-1} \) within a radius of \( R_{200} \), and the 1σ errors. Only clusters that have measured \( T_X \) values have \( L_X \) information (see LD10).
5. The \( R_{200} \) value used to derive the luminosity in Column 4.
6. The power-law slope of the fitted \( \beta \)-profile.
7. The core radius in units of kpc.
8. The spatial model used to derive the luminosity. These models are defined in LD10, but summarised here for completeness. They are all based on spherical \( \beta \)-profile model (Cavaliere & Fusco-Femiano 1976). In Model 0, both \( \beta = 2/3 \) and \( r_c \) are fixed (the later being estimated using the measured \( T_X \)), and it is, therefore, not appropriate to include errors with the derived \( L_X \) values. Model 1 has \( \beta \) fixed at the canonical value of 2/3, but allows \( r_c \) to vary. Model 2 also allows \( \beta \) to vary. Model 3 is similar to 2, but includes a central cusp (to replicate an AGN or a cool core).

Similar information to that in Table [3] appears on the XCS-DR1 webpage table (accessible from http://xcs-home.org/datareleases). The webpage table can be ordered by right ascension, redshift, and temperature. The key advantage of the webpage table, over Table [3], is that each XCS name connects to a separate page that contains X-ray and optical, greyscale and colour-composite, images. There are 3×3 arcmin \( \text{XMM} \) and optical cut-outs, plus the full field-of-view of the respective ObsID. The X-ray images can be viewed with or without the XAPA defined source outlines, and the optical images can be viewed with or without \( \text{XMM} \) surface brightness contours. The optical cut-outs are taken from NXS, SDSS DR7 or SDSS S82, where available. In the event of more than one of these being available, the deepest image is presented. When none are available (i.e. when the candidate was confirmed as being a cluster using either the literature or our own spectroscopy, Section [4.2], the DSS image is shown.
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Table 3. The XCS-DR1 Cluster Catalogue: Part I, redshifts and X-ray temperatures. A full version of Table 3 is provided in electronic format in the online version of the article. Descriptions of column entries and superscripts are provided in Section 5.2.

| XCS ID                | Counts | $z$  | $z$-source | $T_x$ | Alternative name | References |
|-----------------------|--------|------|------------|-------|------------------|------------|
|                      |        |      |            | keV   |                  |            |
| (1)                  | (2)    | (3)  | (4)        | (5)   |                  | (6)        |
| XMMXCS J000013.9−251052.1 | 878    | 0.08 | Lit$^{3g}$ | 1.8$^{+0.4}_{-0.3}$ | APMCC 948 | [1,1]  |
| XMMXCS J000029.8−251211.4 | 652    | 0.15 | NXS$^{2s}$ | 0.81$^{+0.04}_{-0.05}$ |         |     |
| XMMXCS J000103.8−250353.6 | 362    | 0.91 | NXS$^{s}$ |         |                  |      |
| XMMXCS J000141.4−154031.3 | 1135   | 0.12 | Lit$^{3}$ | 1.8$^{+0.3}_{-0.1}$ | RXC J0001.6−1540 | [2,2]  |
| XMMXCS J000626.2+195944.2 | 118    | 0.46 | NXS$^{s}$ |         |                  |      |
| XMMXCS J001116.1+005211.3 | 155    | 0.36 | S82$^{a}$ | 0.7$^{+0.1}_{-0.1}$ |         |     |
| XMMXCS J001328.5−272319.0 | 484    |     | NXS$^{1s}$ |         |                  |      |
| XMMXCS J001345.2−271654.8 | 164    |     | NXS$^{1s}$ |         |                  |      |
| XMMXCS J001639.1−010211.5 | 403    | 0.17 | S82$^{2s}$ | 1.7$^{+1.5}_{-0.4}$ | MaxBCG J004.16184−01.03538 | [3,1]  |

Table 4. The XCS-DR1 Cluster Catalogue: Part II, X-ray luminosities. A full version of Table 4 is provided in electronic format in the online version of the article. Descriptions of column entries and superscripts are provided in Section 5.2.

| XCS ID                | $L_{500}$ | $R_{500}$ | $L_{200}$ | $R_{200}$ | $\beta$ | $r_e$ | Model used |
|-----------------------|-----------|-----------|-----------|-----------|---------|------|------------|
|                      | (1)       | (2)       | (3)       | (4)       | (5)     | (6)  | (7)        |
| XMMXCS J000013.9−251052.1 | 0.066$^{+0.017}_{-0.009}$ | 566$^{+73}_{-28}$ | 0.096$^{+0.032}_{-0.015}$ | 858$^{+111}_{-41}$ | 0.350$^{+0.099}_{-0.021}$ | 1.00$^{+0.013}_{-0.016}$ | 2 |
| XMMXCS J000029.8−251211.4 | 0.066$^{+0.011}_{-0.002}$ | 343$^{+16}_{-11}$ | 0.405$^{+0.131}_{-0.066}$ | 520$^{+15}_{-16}$ | 0.438$^{+0.112}_{-0.088}$ | 1.00$^{+0.003}_{-0.000}$ | 3 |
| XMMXCS J000103.8−250353.6 | 0.177     | 561$^{+55}_{-16}$ | 0.167     | 561$^{+55}_{-16}$ | 0.666   | 0.589 | 0         |
| XMMXCS J00141.4−154031.3 | 0.035$^{+0.166}_{-0.027}$ | 259$^{+73}_{-13}$ | 0.073$^{+0.032}_{-0.059}$ | 394$^{+31}_{-20}$ | 0.350$^{+0.049}_{-0.046}$ | 2.00$^{+0.356}_{-0.335}$ | 3 |
| XMMXCS J000626.2+195944.2 | 0.035$^{+0.166}_{-0.027}$ | 259$^{+73}_{-13}$ | 0.073$^{+0.032}_{-0.059}$ | 394$^{+31}_{-20}$ | 0.350$^{+0.049}_{-0.046}$ | 2.00$^{+0.356}_{-0.335}$ | 3 |
| XMMXCS J001116.1+005211.3 | 0.035$^{+0.166}_{-0.027}$ | 259$^{+73}_{-13}$ | 0.073$^{+0.032}_{-0.059}$ | 394$^{+31}_{-20}$ | 0.350$^{+0.049}_{-0.046}$ | 2.00$^{+0.356}_{-0.335}$ | 3 |
| XMMXCS J001328.5−272319.0 | 0.035$^{+0.166}_{-0.027}$ | 259$^{+73}_{-13}$ | 0.073$^{+0.032}_{-0.059}$ | 394$^{+31}_{-20}$ | 0.350$^{+0.049}_{-0.046}$ | 2.00$^{+0.356}_{-0.335}$ | 3 |
| XMMXCS J001345.2−271654.8 | 0.084$^{+0.148}_{-0.068}$ | 506$^{+225}_{-81}$ | 0.108$^{+0.295}_{-0.092}$ | 768$^{+742}_{-123}$ | 0.733$^{+0.155}_{-0.148}$ | 2.00$^{+1.683}_{-1.015}$ | 2 |

