The $XMM$–$Newton$/2dF survey – III. Comparison between optical and X-ray cluster detection methods

S. Basilakos,1⋆ M. Plionis,1,2 A. Georgakakis,1 I. Georgantopoulos,1 T. Gaga,1,3 V. Kolokotronis1 and G. C. Stewart4

1Institute of Astronomy and Astrophysics, National Observatory of Athens, I. Metaxa & B. Pavlou, Palaia Penteli, 152 36 Athens, Greece
2Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Apartado Postal 51 y 216, 72000, Puebla, Pue., Mexico
3Physics Department, University of Athens, Panepistimioupolis, Zografou, Athens, Greece
4Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH

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ABSTRACT
We directly compare X-ray and optical techniques of cluster detection by combining Sloan Digital Sky Survey photometric data with a wide-field (∼1.6 deg$^2$) $XMM$–$Newton$ survey near the North Galactic Pole region. The optical cluster detection procedure is based on merging two independent selection methods: a smoothing + percolation technique and a matched filter algorithm. The X-ray cluster detection is based on a wavelet-based algorithm, incorporated in the Science Analysis System (SAS) v.5.3 package. The final optical sample counts nine candidate clusters with estimated Automatic Plate Measuring like richness of more than 20 galaxies, while the X-ray based cluster candidates total four. Three out of these four X-ray cluster candidates are also optically detected. We argue that the cause is that the majority of the optically detected clusters are relatively poor X-ray emitters, with X-ray fluxes fainter than the flux limit (for extended sources) of our survey, $f_x (0.3–2$ keV) $\simeq 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

Key words: galaxies: clusters: general – cosmology: observations – cosmology: large-scale structure of Universe.

1 INTRODUCTION
Clusters of galaxies occupy an eminent position in the structure hierarchy, being the most massive virialized systems known, and therefore they appear to be ideal tools for testing theories of structure formation and extracting cosmological information (cf. Bahcall 1988; Böhringer 1995; West, Jones & Forman 1995; Carlberg et al. 1996; Borgani & Guzzo 2001; Nichol 2002, and references therein).

To investigate the global properties of the cosmological background it is necessary to construct and study large samples of clusters (cf. Borgani & Guzzo 2001). This understanding has initiated a number of studies aiming to compile unbiased cluster samples at high redshifts, utilizing multiwavelength data (e.g. optical, X-ray, radio). On the other hand, the study of individual clusters provides complementary information regarding their physical properties and evolutionary processes. Overall, it is very important to fully understand the selection effects that enter into the construction of cluster samples as these could bias any statistical analysis of these samples (cf. Sutherland 1988).

At optical wavelengths there are several available samples in the literature. For example, the Abell/Abell–Corwin–Olowin (ACO) catalogue (Abell, Corwin & Olowin 1989) was constructed by visual inspection of the Palomar Observatory Sky Survey plates and is still playing an important role in astronomical research. Since then, a large number of optically selected samples constructed with automated methods have been constructed: Edinburgh Durham Cluster Catalogue (EDCC; Lumsden et al. 1992); Automatic Plate Measuring (APM; Dalton et al. 1994); Palomar Distant Cluster Survey (PSCS; Postman et al. 1996); European Southern Observatory (ESO) Imaging Cluster Survey (EIS; Olsen et al. 1999); Red-Sequence Cluster Survey (RCS; Gladders & Yee 2000); the Sloan Digital Sky cluster survey (SDSS; Goto et al. 2002; Bahcall et al. 2003). The above cluster samples, based on different selection methods, aim to obtain homogeneously selected optical cluster samples with redshifts that extended beyond the $z \sim 0.2$ limit of the Abell/ACO catalogue. We should mention that the advantage of using optical data is the sheer size of the available cluster catalogues and thus the statistical significance of the emanating results.

A major problem here is that the optical surveys suffer from severe systematic biases which are due to projection effects. Background and foreground galaxies, projected on the cluster could distort the identifications (e.g. Frenk et al. 1990), which is particularly true for poor systems at high redshifts. X-ray surveys provide an alternative method for compiling cluster samples, owing to the fact that the diffuse intracluster medium (ICM) emits strongly at X-ray...
wavelengths. This emission is proportional to the square of the hot gas density, resulting in a high contrast with respect to the unresolved X-ray background, and thus X-ray selected clusters are less susceptible to projection effects. Therefore, the main advantage inherent in the X-ray selection of flux-limited samples is that the survey volume, and hence number densities, luminosity and mass functions can be reliably computed. Furthermore, X-ray cluster surveys can be used to study cluster dynamics and morphologies, the Sunyaev–Zel’dovich effect and finally their cosmological evolution.

