The X-CLASS–redMaPPer galaxy cluster comparison

I. Identification procedures

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ABSTRACT

Context. This paper is the first of a series undertaking a comprehensive correlation analysis between an optically selected and an X-ray selected cluster catalogues. The final goal of this work is to develop a holistic picture of galaxy clusters utilizing optical and X-ray clusters selected catalogues with well understood selection functions.

Aims. Contrary to most of the X-optical cluster correlations to date, the present study focuses on the non-matching objects in either wavebands. We investigate how the differences observed between the optical and X-ray catalogues may originate from (1) short-coming of the detection algorithms, (2) dispersion in the optical/X-Ray scaling relations (3) substantial intrinsic differences between the cluster populations probed in the X-Ray and optical. The aim is to inventory and elucidate these effects in order to account for selection bias issues in the further determination of X-ray/optical cluster scaling relations.

Methods. We performed a detailed and, for a large part interactive, analysis of the matching output between the X-CLASS and redMaPPer cluster catalogues. The overlap between the two catalogues has been accurately determined and possible cluster positional errors were manually recovered. The final samples comprise 270 and 355 redMaPPer and X-CLASS clusters respectively. X-ray cluster matching rates were analysed as a function of optical richness. In a second step, the redMaPPer clusters were correlated with the entire X-ray catalogue, containing point and uncharacterised sources (down to a few $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in the [0.5-2] keV band). A stacking analysis was performed for the remaining undetected optical clusters.

Results. Main results show that neither of the wavebands misses any massive cluster (as coded by X-ray luminosity or optical richness). After correcting for obvious pipeline short-comings (about 10% of the cases both in optical and X-ray), ~50% of the redMaPPer (down to a richness of 20) are found to coincide with an X-CLASS cluster; when considering X-ray sources of any type, this fraction increases to ~80%; for the remaining objects, the stacking analysis finds a weak signal within 0.5 Mpc around the cluster optical centers. The fraction of clusters totally dominated by AGN-type emission appears to be of the order of a few percent. Conversely ~40% of the X-CLASS clusters are identified with a redMaPPer (down to a richness of 20) - part of the non-matches being due to the fact that the X-CLASS sample extends further out than redMaPPer ($z < 1$ vs $z < 0.6$); extending the correlation down to a richness of 5, raises the matching rate to ~65%.

Conclusions. This state-of-the-art study involving two well-validated cluster catalogues has shown to be complex and pointed out a number of issues inherent to blind cross-matching, due both to pipeline shortcomings and cluster properties; these can only be accounted for after manual check. X-ray/optical scaling relations will be presented in a subsequent article.

Key words. galaxy clusters – catalogues – X-ray – optical – observations – cosmology

1. Introduction

The abundance of galaxy clusters is a powerful cosmological probe (e.g. [Henry et al. (2009), Vikhlinin et al. (2009), Mantz et al. (2010b), Rozo et al. (2010), Pierre et al. (2011), Clerc et al. (2012a)]. Indeed, galaxy clusters provided the first line of evidence for dark matter (Zwicky (1933)) and that the matter density of the universe was sub-critical ($\Omega_{m} < 1$, Gott et al. (1974)).

Historically, galaxy clusters were first identified in the optical (Abell (1958)). Early optical cluster catalogs were constructed utilizing single bad photometric data, and were therefore extremely susceptible to selection effects. With the advent of the ROSAT All Sky Survey (RASS, [Voges et al. (1999)]), cluster detection was preferentially pursued in the X-ray, as the detection of X-ray photons provided unambiguous evidence of a deep potential well, and therefore of the reality of the detected galaxy clusters. This led to the generation of a plethora of RASS X-ray catalogs (e.g. [Ebeling et al. (2000), Böhringer et al. (2000), Reiprich & Böhringer (2002), and many others]), which have since been complemented both by targeted [Pacaud et al. (2007) and serendipitous (Lloyd-Davies et al. (2011))] cluster searches with the XMM-Newton telescope. At the same time, the advent of multi-band photometric data has led to dramatic improvements in optical cluster finding and an explosion of algorithms (e.g. (Gladders & Yee (2005), Koester et al. (2007), Wen & Han (2013), Hao et al. (2010), Szabo et al. (2011), and many others).

To date, cluster searches in the X-ray, optical, and now in infra-red wave-band for the $z > 1$ range, are still conducted independently although simultaneous multi-band approaches are being proposed (e.g. Cohn & White (2009), Bellagamba et al. [...])
Throughout the article we assume the WMAP7 cosmology (Komatsu et al. (2011), Larson et al. (2011)).

2. Catalogue overview

The X-CLASS and redMaPPer galaxy cluster catalogues pertain to very different data types and detection methods and are already published. In this section, we briefly summarise the properties of the two samples, as relevant for the present study.

2.1. The X-ray catalogue

2.1.1. X-CLASS clusters

The X-CLASS sample results from a serendipitous cluster search involving XMM archival observations performed until May 2010. Out of these, only observations at galactic latitudes higher than $|b| > 20$ deg were considered; regions such as the Magellanic Clouds or the surrounding of bright nearby galaxies (e.g. as M31) were excluded. Cluster detection was performed using the two-step XMM-LSS pipeline (Xamin), combining wavelet multi-resolution analysis and maximum likelihood fits that make proper use of Poisson statistics. The working radius of the pipeline was restricted to 13 arcmin (XMM has a total field of view of 30 arcmin, but beyond R=13 arcmin, sensitivity and PSF are strongly degraded, hence rendering cluster detection and characterisation unreliable). The whole procedure has been evaluated by means of extensive image simulations (Pacaud et al. (2006)). This enabled us to create an uncontaminated (C1) cluster sample by selecting sources in the [extent-extent_likelihood] output parameter space. From the simulations, we derived the probability for a cluster of given apparent size and flux to be detected as a C1 source. We emphasise again here that, contrary to what was commonly assumed so far, complete and uncontaminated cluster samples cannot be defined by a single flux limit, unless the limit is set very high compared to the survey sensitivity. Rather, cosmological cluster samples are surface-brightness limited and thus must be selected in a two-dimensional parameter space. The X-CLASS catalogue (including the selection function) is described and published by Clerc et al. (2012b), we stress below some features especially relevant for the present study.

