THE XMM-NEWTON DISTANT CLUSTER PROJECT

G. Lamer[1], A. Schwope[1], H. Böhringer[2], R. Faßbender[2], P. Schuecker[2], C. Mullis[3], and P. Rosati[4]

[1]Astrophysikalisches Institut Potsdam, Potsdam, Germany
[2]Max Planck Institut für Extraterrestrische Physik, Garching, Germany
[3]University of Michigan, Ann Arbor, USA
[4]European Southern Observatory, Garching, Germany

ABSTRACT

We report on an ongoing search for distant clusters of galaxies in archival XMM-Newton observations. The aim of the survey is to establish a sample of ~ 30 clusters at redshifts $z > 1$. Here we describe the strategy of the survey from X-ray source detection to optical follow up observations of distant cluster candidates. First results of a pilot survey and the discovery of the most distant X-ray selected cluster at z=1.4 are presented.

Key words: clusters of galaxies; extragalactic surveys; X-rays.

1. INTRODUCTION

Clusters of galaxies are key probes of cosmic structure formation. Their evolution and space distribution is very sensitive to the cosmological framework and therefore measuring their density out to cosmological distances provides strong constraints to cosmological parameters as the matter density parameter Ω_m and the amplitude parameter σ_8 (e.g. Henry 2000, 2004, Schuecker et al. 2003). Samples used for these cosmological studies have to be large and well defined, at the same time probing higher redshifts greatly improves the levarage to constrain the cosmological parameters.

X-ray selection has several advantages for cosmological cluster surveys: The X-ray luminosity of a cluster is tightly correlated with its total mass, the most fundamental parameter (Reiprich & Böhringer 2002). Since the cluster X-ray emission is strongly peaked at the dense core, X-ray selection reduces projection effects as compared to optical surveys.

Other important applications of distant cluster samples are the investigation of galaxy evolution in the dense environment of clusters (e.g. Yee et al. 1996, Dressler et al. 1999) and the evolution of the X-ray emitting intracluster gas (e.g. Ettori et al. 2004).

So far only few clusters at redshifts $z > 1$ are known. Before we started of this project only 5 X-ray selected clusters in this range were known (Stanford et al. 1997, Rosati et al. 1999, Stanford et al. 2002, Rosati et al. 2004, Hashimoto et al. 2004), all of them selected from deep pointed ROSAT observations.

With the launch of *XMM-Newton* the prospects of finding distant X-ray selected clusters have dramatically increased. The large effective areas of the EPIC cameras provide sensitivities for cluster detection in typical observations ($\sim 10^{-14} erg/(s\ cm^2)$ in 20 ksec), which are comparable to those in the deepest ROSAT fields. At the same time the spatial resolution of the EPIC cameras is sufficient over the whole field of view ($r \sim 12'$) to identify even the most distant clusters of galaxies based on their extended emission.

The identification of galaxy clusters from *XMM-Newton* observations has only just begun (e.g. Romer et al. 2001, Willis et al. 2005, Schwope et al. 2004), recently the first discoveries of $z > 1$ clusters have resulted from the project described here (Mullis et al. 2005) and have been reported by the XMM-LSS project (Pierre 2005).

2. THE XMM-NEWTON DISTANT CLUSTER PROJECT

2.1. X-ray data analysis

The *XMM-Newton* data used for our survey are retrieved from the *XMM-Newton* public archive operated by ESAC. The observations are selected by a minimum EPIC exposure time of 10 ksec at galactic latitudes $|bII > 20°|$. The EPIC images are furthermore inspected for their suitability to detect faint extended sources (i.e. they must be free of very bright target point sources and very extended sources dominating the image.) Presently more than 600