The first such sample, with large impact on the studies of clusters, was based on the Extended Einstein Medium Sensitivity Survey, containing 99 clusters (Stocke et al. 1991). The ROSAT satellite with its large field of view (FOV) and better sensitivity, allowed a leap forward in the X-ray cluster astronomy, producing large samples of both nearby and distant clusters (e.g. Castander et al. 1995; Ebeling et al. 1996a,b; Scharf et al. 1997; Ebeling et al. 2000; Böhringer et al. 2001; Gioia et al. 2001; Böhringer et al. 2002; Rosati, Borgani & Norman 2002, and references therein). Recently, the XMM–Newton observatory with ~10 times more effective area and ~5 times better spatial resolution than the ROSAT provides an ideal platform for the study of galaxy clusters.

However, even with the improved sensitivity of the XMM–Newton, optical surveys still remain significantly more efficient and less expensive in telescope time for compiling cluster samples, albeit with the previously discussed limitations (e.g. incompleteness, projection effects, etc.). Therefore, it is necessary to study the different selection effects and biases that enter in detecting clusters in the two wavelength regimes. Using the ROSAT Optical X-ray Survey (ROXS), Donahue et al. (2002) found that using both X-ray and optical methods to identify clusters of galaxies, the overlap was poor. About 20 per cent of the optically detected clusters were found in X-rays, while 60 per cent of the X-ray clusters were identified also in the optical sample. Furthermore, not all of their X-ray detected clusters had a prominent red sequence, a fact that could introduce a bias in constructing cluster samples using only colour information (as in Goto et al. 2002).

The aim of this work is along the same lines, attempting to make a detailed comparison of optical and X-ray cluster identification methods in order to quantify the selection biases introduced by these different techniques. We use XMM–Newton, which has a factor of ~5 better spatial resolution and an order of magnitude more effective area at 1 keV, making it an ideal instrument for the detection of relatively distant clusters.

The plan of the paper is as follows. The observed data sets are presented in Section 2. In Section 3 we discuss the methods employed to identify candidate optical clusters and comment on the systematic effects introduced in our analysis. Also in Section 3, we describe our projected cluster shape determination method as well as the cluster surface brightness based on a King-like profile. In Section 4 we compare the optical and X-ray selected cluster samples. Finally, in Section 5, we present our conclusions. Throughout this paper we use $H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$ and $\Omega_m = 1 - \Omega_x = 0.3$.

## 2 OBSERVATIONS

### 2.1 Optical data

In our analysis we use the SDSS Early Data Release (EDR), covering an area of ~400 deg$^2$ in the sky (Stoughton et al. 2002). The SDSS is an ongoing imaging and spectroscopic survey that covers ~10 000 deg$^2$ of the sky. Photometry is obtained in five bands ($u$, $g$, $r$, $i$, $z$) to the limiting magnitude $r \lesssim 22.5$ mag, providing a homogeneous multicolour photometric catalogue.

Goto et al. (2002) applied an object cluster finding algorithm to the SDSS EDR and produced a list of galaxy clusters (hereafter the CE catalogue), with estimated photometric redshifts which contains 2770 and 1686 galaxy clusters in the north and south slices, respectively. The cluster redshifts were estimated using colour information by identifying the bin in $g-r$ which has the largest number of galaxies around the colour prediction of elliptical galaxies (Fukugita, Shimasaku & Ichikawa 1995) at different redshifts (which define the different $g-r$ bins). Note that the true and estimated redshifts are better correlated for $z < 0.3$, with rms scatter ~0.015, while for $z > 0.3$ it is ~0.021. Note that the CE method is optimized up to $z \lesssim 0.4$ and becomes highly insensitive at higher redshifts.

### 2.2 XMM–Newton data

We analysed nine XMM–Newton fields with nominal exposure times between 2 and 10 ks. The XMM–Newton FOV is a circle with a radius of 15 arcmin and thus our survey covers an area of 1.8 deg$^2$. However, one of the fields, suffering from significantly elevated and flaring particle background, was excluded from the X-ray analysis. This reduces our effective area to 1.6 deg$^2$. The details of the X-ray observations are given in Georgakakis et al. (2003) and Georgantopoulos et al. (in preparation).

## 3 OPTICAL CLUSTER DETECTION

Identifying real clusters using imaging data is a difficult task because projection effects can significantly affect the visual appearance of clusters. Many different algorithms have been proposed and applied on different data sets. In what follows we present a new cluster finding algorithm (based on two distinct algorithms) and apply it on the subsample of the r-band SDSS data$^1$ that overlaps with our XMM–Newton survey.