- All XMM observations processed were cut to 10 ks of clean observing time on each of the three detectors. This in order to ensure homogeneity and, thus, ease the calculation of the selection function (in this case, only background variations from pointings to pointings have to be considered). 10 ks XMM exposures correspond to a point-source sensitivity of $5 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (80% completeness limit, detection likelihood $> 15$ and median background) in the [0.5-2] keV band.
- XMM pointed observations of clusters were not excluded from our processing of the archive. This is a significant difference from other archive processing such as the XMM Cluster Survey (XCS, Mehringer et al. (2012)) and 2XMMi/SDSS Galaxy Cluster Survey (T13,takey et al. (2013)). Main reason for this choice is that excluding some 200 clusters would significantly decrease the final sample. Further, it would introduce a bias that is not a priori less than when including them, all the more so since one tends to propose XMM observations of the brightest clusters at any redshift (see discussion in Sec. 3.5 of Clerc et al. (2012b)).
- All sources flagged as C1 by Xamin were interactively screened by means of XMM/DSS overlays. The purpose...
of this procedure, that involved at least two different persons, is twofold: (1) remove nearby galaxies, saturated point-sources, X-ray artefacts and possible unresolved double-sources that also appear as extended sources (2) provide an approximate distance indicator depending on the existence of a conspicuous optical counterpart to the X-ray emission, namely: NEARBY ($z < 0.3 - 0.4$) and DISTANT ($z > 0.3 - 0.4$), where $z \sim 0.3 - 0.4$ corresponds to the POSS-II plate limit.

- On the basis of extensive simulations, the final C1 sample is estimated to have a degree of purity greater than 95%. These clusters have a typical mass of $M_{500} \sim 5 \times 10^{13} M_{\odot}$ at a redshift of 0.3 (Pacaud et al. 2007). The theoretical calculation of the mass limit as a function of redshift for this X-ray surface brightness selected cluster sample can be found in Pierre et al. (2011) (Fig. 2).

- While only 420 high S/N clusters are published by Clerc et al. (2012b), the present study makes use of the the full X-CLASS 10ks catalogue containing 663 C1 clusters.

The public X-CLASS sample is available at (http://xmm-lss.in2p3.fr:8080/l4sdb/) and provides XMM/DSS overlay as well as the details of the corresponding XMM observations. An example of an X-CLASS cluster is displayed on Fig. 1.

### 2.1.2. The other X-ray sources

In addition to the C1 sample, we shall complement our X-ray/optical correlation analysis by considering all other sources detected in the 10 ks pointings used for the X-CLASS selection. These sources can be classified as follow:

- C2 sources constitute a second, fainter, cluster sample such as to allow for ~50% contamination by misclassified point sources which can be cleaned up a posteriori using optical/X-ray comparisons.

- The Xamin pipeline was designed to ensure best sensitivity for low surface brightness objects in Poisson regime. It is thus not adapted to the characterisation of very nearby clusters filling most of the XMM FOV, producing thousands of photons whereby very little area is left for background estimates. Such sources are detected by the first pass of the pipeline but not analysed by the Maximum Likelihood module. A similar situation occurs for some weaker cluster sources, located close to the border of the detection mask ($R_{500-xmax} = 13$ arcmin). These sources are characterised by a special flag on the detection_likelihood parameter (NaN) and not included in the X-CLASS catalogue, meant to strictly contain only C1-type clusters.

- Bright cluster sources strongly contaminated by a peaked central source (cool core of AGN).

- Unambiguous point-like sources constitute the P1 class and correspond a S/N of at least 5 (Faccioli et al in prep.)

- The remaining sources are too faint (some 20 photons at most) to be characterised, given the XMM PSF and photon noise. They are split into two categories: (1) Those significantly detected, having a detection likelihood greater than 15 (weak sources, W-sources) and (2) those, very marginal sources (M-sources), below this significance threshold; our simulations showed that a large fraction of the latter are spurious. Our policy is to publish the LH>15 sources only (Chiappetti et al. 2013).

The X-ray source classification is summarised in Table 1; we stress that non-cluster sources constitute more than 90% of the extragalactic X-ray source population at our sensitivity level.

### 2.2. The optical cluster sample

redMaPPer is a new red-sequence photometric cluster finding algorithm which was recently applied to the SDSS Data Release 8 (Aihara et al. 2011). The algorithm and SDSS DR8 catalog is described in detail in Rykov et al. (2013). A detailed comparison of redMaPPer to other photometric cluster finding algorithms is presented in Rozo & Rykoff (2014), which also includes a multi-wavelength study of the performance of redMaPPer in the SDSS. A comparison of the redMaPPer catalog to the Planck SZ catalog (Planck Collaboration XXIX 2013) is presented in Rozo et al. (2014).

Briefly, redMaPPer models the red-sequence of galaxy clusters as having gaussian scatter along a mean color–magnitude...
relation. Both the mean color–magnitude relation and the scatter are parameterised via spline interpolation, with the free parameters being the value at the nodes. These values are iteratively self-trained by leveraging both SDSS photometry and spectroscopy: we photometrically identify cluster galaxies about galaxies with spectroscopic redshift, and assign these photometric members the cluster redshift, allowing us to better calibrate the red-sequence at faint magnitudes. The associated spectroscopic requirements for the above training are minimal, and are easily satisfied by existing SDSS spectroscopy.

