**XXL Survey XXI**

The environment and clustering of X-ray AGN in the XXL-South field

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ABSTRACT

**Context.** This work is part of a series of studies focusing on the environment and the properties of the X-ray selected active galactic nuclei (AGN) population from the XXL survey. The present survey, given its large area, continuity, extensive multiwavelength coverage, and large-scale structure information, is ideal for this kind of study. Here, we focus on the XXL-South (XXL-S) field.

**Aims.** Our main aim is to study the environment of the various types of X-ray selected AGN and investigate its possible role in AGN triggering and evolution.

**Methods.** We studied the large-scale (>1 Mpc) environment up to redshift z = 1 using the nearest neighbour distance method to compare various pairs of AGN types. We also investigated the small-scale environment (<0.4 Mpc) by calculating the local overdensities of optical galaxies. In addition, we built a catalogue of AGN concentrations with two or more members using the hierarchical clustering method and we correlated them with the X-ray galaxy clusters detected in the XXL survey.

**Results.** It is found that radio detected X-ray sources are more obscured than non-radio ones, though not all radio sources are obscured AGN. We did not find any significant differences in the large-scale clustering between luminous and faint X-ray AGN, or between obscured and unobscured ones, or between radio and non-radio sources. At local scales (<0.4 Mpc), AGN typically reside in overdense regions, compared to non-AGN; however, no differences were found between the various types of AGN. A majority of AGN concentrations with two or more members are found in the neighbourhood of X-ray galaxy clusters within <25-45 Mpc. Our results suggest that X-ray AGN are typically located in supercluster filaments, but they are also found in over- and underdense regions.

1. Introduction

Over the last decade, many authors have been studying the local and large-scale environment of active galactic nuclei (AGN), investigating a possible link between nuclear activity, host galaxy properties and environment. For example, Gendre et al. (2013) and Karouzos et al. (2014a,b) have shown that AGN reside in any type of environment, including underdense and overdense regions. Gilli et al. (2009) did not find any evidence that AGN with broad optical lines cluster differently from AGN without broad optical lines. On the other hand, others have reported environmental differences between various types of AGN (obscured, unobscured, luminous, faint, FRI, FRII, etc.). In particular, Koulouridis et al. (2006) and Vilarruel & Korn (2016) found that Seyfert-2 galaxies (Sy2) have close neighbours more frequently than Seyfert-1 galaxies (Sy1). In addition, these neighbours present evidence of more recent interactions than their Sy1 peers (Koulouridis et al. 2013). Melnyk et al. (2013) found evi-
To better understand the above issues, the present work is dedicated to the analysis of the small- and large-scale environment and the clustering properties of different types of X-ray selected point-like sources (mainly AGN) in the 25 deg$^2$ XXL-South (XXL-S) field. This field is now characterized by a homogenous optical spectroscopic coverage up to $m_v = 21.8$ owing to two recently dedicated spectroscopic campaigns (Lidman et al. 2016, XXL Paper XIV, and Chiappetti et al., XXL Paper XXVII). More than 4500 redshifts are available for the optical counterparts of X-ray point-like sources, which mainly consist of AGN. The environmental properties of these AGN are reported for the first time in this field.

In §2 we present the sample. In §3, we describe the nearest neighbour analysis, while in §4 we present the methodology and the results of the optical overdensity analysis around X-ray selected point-like sources. The method of X-ray galaxy cluster matching with AGN agglomerates is described in §5. Discussion of the main results and a summary are presented in §6. Throughout this work we use the standard cosmology: $\Omega_m=0.27$, $\Omega_{\Lambda}=0.73$, and $H_0=71$ km/s/Mpc.

2. The XXL Survey and the sample

The Ultimate XMM Extragalactic Survey (XXL) is an international project based on the XMM-Newton Very Large Programme surveying $\sim 50$ deg$^2$ of the extragalactic sky (Pierre et al. 2016, hereafter XXL Paper I). The XXL survey contains two nominally equal fields at a depth of $\sim 4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ and $\sim 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the soft (0.5-2.0 keV) and hard (2.0-10.0 keV) bands, respectively (XXL Paper I, Figure 4). It comprises 622 XMM pointings with a total exposure >6Ms, and a median exposure of 10.4 ks (see XXL Paper I for details).

The two fields have an extensive multiwavelength coverage from X-ray to radio wavelengths (the detailed descriptions are given in [XXL Paper I] and [Desai et al. 2012]). Baran et al. (2016; hereafter XXL Paper VII) presented radio observations of XXL with the Very Large Array (vla) and the Australia Telescope Compact Array (Atca), respectively. Butler et al. 2017 (hereafter XXL Paper XVIII) reported the new observations of the full XXL-S with Atca.

The XXL-S field is one of the two XXL fields, centred at RA=$23^\text{h}30^\text{m}$ and DEC=$-55^\circ00$. It occupies an area of $\sim 25$ deg$^2$ containing 11316 X-ray point-like sources. Figure 1 presents the spatial distribution of the X-ray point-like sources with optical counterparts from the Blanco Cosmology Survey (BCS; Desai et al. 2012). Objects in the 0.2< z <1.0 redshift range, which constitute the target sample of this paper, and the radio sources among them are marked differently on the map. The description of the X-ray–multiwavelength associations is presented in [XXL Paper VII].