### 3.1 Smoothing + percolation procedure

This cluster detection algorithm (hereafter the SMP method) is based on smoothing the discrete distribution using a Gaussian smoothing kernel on a $N_{x} \times N_{y}$ grid

$$W(|x_i - x_{gr}|) = \frac{1}{\sqrt{2\pi R_{sm}}} \exp\left(-\frac{|x_i - x_{gr}|^2}{2R_{sm}^2}\right),$$

(1)

where $R_{sm}$ is the smoothing radius in grid-cell units and $x_i$ is the Cartesian position of the $i$th galaxy. The smoothed surface density of the $j$th cell at the grid-cell positions $x_{gr}$ is

$$\rho_j(x_{gr}) = \frac{\sum_i \rho_i(x_i) W(|x_i - x_{gr}|)}{\int W(|x_i - x_{gr}|) d^2x},$$

(2)

where the sum is over the distribution of galaxies with positions $x_i$. For each cell we define its density fluctuation, $\delta_j$, as

$$\delta_j = \frac{\rho_j(x_{gr}) - \langle \rho \rangle}{\langle \rho \rangle},$$

(3)

where $\langle \rho \rangle$ is the mean projected SDSS galaxy density and the probability density function, $f(\delta)$, which is plotted in Fig. 1. We select all grid cells with overdensities above a chosen critical threshold

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$^1$ We have tested that our results remain qualitatively unaltered when using the i-band.

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Optical and X-ray cluster detection methods

Figure 1. The SDSS probability density function.

\[
\delta \geq \delta_{cr}
\]
and then we use a friends-of-friends algorithm to link all adjacent cells in order to form groups of connected cells, which we consider as our candidate clusters. Note that the grid-cell size is such that at \( z = 0.4 \) it corresponds to \( 100 h^{-1} \text{kpc} \) (\( \sim 19 \text{arcsec} \)).

There are three free parameters in the above procedure: the critical overdensity threshold \( \delta_{cr} \), the smoothing radius \( R_{sm} \) and the number of connected cells \( n_c \) above which we consider a candidate cluster. Due to the fact that clusters should be identified as high-density regions, we choose the critical value of the overdensity to be \( \delta_{cr} \approx 1 \), which corresponds to the \( \sim 98 \) percentile of the probability density function (PDF) plotted in Fig. 1. Had we used lower values of \( \delta_{cr} \) we would have percolated overdense regions through large parts of the whole area.

The \( R_{sm} \) and \( n_c \) parameters were chosen in such a way as to minimize the number of spuriously detected clusters. To this end we perform a series of Monte Carlo simulations in which we randomize the positions of the SDSS galaxies, destroying its intrinsic clustering, while keeping unchanged the galaxy redshift selection function. On this intrinsically random galaxy distribution we apply the procedure described above, by varying the values of the free parameters \( (R_{sm} \text{ and } n_c) \). We define the probability of detecting real clusters in the SDSS data, as \( P(R_{sm}, n_c) = 1 - N_{\text{rand}}/N_{\text{SDSS}} \), where \( N_{\text{rand}} \) is the number of clusters detected in the randomized distribution and \( N_{\text{SDSS}} \) is the number of clusters detected in the true SDSS data. In Fig. 2 we show these probabilities as a grey-scale. Although increasing \( R_{sm} \) and \( n_c \) results in very high probabilities of detecting real high-density regions, it also results in small numbers of detected clusters. We therefore attempt to break this degeneracy by using the expected number of clusters from existing surveys. For example, the continuous line in Fig. 2 corresponds to the expected number of APM clusters in the area covered by our XMM/2dF survey,\(^2\) while the dashed line delineates the corresponding number of the Goto et al. (2002) clusters. The region of the highest probability, which falls within the above cluster number limits, is that corresponding to \( R_{sm} = 28.5 \text{arcsec} \) \( n_c = 12 \), which we choose as our optimal parameters for the detection of real clusters.

In Fig. 3 we plot the smoothed SDSS galaxy distribution, using the above value of \( R_{sm} \) on the equatorial plane with a contour step of \( \Delta \delta = 0.2 \), starting from \( \delta_{cr} = 1 \). Many overdense regions are apparent. Finally, we note that our cluster finding algorithm with \( n_c = 12 \) produces a total of 25 candidate clusters, 11 of which are common with the Goto et al. (2002) sample of 29 clusters in the same region.