A machine-readable version of XCS-DR1, that includes the information in both Table 3 and Table 4 is available from the same URL.

5.2 Selection of the cluster redshift

A particular cluster may be associated with multiple redshift estimates, but each cluster is presented with only a single redshift in Column 3 of Table 3. That redshift is chosen based on the quality of the measurement, with spectroscopic redshifts almost always favoured over photometric redshifts, as we describe below. In total, 464 redshifts appear in XCS-DR1, as summarised in Table 3. We note that the rightmost column of Table 3 sums to four more than 464. This is because the three H11 entries are also included in the ‘Lit (added/changed by hand)’ row. We have also double counted XMMXCS J221559.6−173816.2 because it has used its literature redshift, but since that redshift based on our own spectroscopy, it also appears in the ‘Spec’ row.

If a cluster has more than one spectroscopic redshift, then the typical hierarchy is as follows: those obtained by XCS team members are favoured over those from SDSS LRGs, which in turn are favoured over those taken from the literature (with $z_{10}$ values based on optical spectroscopy bring prioritised over those from X-ray spectroscopy). The redshift source for these clusters are indicated in Column 4 as ‘Spec’, ‘LRG’ and ‘Lit$^{3s}$’ respectively (Lit$^{3}$ is used in the case of X-ray literature redshifts). For the purposes of XCS-DR1, the uncertainty on the optical spectroscopic redshifts is assumed to be insignificant (being at the level of the cluster velocity dispersion, i.e. $\sigma_v < 2000$ km s$^{-1}$). The errors on the two X-ray redshifts used in XCS-DR1 are $\pm 0.05$ and $\pm 0.03$ respectively for XMMXCS J004624.5+420429.5 (or RX J0046.4+4204 at $z_e = 0.3$; Kotov et al. 2006), and XMMXCS J083025.9+524128.4 (or 2XMM J083026+524133 at $z_e = 0.99$; Lamer et al. 2008).

The adopted hierarchy of spectroscopic redshifts is based on the assumption that spectra obtained closest to the XAPA centroid are most likely to be of cluster members. Since most of the literature redshifts were obtained for clusters selected using optical methods, and the optical centroid can differ from the XAPA one, it seemed prudent to use our own (or LRG) spectra rather than published values (even when the published value was based on more galaxies). We have also chosen to adopt a spectroscopic redshift from H11 over our own LRG redshift for the cluster XMMXCS J030659.8+000824.9. The H11 study, a search for ‘fossil’ systems in the XMM archive, involves a redshift allocation process based on SDSS spectroscopy. The H11 method differs from that described in Section 5.2 in that it is based on all available galaxy spectra, rather than just those for LRGs. There is significant overlap (in the common region, i.e. the SDSS footprint) between the objects in the H11 study and the candidate list used for this paper (although, in H11,
non-serendipitous – or XMM-target – sources were also included). We have therefore cross-checked the XCS-DR1 redshift assigned by the default hierarchy against the H11 determined values using 94 XCS-DR1 clusters. The redshifts match very closely with two exceptions. We have examined these and determined that in one instance (XMMXCS J030659.8+000824.9), the H11 value was more reliable than our default choice, because the redshift was based on galaxies closer to the XAPA centroid (in the other, XMMXCS J133605.0+514531.2, it was clear from the DR7 image that our default redshift choice, \(z = 0.53\), was more appropriate than that of H11, \(z_{H11} = 0.234\)). We note, as previously mentioned in Section 3.3, that we have also used H11 redshifts for two confirmed XCS-DR1 clusters that had no other available redshift information. All three of the H11 determined redshifts listed in Table 3 are denoted as ‘H11’ in column 4.

If no spectroscopic redshift was available, but a CMR-redshift was, then this will be listed in column 3, with its origin indicated as ‘NXS’, ‘DR7’ or ‘S82’ in column 4. The uncertainty associated with these CMR-redshifts is \(\sigma_z = 0.08\), \(\sigma_z = 0.03\) and \(\sigma_z = 0.03\) respectively (see Section 5.3).

When more than one CMR-redshift is available for a particular cluster, then the value chosen is governed by the relative quality of imaging, so that those taken from S82 are favoured over those from NXS, which are in turn favoured over those from SDSS DR7. The CMR-redshift algorithm is not able to determine redshifts below \(z = 0.1\) (see Section 2.2). Thus, CMR-redshifts with values of exactly \(z = 0.1\) are taken as upper limits and presented in Table 3 as \(z < 0.1\). In one instance (XMMXCS J064423.6+822626.5), we suspect that the CMR-redshift \((z_{CMR} = 0.84)\) is a catastrophic failure, based on the appearance of the NXS image (the cluster falls over a MOSAIC chip gap; Section 2.1) and we have not included a redshift for it XCS-DR1.

Finally, when no other redshift information is available, but a non-spectroscopic literature redshift is, then that is used in XCS-DR1. One exception to this hierarchy was the use of a photometric literature redshift \((z = 0.29)\) for XMMXCS J090101.5+600606.2. That redshift came from the MaxBCG catalogue (Koester et al. 2007b) and was chosen over the corresponding SDSS DR7 CMR-redshift \((z = 0.23)\) because that system had been included in some initial testing of a multi-colour-based method to determine CMR-redshifts (Section 6.2), and that method placed the cluster closer to the MaxBCG value.