The spectroscopic redshifts were taken from [XXL Paper XIV]. The spectroscopic redshifts were taken from [XXL Paper XIV], and have been significantly enriched (52%) by new observations taken in 2016, described in XXL Paper XXVII, and obtained with the AAOmega spectrograph on the Anglo-Australian Telescope. A few tens of redshifts were taken from the Marseille Cesam database obtained in the frame of[3] the multiwavelength and spectroscopic information of the XXL is summarized on the web page http://xxlmultiwave.pbworks.com

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1. The multiwavelength and spectroscopic information of the XXL is summarized on the web page http://xxlmultiwave.pbworks.com
2. We considered here only point-like sources from the “good” XMM pointings, i.e. with the condition $X_{badfield}<3$, http://cosmosdb.iasf-milano.inaf.it/XXL/
3. http://www.usm.uni-muenchen.de/BCS/
AGN with X-ray sources with radio counterparts
with highest
AGN with X-ray sources with no radio counterparts
with lowest
AGN with X-ray sources with no radio counterparts

Fig. 1. Distribution of the XXL-S X-ray point-like sources with optical counterparts considering all the redshifts (N=3280; black dots) and sources with spectroscopic redshifts in the range 0.2 < z < 1.0 (N=1592; open circles). The positions of the radio-selected X-ray point-like sources (RAD; N=270) are marked with green triangles.

Fig. 2. Redshift distribution of the XXL-S X-ray point-like sources with spectroscopic (N=3280) redshifts. The green histogram represents the redshift distribution of the radio-selected X-ray point-like sources (RAD; N=270).

the ESO follow-up programme with FORS2.

For the purposes of the present study we divided our sample into various subsamples as described below and considered them in two redshift ranges: 0.2 < z < 0.6 and 0.6 < z < 1.0. Table 1 contains a brief description of each sample.

**AGN and GAL.** We separated the full sample into two subsamples, X-ray galaxies (GAL) and AGN. We considered a source as an AGN if \( L_{X,\text{hard}} > 2 \times 10^{42} \text{ erg/s} \) (or \( L_{X,\text{soft}} > 10^{42} \text{ erg/s} \) if the X-ray source was detected only in the soft band) following [Brusa et al. (2010)]. We applied a K-correction to the sources following the formula

\[
L_X = 4\pi d_L^2 \frac{F_X}{(1+z)^2},
\]

where \( d_L \) is the luminosity distance, \( F_X \) is the X-ray hard band flux, and \( \Gamma_X=1.7 \) is the photon spectral index. Typical uncertainties on the single luminosity do not exceed 3% over the whole redshift range.

Figure 3 presents the hardness ratio (HR) distribution of the sources over the full redshift range (0.2 < z < 1.0), with the subset of radio sources highlighted in green. The HR was calculated as \( HR = (H - S)/\sqrt{(H + S)} \), where \( S \) and \( H \) denote the count rate (cts/s) in the soft and hard band, respectively. As in Melnyk et al. (2013) we refer to AGN_{hard} (obscured AGN) when \( HR \approx -0.2 \) and AGN_{soft} (unobscured AGN) when \( HR < -0.2 \). This value for separating type 1 and type 2 AGN is a compromise based on previous studies. In particular, Garcet et al. (2007) compared optical and X-ray spectra of AGN in the XMM-LSS field. The authors demonstrated that 69% of the sources with \( HR > -0.2 \) are optical type 2 AGN and 81% are X-ray type 2 AGN. Similarly, [Brusa et al. (2010)] showed that 80% of the sources with \( HR \approx -0.2 \) are X-ray optically obscured AGN. Based on the analysis of X-ray spectra of the XXL-1000-AGN sample, [XXL Paper VI], it was shown that higher values of \( HR \) correspond to higher absorption systems (Figure 6a). Therefore, we first removed GAL (see above) from the AGN sample and then we divided the sample into AGN_{soft} and AGN_{hard} using the HR criterion.

**RAD and nRAD.** We correlated the positions of the XXL-S 2.1 GHz detected sources from the ATCA catalogue of [XXL Paper XVIII] with the positions of the optical counterparts of the X-ray point-like sources located within 1.0 arcsec. According to the probability function shown in Butler et al. (XXL Survey XXXI), at 1”, there are ~85% genuine matches and ~15% spurious matches. We found 270 common sources, i.e. 5.5% of the full sample. We separated the sample into two subsamples: radio (RAD) and non-radio (nRAD) sources, i.e. with and without radio counterparts, respectively.