Once the red-sequence model has been trained, the algorithm attempts to grow a galaxy cluster centered about every SDSS spectroscopic redshift measurement. The richness estimate \( \lambda \) measures the total number of red-sequence galaxies brighter than \( 0.2L^* \) within a cluster, within a cluster radius \( R(\lambda) \) selected to optimize the signal-to-noise of the measurement. The richness is defined via

\[
\lambda = \sum p_i
\]

where \( p_i \) is the probability of galaxy \( i \) of being a cluster galaxy, as estimated based on the red-sequence model calibrated above and the mean background of non-cluster galaxies, estimated by computing the mean galaxy density across the entire SDSS DR8 footprint.

Once a rich galaxy cluster has been identified (\( \lambda \geq 5 \), where \( \lambda \) is the number of red-sequence galaxies hosted by the cluster), the algorithm iteratively determines a photometric redshift based on the calibrated red-sequence model, and re-centers the clusters about the best cluster center, as gauged from the photometric data. The final catalogue is then further trimmed to a richness limit of \( \lambda \geq 20 \) for \( z \leq 0.35 \). Above this redshift, the catalog becomes “flux” limited due to the SDSS survey depth, and the richness limit increases rapidly with redshift. Roughly speaking, richness measurements are reliable out to \( z = 0.5 \). For \( z \in [0.5,0.6] \), clusters can be detected, but their richness measurements become very noisy. When run on SDSS data, automated cluster finding is not really feasible with the redMaPPer algorithm above redshift \( z = 0.6 \). We note that the red-sequence model is trained over the redshift range \( z \in [0.05,0.6] \). Consequently, clusters near the redshift edges can have unreliable redshifts: robust photometric redshift performance is expected to be limited to \( z \in [0.08,0.55] \). The photometric sensitivity is roughly but not exactly constant over the entire survey area. Variations in depth as a function of position exist but their dependences are not included in redMaPPer v5.2. Because SDSS is roughly uniform, however, the differences induced by these variations are small. As for masked area, the redMaPPer mask is defined to be such that no cluster is masked by more than 20% by the BOSS galaxy mask. The redMaPPer redshift detection range is \( z \in [0.05,0.6] \). The upper redshift limit is driven by the depth of the SDSS: the galaxies in clusters at higher redshifts are not detectable in the SDSS. At low redshifts, the cluster selection is limited by the relative lack of rich galaxy clusters used for photometric calibration (due to small volume) and the fact that the photometry of very bright low redshift galaxies from the automated SDSS pipeline is often compromised (e.g. many galaxies are saturated, and therefore not present in the photometric catalogue).

The redshift-richness distribution of the sample is shown in Fig. 2.

3. Matching the optical and X-ray cluster samples

3.1. Overlap between the two catalogues

Any correlation study requires a careful determination of the region of overlap between the catalogues. Here, the exercise is complicated by the fact that the X-ray coverage is sparse with, moreover, some overlap between the individual XMM observations. Similarly, the sky distribution of the redMaPPer clusters is affected by the BOSS masking. To ease the task, we have thus defined two "common complete samples": one (OPT→X) that will be used for studying the X-ray counterparts of the optical clusters and a second one (X→OPT) for the study of the optical properties of the X-ray clusters.

The sky distribution of the redMaPPer catalogue and XMM pointings is displayed on Fig. 3. In the following, we name ‘XC1’ the sub-sample of C1 X-CLASS clusters falling onto the region covered by the redMaPPer catalogue and XC1*, the XC1 sample supplemented by the clusters manually recovered (detection_likelihood = NaN, 29 objects, see Sec. 4.2.3).
We have first identified all XMM X-CLASS observations containing at least one redMaPPer position. Our search radius was restricted to 12 arcmin from the center of each X-ray observation, to match the working radius of the X-ray pipeline (13 arcmin) when allowing for 1 arcmin source positional errors (see Sec. 3.2). In total, we have identified 223 XMM-CLASS pointings containing 270 redMaPPer cluster positions. The corresponding X-ray area is ∼27 deg², once the overlap between the XMM pointings is removed. The properties of these objects are presented in Fig. 4, differences from the complete sample (Fig. 2), especially in the first two redshift bins can be ascribed to the presence of XMM pointed observations on some clusters of interest (see discussion in 5.1).

Second step was to identify which of the X-ray clusters have a potential redMaPPer counterpart. For this, we make use of the masks defined for the construction of the redMaPPer catalogue: footprint of the BOSS survey minus the regions flagged as ‘bad field’ or excluded areas in the vicinity of bright stars. In total, 355 XC1+ were found to pass the mask selection and constitute the X→OPT sample. The optical properties of this sample are presented in section 5 and its sky distribution shown on Fig. 5.

When matching clusters in position, one needs to define the aperture used for the positional matching. This is an important and not trivial choice. It must be large enough to account for the positional uncertainties of both catalogues. However, its value should be limited by the condition that the number of chance associations will be kept to an acceptable level, when the optical sample is further correlated with the entire X-ray catalogue (i.e. including the numerous point-like or unresolved detections). Basically, there are two possibilities: either use a fix angular scale, or a physical scale, none of them being perfect as discussed below.

We recall that the XC1 and redMaPPer densities are ∼5/deg² (for a uniform X-ray coverage, zlim < 1.5) and 2.5/deg² (λ > 20, zlim < 0.6) respectively. For 10 ks exposures, the XMM source density above a detection likelihood of 15 is ∼400 per square degree in the soft band (Chiappetti et al. (2013)); this corresponds to a mean separation between sources of 3 arcmin. Our experience with the optical follow-up of XMM-LSS clusters (Pacaud et al. (2007)) shows that, for a very large fraction of the C1 population, the X-ray centroid calculated by the pipeline matches better than 1/2 arcmin the position of the cD galaxy. Cases where larger offsets are observed (∼10%) correspond to obvious mergers for which the X-ray emission shows multiple maxima or is very flat; such merger situations also affect the determination of the optical centre. Optical centering is further prone to inherent uncertainties like, in the case of the redMaPPer algorithm, the wrong identification of the cD galaxy which may put the calculated center up to a few arcmin from its actual position.