### 5.3 Photometric redshift accuracy

We have derived CMR-redshifts from NXS and SDSS DR7 and S82 data for 224, 574, and 51 confirmed clusters respectively (including duplicates), see Sections 2.2, 3.1 and Table 5. We have been able to extract optical spectroscopic redshifts for a fraction of these candidates using either our own observations, the SDSS archive, or the literature (Sections 2.3, 3.2 and 3.3 respectively). These spectroscopic redshifts have allowed us to determine the typical accuracy, and the catastrophic failure rate, of the CMR-redshifts presented in XCS-DR1.

Figures 9, 10 and 11 show the results for NXS, SDSS DR7 and S82 respectively, under the assumption that the spectroscopic redshift is the true value. We note that only \textit{gold} and \textit{silver} clusters from XCS-DR1 were included in this comparison. The typical CMR-redshift uncertainty has thus been determined, from a 3σ clipped mean, to be \(\sigma_z = 0.08\), \(\sigma_z = 0.03\) and \(\sigma_z = 0.03\) for NXS, SDSS DR7 and S82 respectively. These redshift uncertainties, are similar to those obtained by other authors using the single colour technique.

Figure 9. A comparison between photometric CMR-redshifts obtained from NXS imaging (Section 2.2) and corresponding spectroscopic redshifts (Sections 2.3, 3.2 and 3.3). The comparison uses 39 clusters optically confirmed as \textit{gold} or \textit{silver} by Zoo\textsubscript{NXS} (Section 4.1). Note that one of these 39 is not shown in the figure (XMMXCS J221559.6-173816.2), because it has an anomalously large redshift offset (see Table 6). The bars indicate the statistical 1σ limits on each CMR-redshift (Section 2.2). Only those clusters with CMR-redshifts obtained from photometrically calibrated data with a minimum of 5 galaxies and with statistical uncertainties of \(\sigma_z < 0.1\) have been used in the comparison. The dotted line shows the one-to-one relation.

Figure 10. A comparison between photometric CMR-redshifts obtained from SDSS DR7 imaging (Section 3.1) and corresponding spectroscopic redshifts (Sections 2.3, 3.2 and 3.3). The comparison uses 138 clusters optically confirmed as \textit{gold} or \textit{silver} by Zoo\textsubscript{DR7} (Section 4.1). The bars indicate the statistical 1σ limits on each CMR-redshift (Section 2.2). Only those clusters with CMR-redshifts obtained from a minimum of 5 galaxies and with statistical uncertainties of \(\sigma_z < 0.1\) have been used in the comparison. The dotted line shows the one-to-one relation.
Table 5. A summary of the redshifts used in XCS-DR1.

| Redshift Source | Candidates | Overlap with DR1 clusters | Used in XCS-DR1 |
|----------------|------------|----------------------------|-----------------|
| Lit (auto NED query) | 493 | 219 | 127 |
| LRG           | 265 | 265 | 111 |
| CMR-NXS       | 224 | 224 | 74  |
| CMR-DR7       | 574 | 574 | 80  |
| Spec          | 35  | 35  | 35  |
| CMR-S82       | 51  | 51  | 19  |
| Lit (added/changed by hand) | 19 | 19 | 19 |
| H11 method    | n.a. | 94 | 3   |

Figure 11. A comparison between photometric CMR-redshifts obtained from the SDSS S82 (Section 3.1) and corresponding spectroscopic redshifts (Sections 2.3, 3.2 and 3.3). The comparison uses 14 clusters optically confirmed as spectroscopic redshifts. The bars indicate the statistical limits on each CMR-redshift (Section 2.2). Only those clusters with CMR-redshifts obtained from a minimum of 5 galaxies and with statistical uncertainties of $\sigma_z < 0.1$ have been used in the comparison. The dotted line shows the one-to-one relation.

For example, Gladders (2004) estimate red-sequence redshift errors of $\sigma_z = 0.05$ between $0.2 < z < 1$ using a single colour.

We note that a mean offset of $\Delta z = 0.03$, $\Delta z = 0.01$ and $\Delta z = 0.02$ was found for NXS, SDSS DR7 and S82 respectively, plus there is a trend to systematically underestimate CMR-redshifts above the statistical errors, and there are very few spectroscopic redshifts available beyond $z \simeq 0.5$ with which to explore the redshift trend, we have not to adjust the CMR-redshifts for them.

All of the $3\sigma$ redshift outliers are listed in Table 6. These outliers either represent catastrophic failures of the CMR technique or indicate incidences where the adopted spectroscopic redshift was wrong. In the following cases the CMR-redshift method has broken down: XMMXCS J133514.1+374905.8 and XMMXCS J221559.6−173816.2 (both clusters are at redshifts beyond the grasp of their respective imaging surveys). In the case of XMMXCS J163341.0+571420.1, the candidate lies right at the edge of the SDSS footprint, so that only a fraction of the extraction region contains catalogued SDSS galaxies; we will refine our CMR-redshift techniques to filter out such objects in future. In the remaining cases (XMMXCS J030646.2−000112.7, XMMXCS J033556.2+003214.7, XMMXCS J124100.8+325959.9, and XMMXCS J204134.7−350901.2), it is difficult to say if the fault lies with the CMR-redshift method or with the adopted spectroscopic redshift, as the $z_{\text{spec}}$ values are based on a single galaxy. More spectroscopy would be needed to confirm these redshifts, and hence improve our estimate of the CMR-redshift catastrophic failure rate. However, assuming all entries in Table 6 to be CMR failures, the failure rate is then $\simeq 5$, $\simeq 3$ and $\simeq 7$ per cent for NXS, SDSS DR7, and S82, respectively.