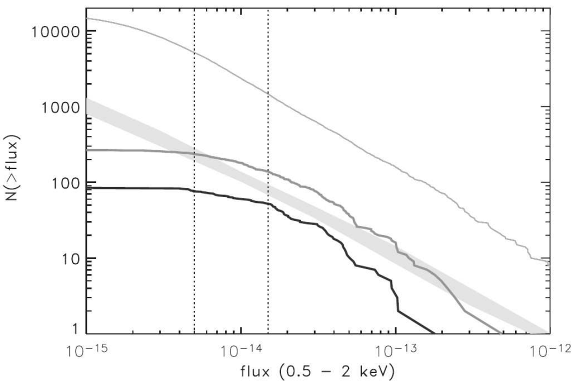

Figure 1. Number counts in the first 12 deg^2 of the survey. Upper line: all sources, middle line: all extended sources, lowest line: Distant cluster candidates (without optical counterparts). The shaded band indicates the cluster logNlogS derived by Rosati et al. (2002) from the RDCS.

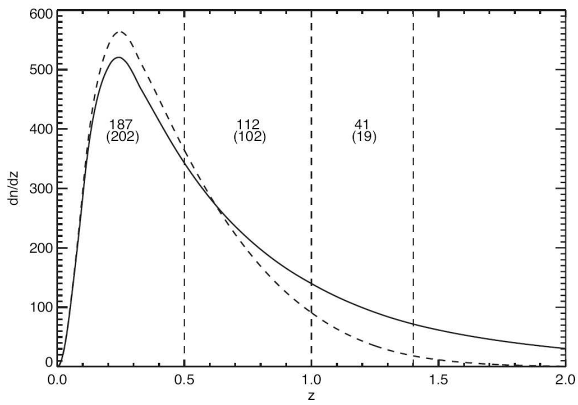

Figure 2. Expected redshift distribution of a 14 deg^2 XMM survey based on the results of the RDCS and 160 deg^2 ROSAT surveys (Rosati et al. 2002, Mullis et al. 2004. The solid line gives the expectations for no evolution and the dashed line and the values in brackets give a realistic prediction including evolutionary effects. (Böhringer et al. 2005)

such observations have been downloaded and processed. We reprocess the data from ODFs with the latest SAS release and apply a strict background flare screening algorithm in order to obtain optimum data quality and sensitivity for source detection.

The images of the 3 cameras are binned into the standard energy bands (0.2-0.5, 0.5-1.0, 2.0-4.5, 4.5-12. keV). For extended source detection we use the standard XMM-SAS source detection package, which uses a sliding-box algorithm (*eboxdetect*) for source detection and PSF-fitting (*emldetect*) for source characterisation. The extent of the sources is determined by fitting a King-profile convolved with the calibration PSF to the source images. Detection and PSF-fitting are performed simultaneously on the 15 (3 cameras $\times$ 5 energy bands) EPIC images in order to reach maximum sensitivity. Simulations of EPIC images including point sources and extended sources show that the source detection method can reliably detect the extent with core radii down to ~ 4 arcseconds and $0.5 - 2$ kev fluxes of $< 10^{-14} \mathrm{erg}/(\mathrm{s\ cm}^2)$ in a typical observation of 20 ksec observation time.

Figure 1 shows the flux distribution in the first 12 deg^2 of the survey, which is consistent with the flux limits derived by the simulations.

The last step of the X-ray data analysis is a visual screening of all extended sources detected by the software in order to remove any spurious extent detection, e.g. in the vicinity of bright point sources, large extended sources or due confusion of several closely spaced point sources.

2.2. Optical follow up observations

Since most new galaxy clusters detected by *XMM-Newton* are expected to have redshifts below z=0.5 (see Figure 2), a strategy is needed to efficiently separate the numerous low redshift clusters from the high-z candidates. We have therefore developed the following method for optical follow up:

The first step is an inspection of second-epoch red digitized sky survey (DSS) images of the X-ray source positions. Most extended X-ray sources outside the galactic plane are clusters of galaxies. Exceptions are nearby galaxies, which can be easily identified on the DSS images. Also low redshift clusters are visible on these images, we have determined that most clusters below $z = 0.5$ are detected on red DSS images. We therefore select only candidates, which appear as blank fields in the DSS for further optical follow-up.