Given these practical limitations, we set a fix angular search radius of 1 arcmin. Between 0.1 < z < 0.6 - where most of the clusters of interest for the present study lay - this angular scale spans 108–402 Mpc. Subsequently, we have visually inspected all clusters for which no or several counterparts were found, in order to correct a posteriori our correlation statistics for any shortcoming of the X-ray or optical pipelines. Two examples of a complex matching configuration solved by visual inspection are presented in Fig. 6.

We finally checked whether the 1 arcmin correlation disk around each of the 355 XC1+ positions was significantly affected by the optical masking: no masking greater than 30% was found.

### 4. The X-ray counterpart of the redMaPPer clusters

For this study we use the OPT→X sample (270 redMaPPer clusters) as defined in Sec. 3.1.1

#### 4.1. Statistics

We first matched the redMaPPer clusters with the XC1 clusters within a radius of 1’. We found 92 (∼34%) matches; Fig. 7 shows the distribution of the corresponding optical-X-ray separations: most of the matches occur for distances less than 0.5 arcmin and their optical characteristics are shown in Fig 8. This distribution is expected to largely reflect the centering offsets between X-ray centers and the true central galaxies of clusters and/or positional uncertainties in the X-ray center.
Fig. 3. Sky coverage of the redMaPPer and X-CLASS catalogues. The grey dots stand for the redMaPPer galaxy clusters (26,138 objects, \( \lambda > 20 \)). The black circles indicate the XMM-Newton pointings pertaining to the X-CLASS catalogue (2409 observations); the size of the XMM FOV (30′) is exaggerated on the figure; The red circles flag the X-CLASS pointings containing at least one redMaPPer cluster within 12′ (223 observations).

Fig. 5. The overall area encompassed by the redMaPPer catalogue (BOSS survey) is mapped by the small black dot distribution as in Fig. 3. The blue circles show the 355 XC1 clusters that have passed the redMaPPer area masking (exclusion of ‘bad’ fields and of the vicinity of bright stars).

4.2. Inventory of the redMaPPer clusters not detected as C1

Each of the 178 redMaPPer clusters not matched with an XC1 within 1′ was then examined by eye on the basis of optical/X-ray overlays. We further correlated the OPT→X sample with the complete X-ray source list as described in Table [1]. Fig. 9 shows the distribution of the distances between the optical and X-ray source centres.

We review below case by case the outcome of this analysis (the percentages are expressed as a function of the OPT→X cardinal i.e. 270 objects).
1. ~ 5% (17) of the redMaPPers are found to have a C2 counterpart within 1′. Most of them have a richness $\lambda < 40$ and a redshift $0.1 < z < 0.5$ with a median value of ~ 0.38.
2. ~ 2% (7) are associated with an extended emission plus strong central peak.
3. ~ 11% (29) are associated with detected X-ray sources but not analysed by Xamin (mostly very nearby objects filling a large fraction of the detector). Such non-matches were manually recovered and a posteriori added to the XC1 sample to constitute the XC1+ sample. An example is shown on Fig.10.
4. ~ 7% (19) are associated with a P1 point-source within 1′.
5. ~ 10% (27) are associated with a W-source within 1′
6. For completeness, we mention that ~ 9% (23) of the redMaPPer are associated with a M-source within 1′. We recall that this last category is defined by a detection likelihood lower than 15 and contains many spurious X-ray detections.
7. ~ 8% (21) of the redMaPPers show a large offset between the optical and C1 X-ray positions, i.e. more than 1′–3′. The eye-inspection showed that for many of these objects the cD was misidentified. These matches were recovered after visual inspection.
8. ~ 13% (35) of the redMaPPer are not associated with any X-ray detection within 1′. An example is shown in Fig.11.

Fig. 6. Two problematic matching cases, that were a posteriori recovered by visual inspection. The SDSS color 7′x7′ image is overlaid on the raw X-Ray photon image + contours (the X-ray image is not corrected for detector cosmetic); the optical and X-ray centres are marked by a white and red cross respectively. Left : Wrong optical centre; the offset between the redMaPPer and X-Ray centres is 2.2′. Right : Complex nearby structure; the offset between the two centres is 1.7′.

Fig. 7. Offsets between the redMaPPer and the XC1 cluster positions (142 objects in total). Clusters missed because of failures of the X-ray or optical pipelines but recovered after visual inspection of the data are added in the first bin.

Fig. 8. Fraction of the redMaPPer clusters detected as XC1, as function of richness and redshift. In total, 92 matches with C1 X-ray clusters for 270 input redMaPPer are found within a radius of 1′. The grey bins indicate redshift-richness combinations not present in the input OPT→X catalogue (Fig.4). A posteriori recovered correlations are not included in this plot (see Fig.14 for a complete census).
Fig. 9. Offsets between the redMaPPer and X-ray source positions (of any type, detection likelihood > 15) superposed on the calculated distribution of chance-coincidences (212 objects in total). Clusters missed because of failures of the X-ray or optical pipelines but recovered after visual inspection of the data are added in the first bin.

Correcting for the large offsets and not analysed clusters, 53% of the redMaPPer have a C1-type counterpart (C1 + categories 3, 7). In total 79% (C1 + categories 1, 2, 3, 4, 5, 7) of the redMaPPer were found to coincide with an X-ray source (not considering the M-sources); The correlation break-down is illustrated in Fig. 20. As easily understandable, a large fraction of the clusters not analysed by Xamin lay in the upper part of the diagram (rich objects, hence expected to be X-ray bright). Undetected redMaPPer clusters lay mostly along the redMaPPer sensitivity limit.