5.4 Selection of alternative names

Many of the XCS-DR1 clusters have been catalogued before by previous authors. In order to give due credit to this earlier work, we have matched XCS-DR1 clusters to catalogued clusters using an automated NED query. This query was run separately to that used to extract literature redshifts (Section 3.3) and involved a simple search for any NED object classified as a galaxy cluster within a fixed radius of the XAPA-defined centroid. The radius used was the mean of the major and minor axes of the XAPA defined source ellipse. In the event of several NED matches within this radius, the default top choice listed by NED (ordered by separation, on the date the query was made) was used. We concede that this approach is not ideal, in that it might not select the historical name of a cluster (e.g. one taken from the Abell catalogue, Abell 1958, if another catalogue (e.g. MaxBCG, Koester et al. 2007a) has an entry with an optical centroid closer to the XAPA position. We also note that if the selected redshift (Section 5.2) of the XCS-DR1 cluster does not come from a literature source, then the redshift in XCS-DR1 might differ from the NED redshift for the previously catalogued cluster. In addition to the automated NED query, some alternative names have been added by hand from papers too recent to have been in NED at the time the search was carried out (see Section 3.3). In total, 248 of the XCS-DR1 clusters have been matched with alternative names.

6 SUMMARY AND DISCUSSION

In Fig. 1 we introduced the steps involved in the development of XCS-DR1. In this paper we have focussed on the steps involving redshift follow-up, quality control and cluster...
sections, we have already started the imaging follow-up for these objects. However we note that these new images will not be as useful to the X-ray community, as those obtained during NXS, because they will not necessarily provide imaging across entire XMM field (opting to target specific candidates instead). Third, we could improve the accuracy of the existing CMR-redshifts using additional observations through other filters. Other authors have shown that multi-colour photometric redshifts are more accurate than our single-colour ones. For example, Song et al. (2011) and High et al. (2010) achieve typical uncertainties of 2 per cent in for and , to and respectively (both studies use the mean colour of the red-sequence as the cluster redshift estimator). Two other multi-colour cluster finders, MaxBCG and GMBCG (Koester et al. 2007a and Hao et al. 2010) achieve uncertainties of and for respectively (both studies use the cluster red-sequence for cluster finding, but adopt the photometric redshift of the identified BCG as the cluster redshift). The addition of extra filters will mostly benefit the high-redshift end, but bluer filters would be of benefit at the low-redshift end also (i.e. allowing us to bridge the 4000 Å break at ).

Section 3.3 presented the results to date (June 2011) from optical spectroscopy performed by XCS team members; 34 new (and one previously published) spectroscopic cluster redshifts (Table 2). We highlighted a new (to the literature) cluster with multi-object spectroscopic confirmation (XMMXS J091821.9+211446.0,  , Fig. 5), and a new (to the literature) cluster, XMMXS J015241.1−133855.9 at  = 0.83, that is most likely associated with the well-studied merger system XMMXS J015242.2−135746.8 (or WARP J0152.7−1357). The new spectroscopic redshifts have been invaluable with regard to the calibration of the CMR-redshifts and the derivation of X-ray temperatures. We intend to continue the spectroscopic follow-up of XCS candidates for several more years, with the emphasis on multi-object spectroscopy where possible.

6.2 Redshift follow-up (archive)

In Section 3 we described how we used data in public archives, and the literature, to collect more redshifts for our candidates (see Table 5 for a summary). In Section 3.1 we described how we applied the CMR-redshift technique designed for NXS to SDSS DR7 and S82 data. Excluding unreliable fits, a total of 574 and 51 CMR-redshift measurements were made using regular SDSS DR7 and S82 data respectively, 80 and 19 of which appear in XCS-DR1. The

Table 6. XCS clusters with CMR-redshifts that were more than 3σ from their respective spectroscopic redshift. The XCS name is given in Column 1. The CMR-redshift, and the imaging survey from which it was derived, are listed in Columns 2 and 3. The measured spectroscopic redshift and its source are given in Columns 4 and 5.

| XCS ID         |  | Imaging survey | Zspec source | Zspec | ZCMR value |
|----------------|---|----------------|--------------|-------|------------|
| XMMXS J030644.2−000112.7 | 0.35 | S82           | LRG          | 0.11  | DR7        |
| XMMXS J033556.2+003214.7 | 0.31 | DR7           | LRG          | 0.43  | DR7        |
| XMMXS J124100.8+325959.9 | 0.15 | DR7           | LRG          | 0.27  | DR7        |
| XMMXS J133514.1+374905.8 | 0.31 | DR7           | Literature   | 0.60  | DR7        |
| XMMXS J163341.0+571420.1 | 0.54 | DR7           | Literature   | 0.24  | DR7        |
| XMMXS J204134.7−350001.2 | 0.67 | NXS           | XCS          | 0.43  | DR7        |
| XMMXS J221559.6−173816.2 | 0.42 | NXS           | XCS          | 1.46  | XCS        |

Looking ahead, plan secure additional CCD imaging on 4-meter class telescopes. This will allow us to improve on, and extend, the current NXS results in three ways. First, we would like to calibrate the 30 NXS-fields that currently lack photometric calibration; this would allow additional CMR-redshifts to be extracted from NXS. Second, there are hundreds of candidates that have yet to be included in an XCS-Zoo identification exercise to the depth of Zoos NXS and ZooSS82, including 467 candidates and 300 that have not been included in any XCS-Zoo, and a further 87 candidates that were classified as bronze in ZooDR7. As mentioned earlier (Section 1.1), we have already started the imaging follow-up of these objects. However we note that these new images will not be as useful to the X-ray community, as those contained in XMM, i.e. deep imaging in two bands over a large number of bronze candidates (see Table 5 for a summary). In Section 3.1 we described how we applied the CMR-redshift technique designed for NXS to SDSS DR7 and S82 data. Excluding unreliable fits, a total of 574 and 51 CMR-redshift measurements were made using regular SDSS DR7 and S82 data respectively, 80 and 19 of which appear in XCS-DR1. The
accuracy (and catastrophic failure rates) of the SDSS CMR-redshifts were estimated to be $\sigma_z = 0.03$ (±3 per cent) and $\sigma_z = 0.03$ (±7 per cent) for SDSS DR7 and S82 respectively. With regard to the future improvement of SDSS CMR-redshifts, many of the statements made above, with regard to NXS, also apply here. However, in the case of SDSS, we already have the option of using more than one colour, so we are now investigating the use of multi-colour data to derive CMR-redshifts from SDSS DR8. We also note that SDSS DR8 covers more area than DR7, so should yield additional (to XCS-DR1) redshifts.