3.2 Matched filter algorithm

In addition to the SMP technique, we have also employed the matched filter algorithm (hereafter MFA) described by Postman

\(^2\) This number (\( \sim 40 \)) is estimated, without assuming any evolution, by multiplying the local (\( z < 0.1 \)) mean number density of APM clusters with the volume element covered by our survey out to \( z \sim 0.45 \) within the concordance cosmological model (\( \Omega_m = 0.7 \)).
et al. (1996) to identify optical galaxy overdensities. The advantage of this method is that it exploits both positional and photometric information producing galaxy density maps where spurious galaxy fluctuations are suppressed. Also, an attractive feature of this method is that it provides redshift estimates for the detected candidate galaxy clusters. A drawback of the matched filter method is that one must assume a form for the cluster luminosity function and radial profile. Clusters with the same richness but different intrinsic shape or different luminosity function from the assumed ones do not have the same likelihood of being detected.

A detailed description of the MFA can be found in Postman et al. (1996). In brief, the filter used to convolve the galaxy catalogue is derived from an approximate maximum likelihood estimator obtained from a model of the spatial and luminosity distribution of galaxies within a cluster. At any given patch of the sky, the number density of galaxies per magnitude bin is

$$D(r, m) = b(m) + \Lambda m P(r/r_c)\delta(m - m^*),$$

(4)

where $D(r, m)$ is the galaxy surface density (cluster + field galaxies) at a given magnitude $m$ and at a distance $r$ from the galaxy cluster centre, $b(m)$ is the field galaxy surface density, $P(r/r_c)$ is the cluster projected radial profile, $\delta(m - m^*)$ is the cluster luminosity function and $\Lambda m$ is an estimator of the cluster richness. The parameters $r_c$ and $m^*$ are the characteristic cluster scalelength and apparent magnitude corresponding to the characteristic luminosity of the cluster luminosity function. Postman et al. (1996) showed that the filter for cluster detection should maximize the expression

$$\int P(r/r_c)\delta(m - m^*) D(m, r) d^2r dm.$$  

(5)

Assuming that the galaxy distribution $D(m, r)$ can be represented by a series of $\delta$-functions at the observed positions and magnitudes, the integral above is reduced to

$$S(i, j) = \sum_{k=1}^{N_C} P(r_i/r_c) L(m_k),$$

(6)

where $L(m_k)$ is defined as

$$L(m) = \frac{\phi(m - m^*)}{b(m)}.$$  

(7)

The quantity $S(i, j)$ is the value of the $(i, j)$ pixel of the convolved galaxy density map and $N_C$ is total number of galaxies in the catalogue. $L(m_k)$ is the luminosity weighting function (i.e. flux filter). In practice, the survey area is binned into pixels $(i, j)$ of given size (for the choice of values, see below) and the sum in equation (6) is evaluated by iterating through all galaxies in the catalogue. This then is repeated for every pixel of the density map. Both $m^*$ and $r_c$ are a function of redshift and hence $S(i, j)$ also depends on redshift through these parameters. The redshift dependence of $m^*$ also includes a $k$-correction as discussed in the next section.

The flux filter in equation (7) has a divergent integral at faint magnitudes for Schechter luminosity functions with $\alpha < -1$. To overcome this problem Postman et al. (1996) modified the flux filter by introducing a power-law cut-off of the form $10^{\alpha_{\text{obs}} - m^*}$. Therefore, the flux filter in equation (6) is defined as

$$L(m) = \frac{\phi(m - m^*)10^{\alpha_{\text{obs}} - m^*}}{b(m)}.$$  

(8)

The radial filter in equation (6) is defined as

$$P(r) = \begin{cases} 
\frac{1}{\sqrt{1+(r/r_c)^2}} & \text{if } r < r_c \\
0 & \text{otherwise}
\end{cases}$$

(9)

where $r_c$ is the cluster core radius and $r_{co}$ is an arbitrary cut-off radius. Here, we assume $r_c = 100 h^{-1}$ kpc and $r_{co} = 1 h^{-1}$ Mpc. The characteristic absolute magnitude of the luminosity function in the $r$ band is taken to be $M^* = -20.83 + 5 \log h$ (Blanton et al. 2003). Both the radial and the flux filter are normalized as described in Postman et al. (1996).

3.2.1 MFA cluster detection

The MFA is applied to a 1.6-deg$^2$ subregion of the SDSS central on our XMM/2dF survey. We consider galaxies with magnitudes brighter than $r = 22.5$ mag. At fainter magnitudes the SDSS is affected by incompleteness. The galaxy density map $S(i, j)$ representing the galaxy density map is independently estimated for redshifts between $z_{\min} = 0.1$ and $z_{\max} = 0.6$, incremented in steps of 0.1. $z_{\max}$ corresponds to the redshift where $m^*$ becomes comparable to the limiting magnitude of the survey. The characteristic luminosity, $L^*$, the faint end slope of the luminosity function, $\alpha$, and the cluster core radius, $r_c$, are assumed to remain constant with redshift.