We finally mention that we have also performed the OPT-\textgreater C1 correlation restricting the redMaPPer catalogue to its low-redshift part. Within 1 arcmin, the matching rates are 45% and 56% for the $z < 0.5$ and $z < 0.3$ sub-samples respectively to be compared to 45% for the full sample, which contains twice as many clusters than when limited to $z < 0.3$. Correcting for positional offsets, these fractions are increased to 53%, 70% and 53% respectively.

4.3. Stacking analysis of the redMaPPer with no X-ray counterpart

In this section, we consider the cumulative X-ray signal of the redMaPPer clusters having no XMM counterpart at all (within our sensitivity limits) and, for comparison, those having a marginal counterpart (M-sources) i.e. objects falling in above-categories 8 and 6 respectively (black and orange stars on Fig. 20). We split the analysis in two subsamples: redMaPPer positions falling within an off-axis angle of 9° or between 9°-12°, knowing that beyond 9° PSF blurring along with vignetting strongly reduce the detection limit.

The stacking analysis of XMM data is a particularly challenging task given the topology of the focal plane (combination of three telescopes, gaps between the CCDs) and should account for the PSF and sensitivity variations as a function of off-axis distance. Further, the mean background is subject not only to local cosmic variations (on a few arcmin scale) but is also affected by the observing conditions inherent to the revolution in question (solar activity) and depends on the position of the spacecraft on the orbit at the observing date. The background consists of two components: the cosmic background, which is subject to vignetting and the particle background uniformly hitting the detector\footnote{http://xmm2.esac.esa.int/external/xmm_sw_cal/background/}. To this, must be added the fact that the signal is Poissonian in our case: as can be appreciated in Fig. 11, many of the 6 arcsec pixels are still empty after 10 ks.

To circumvent these practical difficulties, we have adopted a procedure that stacks not the photons maps, but the putative X-ray profiles. Profiles were calculated from a growth curve analysis, centered on the optical position, estimating the background in the vicinity of the putative cluster within a 150°−500° annulus (i.e. $1 - 3.3$ Mpc at $z = 0.6$, the maximum redshift of the sample); the principle of the analysis is described by Clerc et al. (2012b). Here, profiles were computed for a physical bin-size of 250 kpc and, given the boundaries of the background annulus, all profiles were stopped at 1 Mpc. Error bars for each bin...
were scaled to the mean statistical fluctuations as determined in the background and source annuli. The individual cluster profiles (which may show some negative values) were then averaged for both categories, each data point being weighted by the inverse of the square root of its error bar.

We have further defined a control sample consisting of random positions thrown in the XMM pointings pertaining to the sub-sample. We kept only positions not coinciding with any X-ray source within a radius of one arcmin. In total, 165 positions (out of the 1000 simulated ones) were retained and subsequently assigned a redshift such as to match the redshift distribution of the sub-sample. Results of the stacking analysis for the science and random samples are displayed in Fig. 12 and 13 respectively.

Note that we discarded three clusters out of the 35 of Sec. 4.1.8 since they appeared to be located in the vicinity of bright nearby clusters, hence not allowing a reliable background determination. On Fig. 13 left, we overlaid the signal obtained when removing four redMaPPer positions not associated with any detected source but for which some intensity enhancement is conspicuous on the X-ray pixel images.

In this section, we present the cross-matching between the X-CLASS and redMaPPer samples and use the X→OPT sample.

5.1. Statistics

Out of the 355 XC1+ clusters falling on the redMaPPer detection area (Fig. 5), 144 objects were found to have a redMaPPer counterpart. The correlation between XC1+ and redMaPPer has been performed within a radius of 1 arcmin and yielded 115 matches to which we added the 29 objects recovered after correcting for larger positional offsets (Sec. 4.2.4). We consider that this final set of matches constitutes the most realistic common X-CLASS/RedMapper cluster sample. Their redshift-richness distribution is shown Fig. 14. Compared to the distribution of the full redMaPPer sample (Fig. 2), we observe an overdensity of low-z poor objects (nearby groups) and of rich clusters at any redshift; both can be attributed to the presence of pointed observations. Indeed, a clear trend appears when splitting the matches into two sub-samples: (i) 72 XMM clusters are detected within an off-axis $\leq 3'$ (assumed to be ‘pointed clusters’, Fig. 15) and (ii) 72 XMM clusters found beyond an off-axis $> 3'$ (classified as serendipitous detections, Fig. 16).

We further compared our eye-ball distance estimates (Sec. 2.1) for the matched XC1 with the redMaPPer photometric redshifts. We found that more than 90% of the NEARBY objects have $z_{\lambda} < 0.4$ and more than 75% of the XC1 classified as DISTANT have $z_{\lambda} > 0.4$.

We examine below the X-CLASS clusters found not to have any optical counterpart

5.2. What are the X-CLASS clusters not having a redMaPPer counterpart?

For 211 XC1 clusters, no redMaPPer counterpart was found. From the NASA Extragalactic Database (NED), however, information is available for a significant fraction of them: either they are classified as galaxy clusters (GCclus) or, redshifts exist for a number of individual galaxies within the cluster fields. We have examined each of the non-matches by splitting the sam-
Fig. 15. Redshift-richness distribution of the 72/144 XC1+ clusters detected as redMaPPer and corresponding to targeted XMM observations.