In Section 3.3 we described how spectroscopic redshifts were extracted from the SDSS archive under the assumption that LRGs reside in the centres of X-ray clusters. A total of 265 spectroscopic redshifts were determined from SDSS LRGs, 111 of which appear in XCS-DR1. An additional three spectroscopic redshifts were adopted for XCS-DR1 clusters from the H11 XCS study. We look forward to the public release of additional SDSS spectroscopy from the SDSS-III BOSS project because this will allow us to extract more spectroscopic redshifts for XCS clusters.

In Section 3.3 we described how redshifts were extracted from the literature (mostly via automated queries to NED) and matched to XCS candidates. Whilst the use of $z_{\text{lit}}$’s does cut down on the quantity of new optical follow-up required, it does have associated risks (i.e. that the selected redshift is not appropriate). Therefore, when assigning redshifts to clusters (if more than one redshift source was available), we tended not to use the NED derived value. A total of 493 $z_{\text{lit}}$ values were collected from NED, of which 127 are presented in XCS-DR1. An additional 19 redshifts from literature sources are included in XCS-DR1, bringing the total to 142 (112 of these being spectroscopic in nature).

6.3 Quality control
In Section 4.2 we described checks that were made to confirm the identity of candidates as serendipitously detected clusters. In Section 4.1.1 we described an exercise, XCS-Zoo, that used the consensus opinion of at least five (of 23) volunteers to classify candidates. Those candidates classified as gold and silver were judged to have been ‘confirmed’ as clusters and appear in XCS-DR1. Those classified as bronze do not appear, unless additional information was available. In summary, 387 candidates were confirmed as clusters (i.e. were classified as gold or silver) using XCS-Zoo.

The remaining category, other, was used for candidates that did not fall into the gold, silver or bronze categories. Just over half of all candidates classified by XCS-Zoo were placed in this category. Subsequently to XCS-Zoo, we classified the other candidates, finding that $\approx 25$ per cent required more optical and/or X-ray follow-up before they could be identified (Section 4.1.1). The other $\approx 75$ per cent could be removed from the candidate list without introducing incompleteness in the final XCS cluster sample. We described how we will be able to reduce, by a half, the number of contaminating objects entering candidate list in future (by improving the checks of reduced XMM images before XAPA is run).

Overall, we feel that XCS-Zoo, was a very worthwhile exercise. It has allowed us to efficiently identify several hundreds of X-ray clusters and has highlighted areas where the XCS candidate selection needs to be improved. We are planning to run XCS-Zoo again using additional (to NXS, S82 and DR7) datasets such as SDSS DR8, DSS, CfHTLS, VISTA-Video and UKIDSS-DXS. For the next generation of XCS-Zoo we will include all candidates (i.e. not impose the > 100 count threshold on $\text{Zoo}^{\text{DRIS}}$, as it was in $\text{Zoo}^{\text{DRIS}}$).

In Section 4.2 we described both how we interrogated the literature in order to confirm an additional 103 clusters and how we used our own spectroscopic follow-up to confirm 13 more. This process allowed us to confirm 19 bronze clusters from XCS-Zoo (Fig. 6), and several of those clusters have been included in the preliminary statistical subsample (Section 6.5.7). The remaining 97 clusters were not part of any XCS-Zoo and so they have a heterogeneous selection. These 97 have limited use with regard to statistical studies based on X-ray selection, however they still have value for other purposes, e.g. the study of individual interesting clusters (such as those at high redshift or under going mergers) or the interpretation of optically selected cluster catalogs. We note that of these 97 clusters, 87 have $T_X$ measurements in XCS-DR1 (whereas only 37 had a listed $T_X$ value in BAX at the time of writing).

In Section 6.3 we described checks that were made to ensure that ‘target’ clusters did not enter the XCS-DR1 sample; seven confirmed clusters were removed from XCS-DR1 as a result of these checks.

6.4 The cluster catalogue
In Section 6.1 we presented XCS-DR1 in the form of a tabling listing cluster attributes such as position, redshift and X-ray temperature. In an associated webpage (http://xcs-home.org/datareleases), we also provide similar information together with optical and X-ray (colour-composite and greyscale) images. In Section 6.2 we described the hierarchy used to select the best redshift for a cluster, if more than one estimate was available for it. In Section 6.3 we provided an estimate of the CMR-redshift errors and catastrophic failure rates. We found the errors to be similar to those obtained by other authors using similar, single-colour, techniques. As demonstrated in S09, errors and failure rates at the measured values should not significantly impact our ability to derive meaningful cosmological or evolutionary parameters.

We have found, using NED, that 248 (approximately half) of the XCS-DR1 clusters have been matched with previously catalogued clusters. This large fraction is a reflection of the fact that much of our redshift follow-up to date (June 2011) has come from the SDSS, and there are by now several optically selected cluster catalogues covering the SDSS footprint, e.g. MaxBCG, Koester et al. (2007a) and Cut-and-Enhance, Goto et al. (2002). As our optical follow-up continues, the percentage of previously reported clusters will fall, as evidenced by the fact that less than 20 per cent (67 of 330) of the bronze objects from XCS-Zoo have matches to previously known clusters. Figure 8 of S09
shows that XCS samples the cluster population well beyond the redshifts (z < 0.6) accessible to SDSS photometry, so the *bronce* category from ZooDR7 likely contains many of the distant clusters detected by XCS. It is noteworthy that few of the previously catalogued clusters in XCS-DR1 have been confirmed as X-ray clusters before. For example, we have compared XCS-DR1 to the BAX database and found only 147 matches. Of these, on 56 (roughly a third) have compared XCS-DR1 to the BAX

few of the previously catalogued clusters in XCS-DR1 have

been confirmed as X-ray clusters before. For example, we

are using the best available published redshifts (rather than

errors) to previous data releases that have included X-ray

temperatures. Follow-up of clusters that lie

over CCD chip boundaries or on the edge of the field of

view (see examples in Fig. 19), would allow us to improve
luminosity measurements.