A very efficient method to further classify the remaining candidates is to obtain imaging in the R and z band. Here we make use of the very good red sensitivity of FORS-2 at the ESO VLT. Snapshot images of 20 min in R and 8 min in z are deep enough to detect cluster galaxies out to redshifts of more than z=1.4 and at the same time give us a photometric redshift estimate via the red-sequence technique (Gladders & Yee 2000). The accuracies of the photometric redshifts are expected to of the order $\Delta z = 0.1$. Therefore a spectroscopic confirmation of all candidates with $z > 0.9$ will allow us to identify a complete sample of $z > 1$ clusters.

3. RESULTS OF A PILOT SURVEY

In order to demonstrate the feasibilty of our survey strategy we have undertaken the optical identification of a pilot survey after the first 160 XMM observations had been processed. The effective survey area, where the sensi-

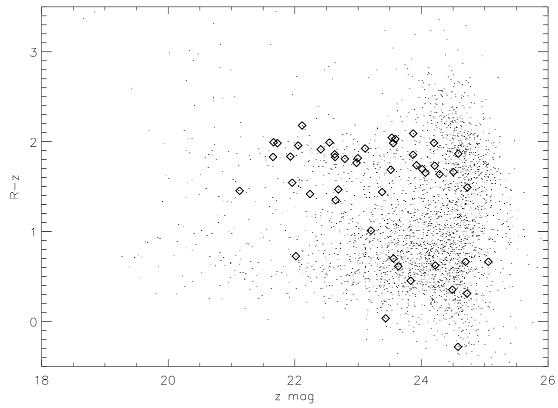

Figure 3. Colour-magnitude diagram of a rich cluster counterpart. Diamonds correspond to galaxies within 30 arcsec of the X-ray position. The red sequence indicates a redshift of $z \sim 1$.

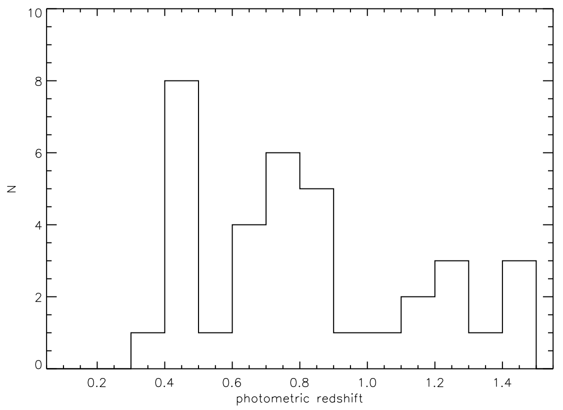

Figure 4. Distribution of photometric redshift derived from the R and z snapshot imaging. Among 36 clusters with a good photometric redshift are 10 candidates for $z > 1$ clusters.

tivity for extended sources exceeded $10^{-14} erg/(s\ cm^2)$, was $\sim 9\ \deg^2$. A total number of 155 extended sources were detected in these fields. After inspection of the source positions on DSS images, we selected 47 positions for R and z band imaging with the VLT in ESO periods P72 and P73. The limiting magnitude of the imaging was typically R=25 and z=24. In most cases a red sequence was detected and a redshift estimate could be derived.

Figure 3 shows an example colour-magnitude plot of a rich cluster at $z \sim 1$ found in the snapshot imaging.

Among the clusters with a photometric redshift are 10 candidates, where the red sequence indicates a redshift $z \geq 1$ (see Figure 4). This result is in good agreement with the prediction of 1 cluster per square degree. The highest estimated redshifts in the sample are $z \sim 1.5$.