Fig. 16. Redshift-richness distribution of the 72/144 XC1+ clusters detected as redMaPPer and corresponding to serendipitous detections in the XMM observations.

ple according to the X-CLASS distance estimates. Following the criteria defined for the XMM-LSS cluster confirmation, we declare that a cluster is confirmed either when at least 3 galaxies with concordant redshifts are available within a radius of 500 kpc around the X-ray centroid or when the cD has a spectroscopic redshift (Adami et al. 2011). We note $z_{\text{min}}-\text{redMaPPer}$ the lowest possible redshift value of the redMaPPer clusters: $z_{\text{min}}-\text{redMaPPer} = 0.054$. Percentages are expressed as a function of the XC1+ cardinal (355 objects in total).

1. ~28% are NEARBY clusters (99 objects) and 86 of them are subsequently confirmed by means of NED information, with the following breakdown:
   - 51 C1 have at least 3 spectroscopic redshifts or are found to be confirmed with spectroscopy in the literature (GC1str); an example is shown in Fig. 17. 22 of them have $z < z_{\text{min}}-\text{redMaPPer}$
   - For 18 C1, a spectroscopic redshift is available for the cD galaxy; 2 of them have $z < z_{\text{min}}-\text{redMaPPer}$
   - 19 C1 have at least 3 photometric redshifts or are found to be confirmed in the literature form photometric redshift information (GC1str); none of them has $z < z_{\text{min}}-\text{redMaPPer}$
   - For 11 C1, no information was available in NED

2. ~31% are DISTANT clusters (112 objects) and 63 of them are subsequently confirmed by means of NED information, with the following breakdown:
   - 17 C1 have at least 3 spectroscopic redshifts or are found to be confirmed with spectroscopy in the literature (GC1str); they span the 0.25 $< z < 1.26$ range (median $z = 0.54$), 7 of them have $z < 0.5$
   - For 19 C1, a spectroscopic redshift is available for the cD galaxy; they span the 0.019 $< z < 0.99$ range (median $z = 0.39$), 14 of them have $z < 0.5$
   - 27 C1 have at least 3 photometric redshifts or are found to be confirmed in the literature form photometric redshift information (GC1str); they span the 0.25 $< z < 1.14$ range (median $z = 0.57$), 11 of them have $z < 0.5$
   - For 49 C1, no information was available in NED

Each DISTANT C1 not identified with a redMaPPer and not already spectroscopically confirmed from NED, was subsequently examined in the WISE W1/W2-bands (WISE: Wide Infrared Survey Explorer, Wright et al. (2010)). The purpose of this exercise was to attempt to grasp information (even limited) beyond the standard SDSS depth. We found that 1/3 of the clusters having a spectroscopic redshift only for the putative cD galaxy, show a conspicuous galaxy over-density. This ratio amounts to about 70% and 60% for the C1 having at least 3 coincident photometric redshifts or no available information in NED respectively. Further, for more than 15% or the remaining objects, the X-ray emission appears clearly centered on an isolated IR galaxy which could be the cluster cD, the other cluster galaxies being too faint to be detected by WISE.
6. Discussion

We have undertaken a detailed correlation analysis between an X-ray and an optical cluster catalogue and concentrated on the objects left-out by the procedure. Primary goals was to understand the relative impact of (i) catalogue biases (incompleteness, (ii) the correlation techniques used and (iii) intrinsic differences between the cluster populations probed by the X-ray and optical wavebands. The ultimate aim of the procedure being to better understand how cluster samples can be reliably used in cosmological studies. For these purposes, we have used two catalogues covering a large fraction of the sky and having undergone extensive tests, certifying a high degree of purity and completeness; namely the C1 X-CLASS and redMapper catalogues. In practice, the exercise turned out to require a huge amount of inter-active work, i.e. the visual inspection of X-ray/optical overlays for all non primary matches, in order to establish an empirical classification of the situations encountered.

6.1. Result summary

After having carefully defined the regions of overlap between the two catalogues, first step was to chose an adequate correlation length. Although a ‘physical’ radius would sound quite legitimate, we used a fixed angular scale of one arcmin mainly considering the mean size of the clusters involved in the study, the limited XMM FOV and the high density of (extended + point-like) X-ray sources, along with the good XMM positional accuracy. By screening the X-ray/optical overlays, real associations that were found to exist beyond this radius were a posteriori added to the matched sample; the reasons for the observed large offsets were in turned registered. In a second step, the screening analysis enabled us to define two types of categories for the non-matched sources: those due to detection pipeline short-comings and those intrinsic to the X-ray and optical cluster populations as probed by the XMM 10ks archival data and the SDSS depths. In the regions of overlap, the X-CLASS and redMaPPer sub-samples involve 355 and 270 clusters respectively. We can summarise our results as follows:

- Global matching rates. After the first correlation step, some 34% of the redMaPPer and 26% of the X-CLASS clusters were found to have an X-ray or optical counterpart respectively. Taking into account correlations a posteriori recovered (see description below) the final matching rates amount to 53% and to 41% respectively.

- Pipeline features. The main causes of technical miss-match can be ascribed to (i) for the X-ray pipeline, its inability to characterise very bright nearby clusters filling most of the XMM detector or strongly peaked (11% of the X-ray clusters) and (ii) for the optical pipeline, the misidentification of the cluster C1 galaxy (and thus miscentering of the cluster) either because the object is not in the input catalogue (saturated or masked source) or because its color is not compatible with that of a red sequence galaxy (8% of the optical clusters). To this, must be added a few cases, generally mergers showing a complex morphology, where the cluster center is poorly identifiable both in the X-ray and optical. These cases where a posteriori attached to the "matched" sample of clusters, that is 144 objects in total. To this, must be added clusters with a centrally peaked emission, mostly well known cool-core clusters, possibly hosting a central AGN (2%).