The conversion from luminosity to apparent magnitude requires an assumption to be made on the $k$-correction of the galaxies. Here we assume a non-evolving elliptical galaxy model obtained from the Bruzual & Charlot (1993) stellar population synthesis code (Pozzetti, Bruzual & Zamorani 1996). It is important to emphasize that the choice of $k$-correction does not significantly affect the cluster detections, but has an impact on the redshift determination.

The pixel size of the galaxy density maps at any redshift is taken to be $\approx 19$ arcsec corresponding to a projected cluster core radius of $r_c = 100 h^{-1}$ kpc at the redshift $z = 0.4$ (see Section 3.1). Galaxy density maps are created for redshifts 0.1–0.6 and stored in FITS images. The peaks of the galaxy distribution are detected using SExtractor (Bertin & Arnouts 1996). The mean and the variance of the background are determined using a global value in each likelihood map. The main input parameters are the detection threshold, $\sigma_{\text{det}}$, given as a multiple of background variance, and the minimum number of pixels, $N_{\text{min}}$, for a peak to be extracted as a candidate cluster. Simulations have been carried out (see next section) to optimize these parameters and to minimize the number of spurious cluster detections ($\approx 5$ per cent). We adopt $\sigma_{\text{det}} = 4.0$ while $N_{\text{min}}$ is set to the area of a circle with radius $r_c = 100 h^{-1}$ kpc at any given redshift.

The significance of a detection, $\sigma$, is defined as the maximum value of all the pixels associated with that detection (i.e. pixels with values above the SExtractor detection threshold), expressed in multiples of the rms noise above the background. The peaks (i.e. candidate clusters) extracted on density maps of different redshifts are matched by positional coincidence using a radius of $\approx 1$ arcmin. The approximate redshift of the candidate cluster is taken to be the redshift where the detection significance is maximum.

Within the area of our XMM/2dF survey, the MFA method identifies 12 cluster candidates, out of which six are found also by Goto et al. (2002) and nine are found by the SMP method.

3.2.2 MFA simulations

Monte Carlo simulations similar to those described in Section 3.2 were employed to test the performance of the MFA and to establish the best choice of extraction parameters. A total of 100 random galaxy catalogues over an area of $\approx 1.6$ deg$^2$ (i.e. similar to that covered by the real catalogue) were produced with the same magnitude distribution as the real data set. The MFA was then applied to these

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Table 1. List of the SDSS clusters in the XMM area. The first column gives the index number, columns 2 and 3 give right ascension α and declination δ of the cluster centre, and columns 4 and 5 give cluster ellipticity ε and φ, which is the cluster position angle (in degrees). Column 6 (C-C) gives the cross-correlation results and column 7 gives the estimated redshift by different methods. The numbers and superscripts in columns 6 and 7 correspond to: 1, the CE method (Goto et al. 2002); 2, MFA; 3, X-ray extended sources (Gaga et al., in preparation); 4, Couch et al. (1991). Column 8 gives the core radius with its 2σ error, and column 9 gives the χ² probabilities (Pχ²) of consistency between the intrinsic cluster density profile and the King model.

| Index | α    | δ     | ε     | φ     | C-C | z      | rc   | Pχ²   | Nₘ     | mₙ   |
|-------|------|-------|-------|-------|-----|--------|------|-------|--------|------|
| 1     | 205.513 | −0.316 | 0.10  | 113.7 | 2   | 0.10²  | 0.10 ± 0.03 | 0.14  | 29    | 17.38 | <0.40|
| 2     | 205.417 | 0.287  | 0.56  | 6.3   | 12.3 | 0.39⁰⁻⁰.40² | 0.50 ± 0.17 | 0.003 | 26    | 18.96 | 1.86 |
| 3     | 205.307 | −0.183 | 0.61  | 4.7   | 1.2  | 0.40⁰⁻⁰.60² | 0.39 ± 0.13 | 0.73  | 34    | 19.37 | <0.16|
| 4     | 205.550 | 0.378  | 0.37  | 170.4 | 1.2  | 0.31⁻⁻⁰.50² | 0.52 ± 0.17 | 0.95  | 49    | 19.76 | <3.91|
| 5     | 205.859 | 0.354  | 0.90  | 7.2   | 2    | 0.60²  | 0.56 ± 0.19 | 0.50  | 50    | 20.06 | <6.37|
| 6     | 205.377 | −0.022 | 0.10  | 158.2 | 2.34 | 0.60⁻⁻⁰.67² | 0.35 ± 0.11 | 0.98  | 33    | 20.03 | 5.55 |
| 7     | 206.296 | 0.078  | 0.56  | 22.0  | 1.2  | 0.37⁻⁻⁰.30² | 0.42 ± 0.14 | 0.59  | 30    | 19.25 | <7.29|
| 8     | 206.363 | −0.438 | 0.43  | 3.3   | 2    | 0.30²  | 0.46 ± 0.15 | 0.63  | 29    | 19.49 | <3.29|
| 9     | 206.210 | 0.468  | 0.10  | 48.0  | 1.23 | 0.36⁻⁻⁰.30² | 0.09 ± 0.03 | 0.46  | 28    | 19.56 | 6.03 |