**Table 1.** Description of the various subsamples of the X-ray point-like source population (see §2 for details). The indicated number of sources refers to the samples in the 0.2 < z < 0.6 and 0.6 < z < 1.0 redshift ranges.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( N_{z&lt;0.6} )</th>
<th>( N_{0.6&lt;z&lt;1.0} )</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1012</td>
<td>580</td>
<td>all sources in the entire redshift range</td>
</tr>
<tr>
<td>GAL</td>
<td>107</td>
<td>0</td>
<td>( L_{X,\text{hard}} &lt; 2 \times 10^{42} \text{ erg/s} ) if no hard band ( L_{X,\text{soft}} &lt; 10^{42} \text{ erg/s} )</td>
</tr>
<tr>
<td>AGN</td>
<td>905</td>
<td>580</td>
<td>( L_{X,\text{hard}} &lt; 2 \times 10^{42} \text{ erg/s} ) if no hard band ( L_{X,\text{soft}} &gt; 10^{42} \text{ erg/s} )</td>
</tr>
<tr>
<td>AGN_{soft}</td>
<td>626</td>
<td>486</td>
<td>AGN with ( HR &lt; -0.2 )</td>
</tr>
<tr>
<td>AGN_{hard}</td>
<td>279</td>
<td>94</td>
<td>AGN with ( HR \geq 0.2 )</td>
</tr>
<tr>
<td>RAD</td>
<td>88</td>
<td>33</td>
<td>X-ray sources with radio counterparts from XXL Paper XVIII catalogue</td>
</tr>
<tr>
<td>nRAD</td>
<td>924</td>
<td>547</td>
<td>sources without radio counterparts</td>
</tr>
<tr>
<td>FAINT</td>
<td>145</td>
<td>89</td>
<td>1/4 of the sample with lowest ( L_{X,\text{hard}} ) luminosities</td>
</tr>
<tr>
<td>LUM</td>
<td>140</td>
<td>89</td>
<td>1/4 of the sample with highest ( L_{X,\text{hard}} ) luminosities</td>
</tr>
</tbody>
</table>

5 FOcal Reducer and low dispersion Spectrograph for the Very Large Telescope (VLT) of the European Southern Observatory (ESO)

6 XMM-LSS is included in the XXL-North (XXL-N) field with central coordinates RA=02°20, DEC=+5°00.
In this section we study the large-scale environment (> 1 Mpc) of X-ray point-like sources using the nearest neighbour method, assuming that in general they closely trace the distribution of optical galaxies. It was mentioned in the previous section that we chose to analyse the distribution of X-ray point-like sources in two redshift ranges: 0.2 < z < 0.6 and 0.6 < z < 1.0. We excluded from this analysis 274 objects with z < 0.2 since this sample mainly comprises nearby faint galaxies (79%). In order to use consistent samples for the large- and the small-scale analysis, we discarded all sources with z > 1 as well. For all these high-redshift objects, we cannot study the fainter environment because of the completeness limit of the optical catalogue (see next section for details).

We also have a negligible number of nearest neighbours < 1 Mpc; see Figure 4.

We located the nearest neighbour of each X-ray source from the XXL-S catalogue and calculated the corresponding value of the nearest neighbour distance \( d_{\text{NNB}} \) (Mpc) using comoving coordinates. We compared the mean values of \( d_{\text{NNB}} \) for each pair of sources, i.e. GAL versus AGN, AGN\(_{\text{hard}}\) versus AGN\(_{\text{soft}}\), RAD versus nRAD, and faint versus luminous AGN.

Figure 4 illustrates the dependence of \( d_{\text{NNB}} \) versus the redshift. Due to the lack of fainter sources at high redshifts (i.e. because of the selection function), the value of \( d_{\text{NNB}} \) increases with redshift. To perform a more consistent analysis, we studied the properties of the selected sources within the two above-mentioned redshift ranges.

Additionally, to eliminate any possible biases caused by the different redshift distributions of the compared pair samples, we applied the stratified random sampling method. In more detail, we divided the number of sources in bins with step \( \delta z = 0.05 \). If the number of sources in one sample was larger than in the other for a certain bin, we randomly discarded \( N \) number of sources from the larger sample so as to match the distributions. Applying this procedure to all bins, we obtained the new normalized redshift distributions, which are not significantly different according to the Kolmogorov–Smirnov test (null hypothesis that the two samples are drawn from the same parent population cannot be rejected at any significant statistical level, see Table 2). Figure 5 illustrates this approach for the RAD/nRAD samples comparing the real (initial) distribution (left panel) and new randomized distribution (right panel).

Using a single random sampling might cause an overestimation or underestimation of the real values due to a possible contamination of outliers, especially if the number of counts is small. Therefore, we performed the stratified random sampling technique ten times (cross validation technique), for each redshift range. In Table 2 we report the median values (of the ten realizations) for the redshift \( z \), the hardness ratio \( HR \), and the nearest neighbour distance \( d_{\text{NNB}} \). Also, we list the two-sample Kolmogorov–Smirnov test \( \text{K-S} \) and the \( \text{t-test} \) probabilities comparing the mean values of \( d_{\text{NNB}} \) for each pair of objects (see also Figure 4).