- We have further correlated the optical clusters with the full X-ray catalogue containing weak cluster candidates (C2 objects), point-sources and sources too weak to be characterised (either as point or as extended sources). While very few redMaPPer clusters (5%) were found to be a C2 source, 7% of them are associated - within a radius of 1’ - with an X-ray source that can be unambiguously flagged as point source; further, only 5 of these sources are found within 10” of the optical center. From this, we can infer that at our working sensitivity level (\textasciitilde 5 \times 10^{-15} \mathrm{erg} \, \mathrm{s}^{-1} \, \mathrm{cm}^{-2} \, \mathrm{for \, point \, sources}) and within the redshift range probed by the redMaPPer, the masking of the ICM emission by a central AGN is a rather infrequent situation. Further, 10% of the redMaPPer are associated with a weak source (\text{detection\_likelihood} > 15), too faint to be characterised. This rate increase to 19% when extending the correlation to \text{detection\_likelihood} < 15 sources, but many of these sources are spurious.

- redMaPPer clusters not coinciding with any detected X-ray emission represent 13% of the redMaPPer population.

- X-CLASS clusters with no redMaPPer counterpart can be split in two subsamples : (i) those above the DSS plate limit (z < 0.3 – 0.4, 97 objects), 87% are very likely to be real clusters according to the information available in NED (for the remaining 13%, no information was available); (ii) those below the DSS plate limit (z > 0.3 – 0.4, 112 objects), some 15% are confirmed clusters according to the information available in NED. For the remaining ones, only partial information or no information was available in NED: inspection of the corresponding WISE images show a significant galaxy over-density for more than 50% of them.

The main outcomes of the study are illustrated in Fig. 20 and statistics summarized in Table 2. The redMaPPer richness appears to be a well-behaved decreasing function of the X-ray detection likelihood: very rich clusters, detected but not analysed, either C1 or C2 populations, point sources, weak uncharacterised emission or no X-ray emission at all. The clusters not analysed by Xamin are mostly nearby rich objects and redMaPPer clusters associated with weak uncharacterised X-ray sources lie preferentially close to the optical detection limit. We further discuss below some of our findings.

6.2. Discussion

The fraction of redMaPPer having an X-CLASS counterpart is comparable to that of the X-CLASS clusters associated with a redMaPPer (30-40%) once pipeline shortcomings are accounted for. Nevertheless, one should keep in mind that even though both catalogues also show a similar cluster density (a few objects / deg^{2}) the two samples probe very different redshift ranges: while X-CLASS safely detects clusters out to \text{z} \sim 1, redMaPPer is limited to \text{z} \leq 0.5. The fraction of undetected clusters that the correlation analysis enabled us to ascribe to short-comings of the X-ray or optical pipelines is rather low, typically around 10% of the total detections, and correspond to well-identified ‘features’ of both pipelines. At least for the X-ray side, the missed bright clusters are straightforwardly recovered by eye. The fact that huge X-ray clusters (possibly hosting a strong central source) do not pass the C1 selection comes from the statistical model used (Poissonian regime, adapted for low-surface brightness objects) and because of the too small area left for the background estimate. Correcting for these obvious pipeline shortcomings, our study shows that no bright/rich, hence massive, clusters are missed by either wave-band beyond the very local universe (\text{z} > 0.05). This is...
conspicuous in Fig. [20] where nearly all redMaPPer clusters having no X-ray (yellow stars) are located within a thin stripe following the redMaPPer detection limit (F[richness, redshift]). Further, the fact that we deliberately do not exclude targeted XMM clusters in the X-CLASS catalogue, artificially raises the fraction of nearby or apparently bright (e.g. cool-core) objects. Compared to the nominal X-CLASS C1 population, the fraction of C2 clusters identified with a redMaPPer is much lower. By definition, the C2 population is fainter than the C1 (clearly visible in Fig. [20] and allows for some 50% contamination by mismclassified point-sources. Consequently, the low matching-rate between C2 and redMaPPer both reflects the fact that about half of the C2 are not clusters and suggests that, because they are low-luminosity objects, they probably host less prominent red sequences of galaxies. Further, the fact that so few redMaPPer are associated with a truly X-ray point-source is informative as to the occurrence of a central X-ray bright AGN in nearby clusters of moderate richness.

The stacking analysis of the redMaPPer not associated with any X-ray source and falling within an off-axis of 9 arcmin, shows a ~ 1-2σ detection out to 0.5 Mpc (of the order of 0.003 c/s integrated out to 0.5 Mpc in [0.5-2] keV); some emission is conspicuous between 0.5 − 1 Mpc, which may be partly attributed to inaccurate optical positions or to foreground/background X-ray sources. After removing 4 redMaPPer out of the 15, the signal becomes insignificant. Hence, we cannot exclude that some of the remaining redMaPPer objects are simply filaments seen in projection along the line of sight and interpreted as clusters in the photometric-redshift space. For comparison, the stacking of the 7 clusters associated with sources having 0< detection likelihood <15, shows a rather convincing emission profile out to 1 Mpc. Regarding the redMaPPer falling at off-axis angles between 9′ − 12′, a 1-2σ emission is again observed, but the situation is less clear (as conspicuous from the control random sample); this could be explained by faint undetected extended or point-source emission washed out because of the strong blurring of the XMM PSF beyond 10′.

By construction, the C1 population has a very low degree of contamination by non-cluster sources and further underwent dedicated screening. For this reason, the C1 NEARBY clusters having no redMaPPer counterpart (30% of the C1 population, for which 90% seem to be confirmed using literature data) deserve special attention. We have subsequently correlated the unmatched XC1 clusters with the deeper redMaPPer (unpublished) catalogue extending down to a richness of 5, using a search radius of 1 arcmin. In this way some 50% of the unmatched XC1 were found to have an optical counterpart (53/99 and 42/112 for the NEARBY and DISTANT classes respectively) another example is shown in Fig. [17] this brings to 64% the fraction of XC1 having a redMaPPer counterpart. The NED information and inspection of the WISE images brought an independent confirmation of more than 60% of the DISTANT C1 not found by redMaPPer (λ > 20). At this stage, it is difficult to be more conclusive as to the nature of these DISTANT objects, since we reach the limit of the comparison study in terms of survey depths (WISE is supposed to detect only massive clusters out to z ∼ 1 (Gettings et al. [2012]). We defer the in-depth study of the XC1 subsample having no λ > 20 redMaPPer counterpart to a future paper (II) in which we shall explore the joint X-ray/optical multi-parameter space, allowing e.g. for the galaxy color criteria to be relaxed.