Mock catalogues and SExtractor was used to identify peaks in the derived density maps.

Following Olsen et al. (1999) we minimize the number of spurious detections using the SExtractor parameters Nₘₐₘᵢₜ and σₖₐₜ as well as other properties of the noise peaks, such as the number of redshifts where a peak is detected, nᵣ. We adopt σₖₐₜ = 4, Nₘₐₘᵢₜ = 7σ₁ as any given redshift and we only consider peaks that appear in at least two consecutive redshifts (i.e., nᵣ ≥ 2). For this choice of parameters we estimate the spurious cluster contamination to be ≈5 per cent.

3.3 Our final optically selected cluster sample

We construct our final optical cluster catalogue by adopting the conservative approach of considering as cluster candidates those identified by both the SMP and MFA techniques. Our final sample, which we call SMPMFA, consists of nine clusters with SDSS richness of more than 20 galaxies, corresponding roughly to APM-type clusters. This estimated richness corresponds to the number of galaxies having r-band magnitudes ≤ m₁ + 2 (where m₁ is the magnitude of the third brightest cluster member) within a radius of 0.75 h⁻¹ Mpc, estimated using the approximate redshift of the cluster.

Comparing our SMPMFA sample with the 29 clusters of Goto et al. (2002), we find five in common.

3.3.1 Cluster shapes

We investigate the reality of our candidate clusters by fitting a King profile to their projected galaxy distribution. We expect that a galaxy enhancement produced by projection effects should have a rather flat profile and thus the goodness of fit should be low.³ The King profile is given by

\[ \Sigma(\theta) \propto \left[ 1 + \left( \frac{\theta}{\theta_c} \right)^2 \right]^{-\alpha} \tag{10} \]

where \( \theta_c \) is the angular cluster core radius. The slope \( \alpha \) is related to \( \beta \), the ratio of the specific energy in galaxies to the specific thermal energy in the gas, by \( \alpha = (3\beta - 1)/2 \), and spans the range 0.6 ≲ \( \alpha \) ≲ 1 (cf. Bahcall & Lubin 1993; Girardi et al. 1995, 1998).

In order to quantify the parameters of the fit we perform a standard \( \chi^2 \) minimization procedure between the measured surface density of each of our clusters and equation (10):

\[ \chi^2 = \sum_{i=1}^{n} \frac{\left[ \Sigma_{\text{data}}(\theta) - \Sigma_{\text{King}}(\theta, \theta_c, \alpha) \right]^2}{\sigma_i^2} \tag{11} \]

In Table 1 we present our cluster positions and the parameters of the King profile, as well as the \( \chi^2 \) probability (Pχ²) of consistency between the King profile and the cluster density profile. The errors are 2σ estimates, corresponding to \( \Delta r_c = 0.14 \) (\( \chi^2 \) min of the absolute minimum value of the \( \chi^2 \)). All but one of the candidate clusters are well fitted by a King profile with \( r_c \) ≳ 0.14, while the slope \( \alpha \) of the profile is ≳ 0.7, corresponding to a \( \beta \)-parameter of 0.8 (cf. Cavaliere & Fusco-Femiano 1976; Jones & Forman 1999). Furthermore, we present the estimated cluster redshifts (either from Goto et al. 2002 or from the MFA method). In the case of cluster 6 we give the spectroscopic redshift from Couch et al. (1991). For those clusters which are well fitted by a King-like profile we can give an approximation regarding their spatial core radius \( r_c \). Different studies (Girardi et al. 1995, 1998) have shown that the radial core radius of Abell clusters has an average value of \( r_c \approx 0.10 - 0.15 h^{-1} \) Mpc. Therefore, having an estimate of the cluster redshift, the corresponding core radius can be easily found from \( r_c = d_L \tan(\theta_c) \), where \( d_L \) is the luminosity cluster distance.