We acknowledge that some XCS-DR1 clusters will suffer
from contamination from line-of-sight, or embedded, point sources (including AGN and cool cores). In practice, contamination by high signal-to-noise point sources is not a significant problem for XCS-DR1, because such sources are distinguished by XAPA from the cluster emission, e.g. in XMMXCS J011140.3−453908.0 and XMMXCS J022726.7−043209.1. Rather, it is contamination by low signal-to-noise point sources that concerns us; we have previously demonstrated (in Hilton et al. 2010, using Chandra follow-up) that the flux from XCS-DR1 cluster XMMXCS J221559.6−173816.2 (z = 1.46) was contaminated at the 15 per cent level by two point sources that had not been detected by XAPA (Chandra is significantly more sensitive to point sources than XMM, although the reverse is true for extended emission). Correcting for those point sources decreased the measured temperature by 2.4 keV (to $T_X = 4.1^{+0.6}_{-0.9}$ keV) and the luminosity by 33 per cent. To determine how common such low-level contamination might be (and the typical impact it has on derived parameters), we are undertaking an exercise that will make use of observations of XCS-DR1 clusters (and bronze candidates) in the Chandra Data Archive. Using the Chandra Simple Image Access service, we have determined that 83 (23) of the XCS-DR1 clusters are covered by Chandra observations (through to the end of 2009). The 83 include 51 clusters.

6.5 Selected subsamples of XCS-DR1 clusters

Finally, we describe seven subsamples of the XCS-DR1 clusters that have particular scientific applications. In each description we include methods that are being, or could be, used to improve and/or extend the respective subsample.

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**Figure 12.** The redshift distribution for the 464 clusters with measured redshifts in XCS-DR1. The green line represents the total sample, while the blue line represents clusters.

**Figure 13.** The temperature distribution for the 402 clusters with measured X-ray temperatures in XCS-DR1. The green line represents the total sample, while the blue line represents clusters.
Figure 14. The distribution on the sky of the 464 clusters with measured redshifts in XCS-DR1. The green hashed lines represent the footprint of the Dark Energy Survey. The colours of the dots represent the redshift of the cluster, as indicated.

Figure 15. The distribution on the sky of the 402 clusters with measured X-ray temperatures in XCS-DR1. The green hashed lines represent the footprint of the Dark Energy Survey. The colours of the dots represent the temperature of the cluster, as indicated.
Figure 16. A comparison of the redshift distributions of XCS-DR1 clusters with previous data releases of X-ray cluster temperatures. The coloured numbers indicate the total number of clusters in the respective sample.

Figure 17. As for Fig. 16 but for the temperature distributions.

6.5.1 High-redshift XCS-DR1 Clusters

There are 10 clusters in Table 3 with $z > 1.0$. Of these clusters, all have been spectroscopically confirmed and are accompanied by $T_X$ measurements. By comparison, 16 (10 with $T_X$ measurements) $z > 1.0$ clusters were registered on the BAX database at the time of writing (June 2011).

Although the BAX database is not completely up to date, e.g. the $z = 1.56$ XDCP cluster (XMMU J1007.4+1237, Fassbender et al. 2011) was not included at the time of writing, this comparison still demonstrates that the XCS-DR1 $z > 1.0$ cluster sample is the largest based on a single selection technique (the 16 BAX clusters had been compiled from 11 different publications, with $T_X$ measurements from seven different publications). Most of the XCS-DR1 $z > 1.0$ clusters were previously known X-ray clusters, e.g. XMMXCS J223520.4−255742.1 at $z = 1.39$ (Mullis et al. 2005; Rosati et al. 2009; Jee et al. 2009).

6.5.2 High-temperature XCS-DR1 Clusters

There are 67 clusters in XCS-DR1 with $T_X > 5$ keV. This is a much smaller number than available on BAX (158 at the time of writing, June 2011); however these clusters are still useful to the Sunyaev–Zeldovich community (SZ, Sunyaev & Zeldovich 1972) because typically it is only the $T_X > 5$ keV clusters that can be detected via their SZ signal (using current instrumentation).

There are more $T_X > 5$ keV clusters in BAX than in XCS-DR1 at all redshifts, but we note that at $z > 0.5$, the numbers are comparable: 31 clusters from XCS-DR1, compared to 39 in BAX. Of these, most (25) were not previously catalogued by BAX. Moreover, the 39 BAX clusters were drawn from a large number of different publications, whereas the XCS-DR1 sample is based on a single selection technique and a single $T_X$ measurement. However we highlight the two XCS discoveries: XMMXCS J221559.6−173816.2 ($z = 1.46$, previously published by us in Stanford et al. 2006) and XMMXCS J091821.9+211446.0 ($z = 1.01$, a spectroscopic redshift based on 16 galaxies, Fig. 3).

We plan to exploit the high-redshift XCS-DR1 clusters to extend our previous (Collins et al. 2009; Stott et al. 2010; Hilton et al. 2010) studies of galaxy, particularly BCG, evolution. Given the importance of high-z clusters to evolution studies, we will request additional X-ray follow-up (XMM and Chandra) of some of these clusters, in order to improve the signal to noise and the spatial resolution. We are also working to extend the size of the XCS high-z sample. We are doing this in a number of ways, including: continuing the spectroscopic follow-up, using the Keck and Gemini telescopes, of promising high-z candidates that were highlighted during XCS-Zoo (regardless of the number of detected counts); using UKIDSS-DXS and VISTA-Video surveys to select additional high-z candidates; and exploiting redshifts measured by other teams, such as XDCP, for XMM clusters as they enter the literature.
experiments, but targets have been supplied to the APEX and AMI teams (Schwan et al. 2010; Zwart et al., 2008), and several XCS-DR1 clusters have already been studied by the AMI SZ experiment (AMI Consortium: Shimwell et al. 2011, in prep). In a separate publication (Viana et al. 2011, in prep.) we present a subsample of XCS-DR1 clusters (including some at $T_X < 5$ keV) that we predict will be detectable by the Planck SZ survey (Planck Collaboration et al. 2011).