We also computed the \( \text{t-test} \) probabilities comparing the mean values of all corresponding pairs of parameters. Since we reach the same conclusions, we decided not to present them in the tables.
Table 2. Comparison of the median $z$, $HR$, and $d_{\text{NNB}}$ values for the paired subsamples. (1) subsample name; (2) number of members; (3) median values of the mean $z$, (5) $HR$, and (7) $d_{\text{NNB}}$. Mpc of ten randomized samples and the respective Kolmogorov–Smirnov two-sample test probabilities of the distributions (4, 6, 8).

<table>
<thead>
<tr>
<th>Samples</th>
<th>N</th>
<th>$z$</th>
<th>$P_{\text{KS}_{0.12}}$</th>
<th>$HR$</th>
<th>$P_{\text{KS}_{0.8}}$</th>
<th>$d_{\text{NNB}}$</th>
<th>$P_{\text{KS}<em>{d</em>{\text{NNB}}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1a)</td>
<td>(2a)</td>
<td>(3a)</td>
<td>(4b)</td>
<td>(5a)</td>
<td>(5b)</td>
<td>(7a)</td>
<td>(7b)</td>
</tr>
<tr>
<td><strong>AGN$_{\text{hard}}$</strong></td>
<td>237</td>
<td>0.41</td>
<td>0.99</td>
<td>0.56</td>
<td>-</td>
<td>14.28</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>AGN$_{\text{soft}}$</strong></td>
<td>537</td>
<td>0.42</td>
<td>0.99</td>
<td>-0.74</td>
<td>-</td>
<td>0.85</td>
<td>14.22</td>
</tr>
<tr>
<td><strong>GAL</strong></td>
<td>42</td>
<td>0.31</td>
<td>0.96</td>
<td>-0.94</td>
<td>-0.25</td>
<td>10$^{-15}$</td>
<td>11.15</td>
</tr>
<tr>
<td><strong>AGN</strong></td>
<td>349</td>
<td>0.31</td>
<td>0.96</td>
<td>-0.25</td>
<td>11.97</td>
<td>0.01</td>
<td>13.84</td>
</tr>
<tr>
<td><strong>RAD</strong></td>
<td>757</td>
<td>0.40</td>
<td>0.98</td>
<td>-0.19</td>
<td>0.01</td>
<td>0.46</td>
<td>13.61</td>
</tr>
<tr>
<td><strong>nRAD</strong></td>
<td>757</td>
<td>0.40</td>
<td>-0.40</td>
<td>0.01</td>
<td>13.84</td>
<td>0.46</td>
<td>13.61</td>
</tr>
<tr>
<td><strong>Faint</strong></td>
<td>43</td>
<td>0.37</td>
<td>0.68</td>
<td>0.23</td>
<td>10$^{-3}$</td>
<td>12.83</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Lum.AGN</strong></td>
<td>43</td>
<td>0.37</td>
<td>-0.31</td>
<td>-</td>
<td>13.52</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of GAL and AGN was made only in the $0.2 < z < 0.6$ redshift range (limit of the GAL sample).

Fig. 5. Left panel: Redshift distribution of the full radio (RAD) and non-radio (nRAD) samples. Right panel: Respective randomized samples (single realization).

4. Small-scale environment

The reason to study the small-scale environment of the X-ray point-like sources is that we can possibly detect variations (which are not traceable in the large-scale analysis) that may play a role in the type of activity (see e.g. Koulouridis et al. 2006). To this end, we calculated the local (0-0.4 Mpc) optical galaxy overdensities around the sources of our subsamples. Due to the lack of extensive spectroscopic coverage of the normal galaxy population (non X-ray sources) we performed a projected (2D) overdensity analysis, following Melnyk et al. (2013) where we used a similar approach for the XMM-LSS field. We considered the same subsamples and redshift ranges as in the previous sections.

4.1. Methodology

Taking into account the redshift and the angular distance $D_A$, we estimated the angular sizes of the linear radius 0.4 Mpc at the source rest-frame. Then we counted the number, $N_0$, of the BCS optical galaxies within a circle of radius 0.4 Mpc and within a range of magnitudes from $m^* - \Delta m$ to $m^*$ (bright environment) and from $m^*$ to $m^* + \Delta m$ (faint environment), where $\Delta m = 1$ and $m^*$ is the apparent magnitude corresponding to the knee of the $i'$-band luminosity function $\Phi(L)$, given by

$$m^* = 5 \log_{10} d_L + 25 + M_i^* + Q_{0.1}(z) + K_{0.1}$$

where $M_i^* = -20.82 + 5 \log_{10}(h)$ is the absolute magnitude at the knee of the $i'$-band $\Phi(L)$ taken from Blanton et al. (2003), $Q(z)$ and $K(z)$ are the evolution and $K$-corrections, respectively, taken from Poggianti (1997) and shifted to match their rest-frame shape at $z = 0.1$; and $d_L$ is the luminosity distance. Here, we used the magnitudes as a proxy for the stellar mass. The $\Delta m$ limits are similar to what is used to evaluate the cluster members (e.g. Martini et al. 2013, Koulouridis et al. 2014, and Bufanda et al. 2017).
Next we calculated the galaxy overdensities, \( \delta \),

\[
\delta = \frac{N_{\text{gal}}}{N_{\text{lo}}A_0} - 1 ,
\]

where \( N_{\text{lo}} \) is the total number of objects in considered circle with surface area \( A_0 \), and \( N_{\text{gal}} \) is the local background counts estimated in the annulus between 3.1 and 5 Mpc with surface area \( A_r \).