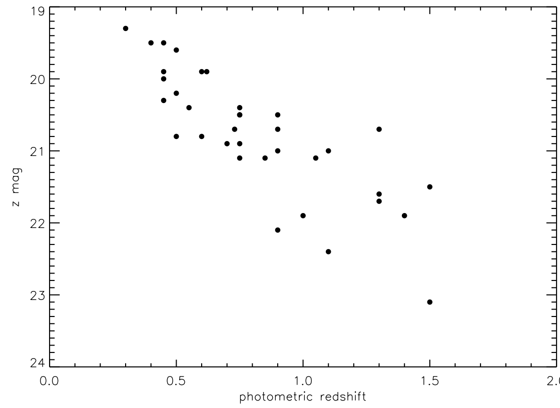

Figure 5. Photometric redshifts vs. z magnitudes of the brightest galaxy on the red sequence.

4. AN X-RAY SELECTED CLUSTER AT Z=1.4

One of the most promising candidates of the pilot survey (XMMU J2235.3-2557) has been observed spectroscopically with FORS-2 at the ESO VLT. Its red sequence colour R-z = 2.1 indicated a redshift of $z \sim 1.4$. The spectraoscopy confirmed this estimate with a $z = 1.393$, based on concordant redshifts of 12 member galaxies (Figure 6, Mullis et al. 2005).

From the measured X-ray flux of XMMU J2235.3-2557 $f_X = 3.6 \cdot 10^{-14} \mathrm{erg(cm^2)s}$ (0.5-2 kev) follows a luminosity of $L_X = 3 \cdot 10^{44} \mathrm{erg/s}$. Together with the X-ray temperature estimate of $6.0^{+2.5}_{-1.8}$ keV this results in a mass estimate of $3 \cdot 10^1 4 M_{\odot}$. This makes XMMU J2235.3-2557 not only the most distant X-ray cluster, but probably also the most massive distant cluster known so far.

5. CONCLUSIONS

Our pilot survey has shown that our search strategy is very efficient to find very distant clusters with a moderate requirement of telescope time. The relatively short snapshot exposures with the VLT have been proven to be sufficient to detect cluster galaxies and provide redshift estimates up to $z \sim 1.5$. The confirmation of the photometric redshift for XMMU J2235.3-2557 demonstrates the power of the R - z red sequence technique in this redshift range. About tree quarters of the newly deteced XMM clusters can be rejected based on DSS imaging. Of the remaining sources, about one quarter are candidates for $z > 1$ clusters. This is in very good agreement with the predicted surface density of ~ 1 per square degree. In order to construct a larger sample of very distant clusters (~ 50 objects), the large area of an XMM serendipity survey is clearly needed. Our next goal is to use the survey strategy outlined here in order to establish a sample of 30 $z > 1$ clusters in the southern sky.

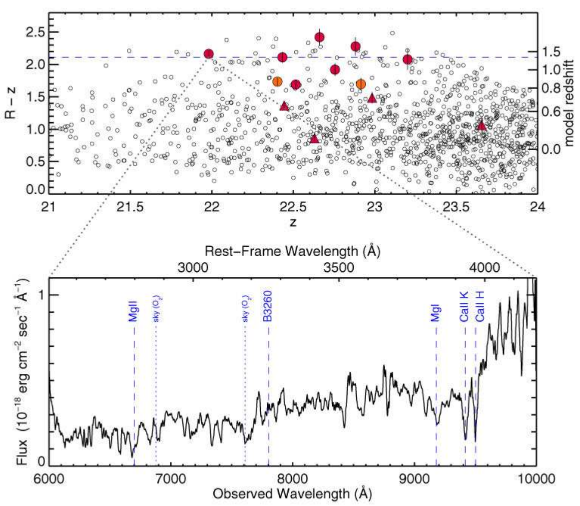

Figure 6. Top: Colour magnitude diagram of XMMU J2235.3-2557, indicating a redshift of $z \sim 1.4$, the filled circles indicate spectroscopically confirmed member galaxies. Bottom: VLT spectrum of the brightest cluster galaxy at $z = 1.39$.

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