The redshift-richness distribution of the matched clusters reveals significant differences when splitting the sample between targeted and serendipitous clusters (Fig. 16 and 15). Given the very large number of clusters (~ 200) that have now been pointed by XMM (and being most of the time, as conspicuous in the figure, the brightest objects in any redshift slice) one cannot simply exclude, as usually done, these objects from the final cluster samples; this is especially critical if these samples are used for subsequent scaling-relation or cosmological analyses. As a test, we have correlated the X-CLASS clusters matched with redMaPPer with two other cluster catalogues also extracted from the XMM archive (XCS and T13); neither sample includes targeted clusters. The results are shown in Fig. [18] we find that only 22% and 24% of the XCS and T13 clusters are in common with the X-CLASS-redMaPPer sample. Removing the targeted clusters from X-CLASS, these percentages are raised to 37% and 41%. It is not the purpose of the present paper to perform a comparison between the various serendipitous XMM cluster catalogues - all the more so, since XCS and T13 did not make explicit their selection function - but from the present plots it is clear that the differences are significant.

7. Conclusions

We have undertaken a non-blind generic comparison between two cluster samples defined in the X-ray and optical wavebands, concentrating on the left-out. The overlap samples involve some 270 (optical) and 355 (X-ray) objects and have well-defined selection functions, which does not a priori imply a one-to-one correspondence: the C1 clusters constitute a high X-ray surface brightness sample out to a redshift of z < 1.5, the redMaPPer objects are red-sequence clusters limited to z ∼ 0.5 – 0.6. The analysis of the non-matched objects has benefited from exten-
sive human inspection. Main conclusion is that we found no evidence for any optically rich cluster to be devoid of X-ray emitting gas and vice versa; neither of the wavebands appeared to have missed any massive cluster.

The comparison has not only usefully enlightenened a few shortcomings of both detection methods but also, most importantly, enabled us to pinpoint key issues for future cluster science. It is difficult to define a unique matching radius that takes into account all specificities of the two samples, both from the instrumental and from the cluster physics points of view; hence, the need for an interactive approach. Further, the limited XMM field of view, vignetting and PSF clearly set practical limits to the stacking analysis. Similarly to optical cluster catalogues, X-ray serendipitous catalogues show significant differences between each other. In any case, the selection functions have to be explicitly involved in the process. All these aspects have a critical impact for any X-ray/optical scaling-relation work. This leads us to stress again here, the fact that cluster evolution, selection effects and cosmology cannot be worked out independently. In paper III, we shall present the joint X-CLASS/redMaPPer catalogue along with scaling relations. This very instructive approach has only provided an overview of the difficulties and promises of dedicated X-ray/optical cluster studies involving hundreds of objects and could be easily extended to X-ray/X-ray, optical/optical/S-Z (e.g. Rozo et al. (2014)), etc... comparisons. The current lack of redshifts for a large fraction of the southern X-CLASS clusters is being addressed by systematic multi-band observations with the GROND instrument on the MPG/2.2m telescope at La Silla (Greiner et al. (2008)), to obtain images and reliable photo-z for a large fraction of the catalogue in the southern sky (Clerc et al. in prep).

Next steps are obviously to extend the comparison to optical catalogues based on other detection methods and going deeper in the optical and IR wavebands as well as using ancillary deeper XMM observations when available. It is nevertheless anticipated that projection effects and cluster evolution issues will get more severe with increasing redshift, hence the need for a truly multi-wavelength approach. It is also obvious that numerical simulations are to play a growing role in cluster detection and subsequent matching studies. In this respect, the XXL project provides a unique data set (Pierre et al. in prep).

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Table 2. Summary of the correlation statistics

|                    | redMaPPer       | X-CLASS        |
|--------------------|-----------------|----------------|
| density            | \(\sim 2.5/\text{deg}^2\) | \(\sim 5/\text{deg}^2\) |
| redshift range     | 0.054 < z < 0.6 | 0 < z < 0.3 – 0.4, 0.3 – 0.4 < z < 1.5 |
| median mass range  | \(1.4 \times 10^{14} h^{-1} M_\odot\) | \(2 \times 10^{13} h^{-1} M_\odot\), \(5 \times 10^{14} h^{-1} M_\odot\) |
| overlap sample     | 270 clusters    | 355 clusters   |
| fraction of matched objects | 34%              | 33%            |
| fraction of recovered matches (large offsets, pipeline failures) | 8%               | 11%            |
| fraction with no counterpart at all | 13%(*)           | 59%(**)       |

(*) not matched with any type of X-ray source
(**) either not seen by redMaPPer or beyond z > 0.6

Fig. 19. Optical and X-ray images of the cluster conspicuous in Fig. 20 at redshift = 0.24 and richness = 77, as being not detected by Xamin. Marginal X-ray emission is present for this object located close the edge of the XMM FOV, hence not entirely covered by the three detectors (sharp discontinuities are visible on the image); this cluster was a posteriori removed from the stacking analysis of Fig. 13.
Fig. 20. \textit{redshift-richness} diagramme summarizing the X-ray properties of the redMaPPer clusters (sample OPT→X). Matching categories are numbered following the list presented in Sec. 4.2. The 'undetected' cluster located at redshift $= 0.24$ and richness $= 77$ is shown on Fig. 19.