In order to check for possible evolutionary trends regarding the cluster core, we have plotted the core radius as a function of redshift. As shown in Fig. 4 we find a significant correlation; the coefficient is ≈0.60 with the probability of zero correlation being < 10⁻⁵. In the local Universe (0 < z < 0.15), the core radius is approximately equal with \( \sim 0.10 h^{-1} \) Mpc, which is similar to the value derived by Girardi et al. (1998). The line of the best fit is given by

\[ r_c \approx 0.530(\pm 0.291)z + 0.138(\pm 0.134) \tag{12} \]

In order to check if the observed evolutionary trend is an artefact of possible systematic effects, we have first investigated the effect of the SDSS redshift selection function. We have determined the predicted SDSS redshift distribution using the r-band luminosity function of

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Blanton et al. (2003) for galaxies between 0.02 \( \leq z \leq 0.22 \). We have extrapolated their luminosity-dependent density evolution model up to \( z = 2 \) and find that the SDSS redshift distribution increases up to \( z \approx 0.45 \) (see inset of Fig. 4). This implies that the sample is roughly volume limited out to this distance and thus the \( r_c-z \) trend seen in Fig. 4 should not be due to systematic effects related to undersampling of the cluster galaxy population. Because we have used a single band (\( r \) band) to detect clusters, we also explore the effect of determining their morphological characteristics in different rest-frame bands. We note that the wavelength difference (effective \( \lambda \)) between the Sloan \( r \) and \( z \) bands is \( \approx 2800 \) A, which corresponds to a redshift difference of \( \approx 0.45 \). Therefore, the rest-frame \( r \) band at low redshifts (\( z \leq 0.15 \)) roughly shifts to the \( z \) band at \( z \approx 0.6 \). We then compare the mean core radius of our most distant clusters (at \( z \approx 0.6 \) and 0.67) using the \( z \) band (within its completeness limit \( m_z \leq 21.5 \)) with the mean core radius of our relatively nearby clusters (\( z < 0.3 \)) determined in the \( r \) band (within its completeness limit of \( m_r \leq 22 \)). We find that the \( r \)-band core radius of the four low-\( z \) clusters is \( 0.27 \pm 0.19 \), while the \( z \)-band core radius of the two high-\( z \) clusters is \( 0.65 \pm 0.35 \). Therefore, it seems that the effect of the different rest-frame bands in the definition of the cluster morphology (at least for our sample and the redshifts covered) neither creates nor masks the observed evolutionary trend.

We list in Table 1 the cluster shape parameters determined by using the moments of inertia method (cf. Carter & Metcalfe 1980; Basilakos, Plionis & Maddox 2001). This method is based on evaluating the moments

\[
I_{11} = \sum \delta_j \left( r_j^2 - x_j^2 \right)
\]

\[
I_{22} = \sum \delta_j \left( r_j^2 - y_j^2 \right)
\]

\[
I_{12} = I_{21} = -\sum \delta_j x_j y_j,
\]

where \( \delta_j \) is the galaxy overdensity of each cell and \( x \) and \( y \) are the Cartesian coordinates of each cell, after transforming the equatorial coordinates into an equal area coordinate system, centred on the cluster centre. Then, diagonalizing the inertia tensor

\[
\text{det}(I_{ij} - \lambda^2 M_2) = 0 \quad (M_2 \text{ is a } 2 \times 2 \text{ unit matrix}),
\]

we obtain the eigenvalues \( \lambda_1 \) and \( \lambda_2 \), from which we define the ellipticity of the configurations under study by \( \epsilon = 1 - \lambda_2/\lambda_1 \), with \( \lambda_1 > \lambda_2 \). The corresponding eigenvectors provide the direction of the principal axis. It is evident that three out of nine clusters have large projected ellipticities (\( \epsilon > 0.5 \)).

4 COMPARING CLUSTERS IN THE OPTICAL AND X-RAY BANDS

4.1 X-ray cluster detection

The full details of the cluster detection procedure and the cluster X-ray luminosity and temperature determinations will be described in Gaga et al. (in preparation). Here we only briefly present the main method and results.

In order to detect candidate clusters in our XMM fields we use the soft 0.3–2 keV data because this band maximizes the signal-to-noise ratio, especially in the case of relatively low-temperature galaxy clusters. In particular, we use the EWALET detection algorithm of the XMM–Newton Science Analysis System (sas) v.5.3 analysis software package, which detects sources on the wavelet transformed images.