To estimate the \( \sigma \) uncertainties we used the Jackknife resampling technique (Efron et al. 1983). To check the significance of the results we compared the overdensity of galaxies around each source with that expected from the mock X-ray source distributions. The mock catalogues have random coordinates, but the same fiducial magnitude (\( m^\star \)) distribution. For the mock randomly distributed sources, we used the same BCS optical catalogue to search for neighbours as we did for the real ones including the Jackknife technique.

For each catalogue we calculated the cumulative overdensity distribution

\[
F(\delta) = \frac{N(\delta)}{N_{\text{tot}}},
\]

which is defined as the percentage of all sources \( N_{\text{tot}} \) having an overdensity above a given \( \delta \) value. Finally, we compared the real distributions with the random ones.

### 4.2. Results

First, we calculated the overdensity distributions for the different randomized subsamples in two redshift ranges for the bright \( (m^\star - 1 < m < m^\star) \) and faint \( (m^\star < m < m^\star + 1) \) environments and compared them with the mock distributions. We did not study the faint environment of sources in the high-redshift range because of the completeness of the optical BCS catalogue at about \( i \sim 23 \), which corresponds to our rest frame \( m^\star \) at \( z=1 \).

We used the Kolmogorov–Smirnov (KS) two-sample test to estimate quantitatively the differences between the real and mock overdensity distributions. The typical KS probabilities \( (P_{KS}) \) of the two corresponding distributions of overdensities being drawn from the same parent population are < \( 10^{-3} \), meaning that the real and mock distributions are significantly different in the first redshift range. The exceptions are the GAL overdensities in both environments and the luminous and faint AGN in bright environments and in both redshift ranges.

Figures 6 and 7 present the cumulative distributions of overdensities for the real and mock subsamples in the low- and high-redshift range, respectively. In Table 3 we list the value of \( F(\delta) \) at the point \( \delta > 0 \). We also list the corresponding 1\( \sigma \) intervals for the real and mock samples. The \( \sigma_p \) indicates the difference (in \( \sigma \) units) that the fraction of real sources at a given overdensity level is higher than the corresponding fraction of the mock sources. For example, in the \( 0.2 < z < 0.6 \) redshift range, the fraction of AGN\(_{\text{hard}}\) in bright overdense environments with \( \delta > 0 \) is 66%. This is higher than the random expectations at the 5.6\( \sigma \) level. In the faint overdense environment, the corresponding fraction is 65%, which is higher than the random expectations at the 4.0\( \sigma \) level. In the high-redshift range, we find \( F(\delta > 0) = 55% \), which is not significantly different from the random expectations at the 0.3\( \sigma \) level.

Our results show that, in general, X-ray point-like sources inhabit both dense and underdense environments. However, there are significantly more X-ray sources than in their corresponding mock catalogues which inhabit overdense regions in both redshift ranges (in agreement with Melnyk et al. 2013), especially in the low-redshift range. The difference is less than 3\( \sigma \) only for GAL, RAD, faint, and luminous AGN in both environments. However, the low significance is most likely due to small sample sizes. At higher redshifts we do not have clear evidence of overdensities (except for the nRAD sample) probably because of the small sample sizes.

These results are not unexpected given that AGN are known to be clustered. Our main interest, though, is to study the environmental trends for the subsamples defined in Table 1.

In the last column of Table 3 (\( \sigma_p \)) we compare the real samples at the point of \( \delta = 0 \) in \( \sigma \) units. As can be seen, there are no significant differences for any pair of samples. Therefore, pairs of GAL and AGN, AGN\(_{\text{hard}}\) and AGN\(_{\text{soft}}\), radio and non-radio sources, and faint and luminous AGN occupy similar environments.

It is worth mentioning that the small- and large-scale environments of our sources do not correlate, i.e. isolated objects as defined in the large-scale analysis are found in a variety of small-scale environments, not necessarily in isolation.

### 5. X-ray clusters versus AGN agglomerates

In this section we study the XXL-S AGN-supercluster candidates defined as the super structures comprising X-ray point-like sources. These structures were obtained by applying the classical bottom-up hierarchical clustering method\(^9\) to the sampled catalogues to search for neighbours as we did for the real ones.

\(^9\) Linkage of clusters starts by considering each object as a cluster. Then, one by one, it merges all elements into a single cluster. Depending on the input free parameter of clustering radii, the hierarchical tree is cut dividing the sample on clustered and unclustered objects. We used the minimum distance between clusters for linkage.