Given the importance of high temperature clusters to SZ studies, and the fact that the accuracy of $T_X$ measurements drops with increasing temperature (see Figure 16 in LD10), it would be worthwhile to obtain additional X-ray observations of this sub-sample (regardless of the XAPA count value), in order to increase the $T_X$ precision. Re-observing off-axis clusters at the XMM aim point, and/or with Chandra, will also increase the spatial resolution and allow us to correct for point source contamination (uncorrected AGN contamination will artificially raise the measured $T_X$).

6.5.3 Low-temperature XCS-DR1 clusters

There are 131 clusters in XCS-DR1 with $0.4 < T_X < 2$ keV in the redshift range $0.06 < z < 1.46$. This is dramatically more than in BAX (which lists only 27 such systems). We are already exploiting this unique data set to investigate AGN-ICM feedback mechanisms.

6.5.4 High signal-to-noise XCS-DR1 clusters

The XCS-DR1 $T_X$ values come primarily from the discovery data (the exception being those clusters that are both XMM targets and serendipitous detections, Section 6.3, and so the $T_X$ errors tend to be larger than the comparison samples, especially at the high-temperature/low-count end (Fig. 18). However, this is not always the case and, in particular, we note that there are 40 systems (Fig. 19) from which it should be possible to measure $T_X$, to better than 15 per cent accuracy, in three or more radial bins (where these expectations are based on the results in LD10 concerning $T_X$ accuracy as a function of number of counts and $T_X$). The 40 clusters featured in Fig. 19 comprise of 23 clusters ranging in temperature from $2.6 < T_X < 11.1$ keV, and 17 groups ranging from $1.0 < T_X < 1.8$ keV.

The measurement of $T_X$ profiles will permit the measurement of cluster masses, under the assumption of hydrostatic equilibrium. This is important since mass calibration will be required before XCS-DR1 clusters can be used to constrain cosmological parameters (S09). We hope to increase the number of XCS-DR1 clusters with $T_X$ profiles by securing additional XMM observations. In particular, we wish to re-observe some systems that are representative of the $L_X - T_X$ relation in the $1.8 < T_X < 2.6$ keV range (i.e. where there is a gap in the current high signal-to-noise sample).

6.5.5 XCS-DR1 clusters in the Stripe 82 footprint

There are 35 clusters in XCS-DR1 that fall within the Stripe 82 (S82) co-add region of SDSS DR7. Of these, 27 have measured X-ray temperatures. The S82 region is of interest to many cluster scientists, primarily because it provides public high-quality imaging in several colours ($\sim 2$ magnitudes deeper than regular SDSS) over a considerable area of sky. Optical cluster catalogues have been produced from S82, e.g. (Geach et al. 2011), but prior to XCS-DR1, there were only been a handful of known X-ray clusters to use for S82 catalogue validation.

The Stripe 82 region will be re-observed by DES, to similar depths and in the same bands. Therefore, the 27 XCS-DR1 clusters with $T_X$ measurements can be used immediately to investigate how DES-like cluster richnesses will correlate with the more reliable mass proxies.

6.5.6 XCS-DR1 clusters in the DES footprint

In total, there are 100 XCS-DR1 clusters in the DES footprint (including the 35 in S82). Of these, 78 have measured X-ray temperatures. All these clusters are worthy of further study (optical and X-ray) in order to support DES cluster science. The value of X-ray information about DES cluster has been demonstrated by Wu et al. (2010), who showed that with 200 follow-up observations, the dark energy figure of merit could be improved by 50 per cent. Although, with XCS-DR1, we have only been able to provide half that number, we note that there are several hundred more XCS clusters candidates in the DES footprint that have yet to be identified (as clusters or contaminants). Most of them have not been included in XCS-Zoo before, but their identification should be straightforward once DES photometry (which reaches a depth comparable to S82) is available. Given that DES photometry will cover several bands, it should be possible to measure accurate CMR-redshifts for all DES-identified clusters.

We cannot at this stage predict how many of the DES-identified clusters will yield $T_X$ values, but we note that the number of unidentified candidates in the DES footprint is 156. In addition, we are applying the XCS X-ray analysis pipelines to an additional $\approx 40$ clusters with XMM detections. These additional clusters are not in our candidate list, because they were the targets of their respective ObsID, however, they are still very useful to DES because they will help us reach the Wu et al. (2010) target of 200. These 40 are likely to be particularly useful to DES since many will have been detected with sufficient signal-to-noise to yield mass estimates via the hydrostatic equilibrium method.

6.5.7 XCS-DR1 clusters for statistical studies

Although the optical follow-up of XCS<sup>300</sup> is still ongoing, we have nevertheless been able to define a subsample of XCS-DR1 clusters that should be sufficiently complete to be suitable for preliminary statistical studies. For this we have only used clusters<sup>300</sup> that were classified by XCS-Zoo and optically confirmed. We confined the sample to the redshift range that should yield CMR-redshifts from the respective imaging (i.e. $z < 0.3$ for Zoo<sub>DR7</sub><sup>300</sup> and $z < 0.6$ for Zoo<sub>NNX</sub><sup>300</sup> and Zoo<sub>S82</sub><sup>300</sup>— refer to Fig. 2, 8 and 20 to see how the galaxy density changes with cluster redshift and survey depth). We also impose a lower redshift cut of $z > 0.1$, because this is the minimum allowed by the CMR algorithm.

Setting these limits, we have selected a total of 105
Figure 19. Forty XCS-DR1 clusters that were detected with sufficient counts that it should be possible measure X-ray temperature profiles. The names of the clusters are as indicated within the sub-panels. Note that these are count, rather than count rate maps, i.e. they have not been corrected for variations in the exposure map. Several of the clusters lie over chip gaps, while others fall close to the edge of the field of view, hence some of the morphologies are artificially distorted. The ObsID images on the XCS-DR1 webpage provide a clearer impression of the exposure map variations.
clusters $^{300}$, of which 69 come from Zoo$^{DR7}$ and an additional 36 come from Zoo$^{NXS}$ or Zoo$^{S82}$. To put this sample into context, we can compare it to the influential study by Vikhlinin et al. (2009) that used 88 clusters (49 in the range $0.025 < z < 0.2$ and 39 in the range $0.35 < z$) to derive constraints on dark energy parameters.