We search for sources down to the 5\( \sigma \) detection threshold, on the PN and the co-added MOS1 and MOS2 detector images, separately. The output list is fed into the SAS EMDTECT algorithm which performs a maximum likelihood point spread function (PSF) fit on each source, yielding a likelihood for the extension. We are using an extension likelihood threshold corresponding to a level of less than \( \sim 0.5 \) per cent spurious extended sources. We have detected seven candidate clusters on the MOS mosaic, while five extended sources have been detected on the PN images, out of which three overlap with the MOS candidates.

We have also visually inspected the candidate clusters and found that on some occasions the high extension likelihood was due to multiple point sources (confusion). These spurious detections are excluded from our final X-ray selected cluster candidate list. This results in a final list of four X-ray cluster candidates, out of which two are detected on both the MOS and PN, one is detected only on the MOS (there was no valid PN image) and the last one is detected only on the PN (note that this cluster was detected with a slightly smaller likelihood probability, \( \sim 0.99 \)). The faintest extended source has a flux of \( \sim 2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \). Note that for the (0.3–2) keV energy band the net X-ray count rate for our detected extended sources is \( 3 \times 10^{-3} \) counts s\(^{-1} \), within a 30-arcsec radius circle.

In Table 2 we present the properties of the X-ray cluster candidates.

4.2 Optical versus X-ray cluster detections

We perform a cross-correlation between the different cluster catalogues (optical, X-ray), using a 3-arcmin matching radius to identify common objects. In Fig. 5, we plot the positions of (i) our optically detected cluster candidates (SMPMFA sample), (ii) the Goto et al. (2002) clusters and (iii) the X-ray detected XMM–Newton clusters. All four X-ray detections coincide with optical cluster candidates from different methods, with the largest coincidence rate (three out of nine) being with our SMPMFA optical candidates. The most distant cluster in our SMPMFA sample, located at \( \alpha = 13^h 43^m 5\delta = 00^\circ 00' 56''. \) found also in X-rays, is missed by Goto et al. (2002).

The cross-correlation results between the different cluster detection methods are presented in Table 3. The first column lists the...
Table 2. The X-ray cluster properties: columns 1 and 2, equatorial coordinates (J2000); column 3, X-ray luminosity (erg s\(^{-1}\)) in the 0.3–2 keV band; column 4, X-ray flux (0.3–2) keV, in units of 10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\); column 5, cluster temperature from Gaga et al. (in preparation); column 6, the \textit{XMM} field; column 7, optical follow-up; column 8, the cluster redshift.

| \(\alpha\)   | \(\delta\) | \(L_x\) | \(f_x\) | \(T\) (keV) | \(XMM\) field | Optical | \(z\) | Detector |
|-------|-------|-------|-------|-------|--------------|--------|-----|--------|
| 13 41 39.1 | +00 17 39.3 | 10\(^{42.63}\) | 1.86 | \(\sim\) 3 | F864-1 | SMPMFA+CE | 0.40\(^a\) | PN+MOS |
| 13 43 04.8 | –00 00 56.3 | 10\(^{43.60}\) | 5.55 | \(\sim\) 2 | F864-5 | SMPMFA | 0.67\(^b\) | PN+MOS |
| 13 45 11.9 | –00 09 52.6 | 10\(^{42.00}\) | 5.05 | \(\sim\) 1 | F864-6 | CE | 0.12\(^c\) | MOS |
| 13 44 49.7 | +00 27 53.3 | 10\(^{42.87}\) | 6.03 | \(\sim\) 1 | F864-3 | SMPMFA+CE | 0.30\(^d\) | PN |

\(^a\)MFA method.
\(^b\)Couch et al. (1991).
\(^c\)CE method (Goto et al. 2002).

5 CONCLUSIONS

We have made a direct comparison between optical and X-ray based techniques to identify clusters. We have searched for extended emission in our shallow \textit{XMM–Newton} survey, which covers a \(\sim\) 1.6 deg\(^2\) area (eight out of nine original \textit{XMM} pointings) in the North Galactic Pole region and we have detected four candidate X-ray clusters. We have then applied a new cluster finding algorithm on the SDSS galaxy distribution in this region, which is based on merging two independent selection methods: the SMP technique and the MFA. Our final optical cluster catalogue, called the SMPMFA list, counts nine candidate clusters with a richness of more than 20 galaxies, corresponding roughly to the APM richness limit.

Out of the four X-ray candidate clusters, three are common with our SMPMFA list. This relatively small number of optical SMPMFA cluster candidates observed in X-rays suggests that some of the optical cluster candidates are either projection effects or poor X-ray emitters, and hence they are fainter in X-rays than the limit of our shallow survey. Some of these X-ray emitters, and hence they are fainter in X-rays than the limit of our shallow survey. Some of these X-ray emitters, and hence they are fainter in X-rays than the limit of our shallow survey.

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