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**Table 3.** Comparison of the fraction \( F \) of sources with overdensity values \( \delta > 0 \) in the randomized samples and their respective mock catalogues. \( \sigma_r \) is the difference between \( F_{\text{real}} \) and \( F_{\text{mock}} \) in units of its typical standard deviation, calculated as \( |F_{\text{real}} - F_{\text{mock}}|/(\sigma_{\text{real}} + \sigma_{\text{mock}})^{1/2} \); \( \sigma_p \) is the corresponding difference between pairs of the samples AGN\(_{\text{hard}}\)/AGN\(_{\text{soft}}\), etc.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( N )</th>
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<th>( F_{\text{mock}} \sim \sigma_{\text{mock}} )</th>
<th>( \sigma_r )</th>
<th>( \sigma_p )</th>
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<td>1.7</td>
</tr>
<tr>
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<tr>
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<td>44±5.8</td>
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<tr>
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<td>RAD</td>
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<td>3.0</td>
<td>2.5</td>
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<tr>
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<td>50±9.8</td>
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<td>41±8.5</td>
<td>0.7</td>
<td>1.8</td>
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<tr>
<td>Lum. AGN</td>
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<td>71±7.6</td>
<td>59±8.4</td>
<td>1.0</td>
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ple of X-ray point-like sources using comoving coordinates. To distinguish between X-ray galaxy clusters (i.e. virialized structures that are detected as X-ray extended sources) and the structures which were obtained with the hierarchical method, we use the term ‘agglomerate’. This is in analogy to the study by Karachentsev et al. (2012). Then, we checked if the agglomerates trace the distribution of X-ray galaxy clusters (X-ray extended sources).

In this analysis we defined AGN agglomerates at clustering radii of 16.76 Mpc and 28.32 Mpc in the 0.2 < z < 0.6 and 0.6 < z < 1.0 redshift ranges, respectively. Adopting these values, 2/3 of the sources are in agglomerates and 1/3 are isolated in our sample. Here we followed the proportion ∼ 70% of clustered and ∼ 30% unclustered galaxies in the Local Universe (see Karachentsev et al. (2012) and references therein). Figure 8 shows the dependence of the typical distances between the sources in the agglomerates < D > versus the number of their X-ray point-like members.

The XXL X-ray cluster sample (C1 and C2 types) is described in XXL Paper I, Pacaud et al. (2016; hereafter XXL Paper II) and Adami et al. (XXL Paper XX). The considered samples of spectroscopically confirmed X-ray galaxy clusters from XXL Paper XX contain \( N_c = 81 \) and 22 clusters, respectively, in the 0.2 < z < 0.6 and 0.6 < z < 1.0 redshift ranges.

To avoid biases related to inhomogeneity of the X-ray point-like sources in the field with respect to cluster positions we have performed the following test. Separately for the two considered redshift ranges around each X-ray cluster within with an angular radius \( r \), we counted the number of all point-like X-ray sources such that \( m^* - 2 < m < m^* + 1 \), where \( m \) is the rest-frame i-band magnitude of a cluster and \( m^* \) is the apparent magnitude of an X-ray AGN/galaxy. According to this method, we calculated the number of point-like sources with available spectroscopic redshifts and without it. In Figure 9 we plotted the ratio between the numbers of X-ray point-like sources with spectro-z and the whole sample for different angular radii around the X-ray clusters. The error bars show the boundaries of the confidence interval at the 95% level. As can be seen, the completeness of the spectroscopic redshifts for the X-ray point-like sources is 78% and 30% of the total population of sources in the 0.2 < z < 0.6 and 0.6 < z < 1.0 redshift ranges, respectively. This percentage does not depend significantly on the distance from the X-ray clusters. We conclude that the distribution of the X-ray point-like sources near the X-ray clusters is non-biased.

We also computed the minimum distances between each cluster and all the agglomerates (geometrical centres of the agglomerates). Then we built the distributions of the minimum distances and compared them with the respective distributions of the galaxy clusters and randomly chosen agglomerates. To build the mock catalogues, we chose random coordinates and redshifts from the real sample of the X-ray point-like sources in the corresponding redshift ranges. Therefore, our mock catalogues have...

Fig. 6. Cumulative distributions of the overdensities for the randomized and mock samples in the 0.2 < z < 0.6 redshift bin. The different samples are coded as indicated in the label of each panel. The error bars correspond to 1 σ deviations.
Fig. 7. Cumulative distributions of the overdensities for the randomized and mock samples in the $0.6 < z < 1.0$ redshift bin. The different samples are coded as indicated in the label of each panel. The error bars correspond to $1\sigma$ deviations.

Fig. 8. Median values of the average distances between the members of agglomerate within their interquartile ranges vs. the number of agglomerate members.

Fig. 9. Ratio between the numbers of X-ray point-like sources with spectroscopic redshifts ($N_{sp}$) and the whole sample ($N_{tot}$) for different angular radii $r$ around the X-ray clusters.

Fig. 10. Distributions of the minimum distances between all the X-ray clusters and all the real/mock agglomerates ($2+$).