We hope the sample will be widely used by the community, and have indicated the 105 members in Table 5. However, we stress that it is not applicable for all types of statistical studies, because it is not complete: some clusters in the selected redshift range will not have been ‘confirmed’ yet and so do not appear in XCS-DR1. We do not know how many such clusters there are, but we estimate the number to be $\simeq 50$; there are 40 bronze clusters $^{300}$ and 9 other candidates $^{300}$ with CMR-redshifts in the respective ranges (where the other candidates $^{300}$ are in the sub-categories that ‘require additional follow-up’, Section 4.1.1). Assuming all 49 are clusters, then the current sample of 105 is only 68 per cent complete. Moreover, this sample cannot be used without reference to the XCS survey selection function (LD10) for science applications that require the volume density to be known. In future publications, we will apply this sample to a variety of investigations, e.g., the derivation of cosmological parameters and the measurement of cluster scaling relations. The scaling relations we plan to examine are those between: X-ray luminosity and $T_X$; optical richness and $T_X$; and halo occupation number and $T_X$.

We look forward to increasing the size, and completeness level, of future ‘statistical’ sub-samples of XCS clusters using the Dark Energy Survey. The combination of DES and XCS will yield a homogeneously selected set of confirmed X-ray clusters that is at least twice the size of the current statistical sub-sample. It is important to note, in this context, that the fraction of bronze and other systems in the similarly (to DES) deep S82 region is significantly lower than that in the DR7 region. Extrapolating from the Zoo$^{S82}$ results, we expect completeness levels of XCS clusters samples in the DES region to be at least 80 per cent. If the Pan-Starrs$^{29}$ project is successful, then even larger samples could be gathered because that optical survey will cover the whole sky north of $\sim 30$ deg, to similar depths to DES.

7 CONCLUSIONS

We have presented the first data release from the XMM Cluster Survey (XCS-DR1). This consists of 503 optically confirmed X-ray clusters serendipitously detected in XMM archival imaging. Optical confirmation was established in one or more of three ways: through multi-object spectroscopy; by matching XCS candidates to clusters in the literature; or by visual inspection of optical CCD images via an exercise referred to as XCS-Zoo. Redshifts for the clusters were derived from a variety of spectroscopic and photometric sources, namely public archives, the literature, and our own follow-up campaigns. X-ray temperatures and luminosities were measured for those clusters detected with sufficient signal-to-noise using an automated pipeline. We have established whether the clusters (and/or their X-ray temperature measurements) are new to the literature using comparisons with NED and BAX. Compared to previous data releases of cluster samples with $T_X$ information, XCS-DR1 contains more clusters (especially at low temperature) and probes to higher redshifts. The XCS-DR1 catalogue, together with optical (colour-composite and greyscale) and X-ray imaging for each of the XCS-DR1 clusters, is publicly available from http://xcs-home.org/datareleases.

Some key statistics for the XCS-DR1 catalogue of 503 clusters are as follows:

(i) Redshifts: 464 clusters are accompanied with redshift information ($0.06 < z < 1.46$). Of these, 261 are spectroscopic, with most of the remainder coming from the photometric CMR-redshift technique (applied to single-colour optical imaging). Ten of the redshifts exceed $z = 1.0$ (these include a new spectroscopically-confirmed cluster at $z = 1.01$). The CMR-redshift accuracy (and catastrophic failure rates) were found to be $\sigma_z = 0.08$ ($\approx 5$ per cent), $\sigma_z = 0.03$ ($\approx 3$ per cent) and $\sigma_z = 0.03$ ($\approx 7$ per cent) from NXS, SDSS DR7 and Stripe 82 data, respectively.

(ii) Temperatures: 402 clusters are accompanied with X-ray temperature information ($0.4 \text{ keV} < T_X < 14.7 \text{ keV}$). Of these, 67 clusters have temperatures above $T_X = 5 \text{ keV}$ (these systems will be particularly useful for SZ studies), and 131 clusters have temperatures below $T_X = 2 \text{ keV}$ (these systems can be applied to studies of cluster physics and BCG evolution). A small subset, of 40 clusters, were detected with sufficient signal-to-noise that mass measurements can be made using temperature profiles (these will be important to cosmology studies, as they will aid the mass calibration of XCS). All clusters presented with $T_X$ values are also presented with $L_X$ measurements.

(iii) New discoveries/measurements: 255 clusters were not previously catalogued in the literature, and 356 of the X-ray temperature measurements were not previously catalogued in BAX.

(iv) Preliminary statistical subsample: Of the 503 XCS-DR1 clusters, 105 can be used, in conjunction with the XCS selection function, for statistical applications such as the derivation of cosmological parameters and the measurement of cluster scaling relations (including those between X-ray luminosity and $T_X$, and optical richness and $T_X$).

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Figure 20. A selection of optically confirmed XCS clusters as imaged by SDSS DR7 and classified as \textit{gold} in Zoo$^{\text{DR7}}$ (Section 4.1). False colour-composite images are $3' \times 3'$ with X-ray contours overlaid in blue. From left to right and top to bottom, the compilation displays the clusters: XMMXCS J115112.0+550655.5 at $z = 0.08$; XMMXCS J010858.7+132557.7 at $z = 0.15$; XMMXCS J123019.6+161634.1 at $z = 0.20$; XMMXCS J001737.4-065235.4 at $z = 0.21$; XMMXCS J092018.9+370617.7 at $z = 0.21$; XMMXCS J100047.4+013926.9 at $z = 0.22$; XMMXCS J083454.8+553420.9 at $z = 0.24$; XMMXCS J130749.6+292549.2 at $z = 0.24$; XMMXCS J170041.9+641257.9 at $z = 0.24$; XMMXCS J133254.8+505153.1 at $z = 0.28$; XMMXCS J092052.4+302804.8 at $z = 0.29$; XMMXCS J141832.3+251104.9 at $z = 0.29$; XMMXCS J105318.5+572043.7 at $z = 0.34$; XMMXCS J115824.6+440533.9 at $z = 0.41$; XMMXCS J153629.7+543920.8 at $z = 0.41$; and XMMXCS J111515.6+531949.5 at $z = 0.47$.

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