Table 4 presents the mean values of the minimum distances between the X-ray clusters and the real or mock AGN agglomerates with different populations: $2+$ (two or more members), $3+$, $5+$, and $10+$. In both redshift ranges, the null hypothesis that the real and mock distributions are drawn from the same parent set can be rejected at a high level of significance. In other words, we report significantly smaller distances between the X-ray clusters and the AGN agglomerates with different a number of members than expected from the mock realizations.

Mainly, the AGN agglomerates follow the distribution of the X-ray clusters at the $<25$ Mpc scale in the $0.2 < z < 0.6$ and $<45$ Mpc in the $0.6 < z < 1.0$ ranges, respectively: $73^{+7}_{-8}$ and $86^{+9}_{-13}$%. The corresponding random expectations are $39^{+1}_{-1}$% and $55^{+1}_{-1}$%, respectively. The above-mentioned uncertainties correspond to the 95% confidence level, so these results are highly significant.

In Table 5 we present the geometric centres of the most populated agglomerates ($>10$ members) and their possible associations with X-ray clusters, supercluster candidates, and pairs of clusters from XXL Paper XX. In the columns we indicate the published names of the cluster, supercluster, or pair and the minimum distances between the corresponding galaxy structure and the given agglomerate. We conclude that the most populated concentrations of AGN are associated with supercluster candidates.
Table 4. Kolmogorov–Smirnov $p_{KS}$ and t-test $p_t$ probabilities of the real and mock minimum distance distributions ($D_{\text{min,real}}$ and $D_{\text{min,mock}}$ in Mpc) and the corresponding mean values between the clusters and the agglomerates with different populations being drawn from the same parent population. For example, $2+$ means two or more members in an agglomerate.

<table>
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<tr>
<th>Aggl.</th>
<th>$N_{\text{real}}$</th>
<th>$N_{\text{mock}}$</th>
<th>$&lt; D_{\text{min,real}} &gt;$</th>
<th>$&gt; D_{\text{min,mock}} &gt;$</th>
<th>$r_{KS}$</th>
<th>$p_{KS}$</th>
<th>$p_t$</th>
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<td>143</td>
<td>81</td>
<td>21.0±12.7</td>
<td>30.6±14.2</td>
<td>$10^{-9}$</td>
<td>$10^{-9}$</td>
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<tr>
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<td>81</td>
<td>25.0±15.2</td>
<td>37.6±14.9</td>
<td>$10^{-10}$</td>
<td>$10^{-10}$</td>
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<tr>
<td>5+</td>
<td>39</td>
<td>81</td>
<td>32.2±20.2</td>
<td>50.1±24.9</td>
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<tr>
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<td>81</td>
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<td>89.7±59.2</td>
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<td>$10^{-10}$</td>
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<td>0.6 &lt; $z$ &lt; 1.0</td>
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<tr>
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<td>146.7±76.0</td>
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<td>$10^{-4}$</td>
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6. Discussion and conclusions

We have studied in the present paper the environment and the clustering properties of the X-ray selected point-like sources in all kinds of environments. This is in agreement with previous works for AGN selected in the optical, X-ray, and radio environments because they inhabit the most massive galaxies and not because they are triggered by interactions, supporting the scenario of secular AGN evolution. Our findings are also in general agreement with recent environmental studies of optically selected AGN. In particular, Sabater et al. (2015) used a sample of about 250,000 galaxies and showed that the effects of the large-scale environment and galaxy interactions are minimal on both the prevalence of optically selected HLAGN and on their luminosity, supporting the scenario of a secular AGN evolution. We are motivated to test the nearest neighbour effect in the XXL-N field in the future, where many spectroscopic redshifts have become available.

The differences between the environment of AGN_{soft} (i.e. mainly unobscured or broad-line AGN, HLAGN, type 1) and AGN_{hard} (mainly obscured AGN, narrow-line, MLAGN, type 2) are also negligible. This is in agreement with the classical unified scheme for AGN by Antonucci (1993). In our previous work for the XMM-LSS field (Melnik et al. 2013), we found some evidence that AGN_{hard} are located in more over-dense regions than AGN_{soft}, although the significance level was relatively low (<3$\sigma$) and the number of sources was three times lower than in the present study. It is also in agreement with Gilli et al. (2009) and Strand et al. (2008).

We have to note that the considered small-scale overdensities were computed within 400 kpc, while other studies have reported the difference between obscured and unobscured AGN at very small distances, <30-100 kpc (see e.g. Koulouridis et al. 2006 & 2013, Koss et al. 2012, Sañayapal et al. 2014). Also, we do not consider the host galaxy types in this paper.

We did not find that X-ray radio-selected AGN prefer denser environments than non-radio-selected ones, unlike previous studies (Lietzen et al. 2011, Sabater et al. 2013, Karouzos et al. 2014a & b, Ineson et al. 2015, Argudo-Fernandez et al. 2016, and Bradshaw et al. 2011). However, we found that among the X-ray selected sources, radio detections display significantly higher hardness ratios than radio undetected sources.

We did not find evidence for any influence of the large-scale (>1 Mpc) environment on X-ray or radio properties of the sources. We again note that our assumption here was that the X-ray sources closely trace the distribution of optical galaxies. According to Song et al. (2016), the optical quasar density changes somewhat more slowly than the galaxy density. Nevertheless, taking into account the field galaxies, those authors showed a weak positive correlation between the black hole mass and the large-scale environmental density, and a negative correlation between the optical luminosity and the density. As previously noted, due to very non-homogeneous spectroscopic coverage of the XXL-S field galaxies, we were not able to calculate the environmental density of the field galaxies.

6.2. Large-scale structure of the XXL-S

We find no correlation between the small-scale and large-scale environments of the X-ray sources, implying that there does not seem to be any preferable environment for X-ray sources. Nevertheless, they avoid the most empty regions of galaxies (voids). This is in agreement with the fact that powerful X-ray AGN are rarely observable among isolated galaxies in the Local Universe (Pulatova et al. 2015). In an earlier work by Georgakakis et al. (2007) it was also shown that X-ray selected AGN at $z \approx 1$ avoid underdense regions at the 99.89% confidence level.

10 This classification is not explicit.
We found that X-ray AGN typically reside at relatively small distances from the centres of X-ray clusters (<5 Mpc), which may refer to the absence of the ‘AGN suppression’ effect which was reported in previous works by Koulouridis & Plionis (2010) and Ehlert et al. (2014). However, our findings are in agreement with Koulouridis et al. (2014) where the effect of AGN suppression in X-ray clusters was not found for the poor clusters in the XMM-LSS field. Koulouridis et al. (2016; XXL Paper XII) argue that the total number of AGN in the vicinity of three superclusters significantly exceeds the field expectations. Although superclusters represent the most extensive concentrations in the Universe, they do not represent the densest environments. We expect that future XXL papers dedicated to studying AGN counts in X-ray clusters will clarify this issue.

In general, there seems to be an anticorrelation between high density and AGN activity. We found that X-ray AGN trace the distribution of X-ray clusters at < 25−45 Mpc scale: the fraction of agglomerates located in the vicinity of X-ray clusters is ~1.5−2 times higher than for randomly distributed agglomerates in both considered redshift ranges. This is in agreement with Arnold et al. (2009) and also with optical AGN studies by Hwang et al. (2012) and Song et al. (2016), where the authors show that the AGN fractions in the field environment are higher than in clusters. Kocevski et al. (2009) found that Seyfert-2 galaxies avoid the densest regions of superclusters and are instead located in intermediate density environments. Moreover, we found that the most populated agglomerates are associated with supercluster candidates (see XXL Paper XX). We interpret our results as showing that X-ray AGN mainly reside in supercluster filaments/field environments.

To summarise our results:

1. The large-scale environment does not correlate with any specific AGN population studied here.
2. Obscured/unobscured AGN, radio, and non-radio sources typically reside in small-scale overdensities, a trend which is stronger at lower redshifts.
3. No correlation was found between small-scale overdensities and X-ray luminosity, nor between environmental density and the type of AGN. Radio sources also prefer the same locally overdense environments as non-radio AGN.
4. A large number of AGN concentrations with two or more members correlates with the presence of X-ray galaxy clusters within <25−45 Mpc.

Acknowledgements. XXL is an international project based around an XMM Very Large Programme surveying two 25 deg^2 extragalactic fields at a depth of ∼5 × 10^{-15} erg cm^{-2} s^{-1} in the [0.5-2] keV band for point-like sources. The XXL website is [http://irfu.cea.fr/xxl](http://irfu.cea.fr/xxl) Multi-band information and spectroscopic follow-up of the X-ray sources were obtained through a number of survey programmes. [http://xxlmultisource.pbworks.com/](http://xxlmultisource.pbworks.com/)

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References

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**Table 5. XXL-S supercluster candidates, the most populated agglomerates, and possible correlations with X-ray clusters. N\textsubscript{mem} represents the number of members in the agglomerate, RA and DEC are the coordinates of the centre, < z > is the average redshift, D\textsubscript{max} is the maximum distance between members of the agglomerate, < D > is the average distance between its members, and D\textsubscript{min,real} is the distance between a given cluster and its nearest agglomerate.**

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<td>-56.039</td>
<td>0.47</td>
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<td>20.8</td>
<td>639, 609</td>
<td>17, 8</td>
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<td>-53.599</td>
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<td>47.6</td>
<td>560</td>
<td>42</td>
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</tr>
</tbody>
</table>

* The name of the X-ray cluster given in XXL Paper XX.
** Supercluster candidates (and also cluster pair) defined in XXL Paper XX as concentrations of X-ray clusters, ‘part’ means that half or more of the members of the supercluster are associated with the corresponding agglomerate.
Butler, A., et al. in prep. (XXL Paper XXXI)
huappetti et al. in prep. XXL Paper XXVII
fron, B., Gom, G., 1983, American Statistician, 37, 36