Galaxy groups and low mass clusters at $z < 0.6$: A perspective from the XMM Large Scale Structure survey

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Galaxy groups and low-mass clusters provide important laboratories in which to study X-ray gas physics and the interplay between galaxy evolution and environmental effects. The X-ray Multi-Mirror (XMM) Large Scale Structure (LSS) survey has currently imaged 5 deg$^2$ to a nominal extended source flux limit of order $10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ and is dominated numerically by low-mass groups and clusters at redshifts $0.2 < z < 0.6$. We discuss the generation of the XMM-LSS cluster sample, initial results on the physics of groups and low-mass clusters and the prospects for detailed follow-up studies of these systems.

1 An introduction to the XMM-LSS survey

The XMM-LSS survey (Pierre et al. 2004) is a medium-deep X-ray survey undertaken to determine the values of key cosmological parameters on the basis of the observed abundance and correlation statistics of X-ray galaxy clusters. The XMM-LSS consists of a contiguous grid of 10-20 ks XMM pointings currently covering 5 deg$^2$. Observations extending the X-ray coverage to 10 deg$^2$ are in progress during 2006. The XMM-LSS field is located at $\alpha = 02^h26^m$, $\delta = -5^\circ$ and overlaps with Canada France Hawaii Wide Synoptic Survey (optical), the UKIDSS Deep Extragalactic Survey (NIR), the SWIRE survey (mid-IR), the VIMOS-VLT Deep Survey (VVDS - optical spectra) and is accompanied by additional imaging at radio and SZ wavebands - see Figure 1 for more details.

The XMM-LSS currently contains X-ray structures over the redshift interval $0.05 < z < 1.22$ (Figure 1) yet is dominated numerically by cooler, lower mass clusters $kT < 4$ keV at redshifts $0.2 < z < 0.6$. The nominal flux limit of XMM-LSS is approximately $10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ in the [0.5-2] keV energy band and corresponds to a bolometric X-ray luminosity $L_X \approx 10^{43}$
ergs s\(^{-1}\) at \(z = 0.6\). This sample represents a considerable extension of the distance over which such systems can be identified in moderate depth, moderate field X-ray surveys and it is now possible to study the physical evolution of X-ray clusters selected uniformly over both a wide interval of redshift and X-ray luminosity. In particular, two broad areas of research that we will touch upon in these proceedings are a) understanding the evolution of the intracluster medium (ICM) through observed correlations between X-ray luminosity, X-ray temperature and the cluster velocity dispersion \(\sigma_v\), and b) determining the extent to which intermediate redshift groups and low mass clusters act as sites of continuing galaxy evolution.

2 Compiling the XMM-LSS sample

2.1 Creating a high-quality sample of X-ray clusters

A detailed description of the procedures used by the XMM-LSS to compile a highly complete sample of X-ray clusters displaying low or no contamination is provided by Pacaud et al. (2006) and we summarize the main considerations here. The raw X-ray observations were reduced using the standard XMM Science Analysis Software (XMM SAS) and raw photon images were produced by combining the data from the pn, MOS1 and MOS2 detectors to produce an image with a scale of 2.5 arcseconds per pixel. Cluster detection was performed using a wavelet based algorithm and was restricted to the inner 11 arcminutes of each XMM pointing. Source classification was performed using a maximum likelihood routine \textit{Xamin} (Pacaud et al. 2006) and employs the parameters \textit{extent, likelihood of extent} and \textit{likelihood of detection}. In simple terms, X-ray source samples generated using these parameters correspond to surface brightness limited samples. Table 1 describes the three classes of X-ray source generated using this approach: C1, C2, and C3 (with C1 representing the highest quality detections).

2.2 Confirming optical redshifts

The nature of each X-ray source – whether a galaxy cluster at specific redshift or a non-cluster source – was determined via optical photometry and spectroscopy. A combination of either

\footnote{Assuming a surface brightness model characterised by \(\beta = 2/3\) and core radius = 180 kpc.}
Table 1: Properties of the three cluster classes generated by XMM-LSS

| Class | Selection criteria | contamination | surface density |
|-------|--------------------|---------------|-----------------|
| C1    | extent> 5′         | 0%            | ~ 5 deg²        |
|       | extent likelihood> 33 |
|       | detection likelihood> 32 |
| C2    | extent> 5′         | 50%           | ~ 3 deg²        |
|       | 15 < extent likelihood< 33 |
|       | detection likelihood> 32 |
| C3    | 2′ < extent< 5′    | unknown       | ~ 4 deg²        |
|       | extent likelihood> 4 |
|       | > 30 photons detected |

CTIO/MOSAIC Rz′ (Andreon et al. 2004) or CFHT/MEGACAM ugriz imaging was used to associate the location of each X-ray source with the spatial barycentre of a significant overdensity of galaxies displaying characteristically red colours. Galaxies lying within a given colour tolerance of this “red sequence” were flagged as candidate cluster members and given a high priority in subsequent multi-object spectroscopic observations. A small number of low X-ray temperature (≈ 1 keV) groups at moderate redshift (z > 0.2) and local (z < 0.2) optically poor groups were not associated with a statistically significant galaxy overdensity. These systems were inspected visually and spectroscopic targets were assigned manually. Spectroscopic data were reduced using standard procedures described in detail in previously published XMM-LSS samples (Valtchanov et al. 2004; Willis et al. 2005; Pierre et al. 2006). Cluster redshift values were then computed as the unweighted mean of all galaxies within Δz = 0.02 of the visually assigned redshift peak.

3 The Luminosity-Temperature relation

3.1 Fitting robust temperatures to faint, low-temperature clusters

Galaxy clusters selected within the C1 and C2 classes display total X-ray count levels as low as 100 photons. However, by virtue of the coincidence of temperature sensitive Iron L-shell emission at energies of order kT < 4 keV with the energy range of peak sensitivity of the XMM detectors, it remains possible to fit reliable temperature values to these faint systems. The details of the spectral analysis procedure are described in Willis et al. (2005) and fit an absorbed APEC hot plasma model (Smith et al. 2001) to the source spectral energy distribution (SED) using the Xspec routine (Arnaud 1996). The main modification is that the source and background spectra are rebinned to a common spectral scale such that the background SED displays a minimum of 5 counts per spectral bin. Extensive simulations indicate that this procedure generates reliable temperature estimates (i.e. a small systematic offset from the true temperature and Xspec errors that provide a realistic measure of the distribution of fitted temperatures) when fitting clusters

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aData are taken from the CFHT Wide Synoptic Legacy Survey. See the URL www.cfht.hawaii.edu/Science/CFHTLS/ for further details.
as cool as $kT = 1$ keV with as few as 100 total counts.

### 3.2 The $L – T$ relation

Figure 2 displays the X-ray luminosity temperature relation for 12 groups and clusters analysed within an initial XMM LSS sample (Willis et al. 2005). This sample represents a mix of seven C1+C2 and five C3 systems. Bolometric luminosity values are computed by extrapolating the measured flux in the [0.5-2] keV energy band to all wavelengths employing the fitted spectral emission model. In addition, each X-ray system is fitted with a spatial emission model consisting of a circular $\beta$-model convolved with the local PSF. The value of $r_{500}$ for each system is determined using the fitted temperature and the mass-temperature relation of Finoguenov, Reiprich & Bohringer (2001) and the spatial emission model is extrapolated to this scale radius to present brightness measures as $L_{\text{bol}}(r_{500})$.

![Figure 2: Left panel: Distribution of X–ray luminosity computed within a scale radius $r_{500}$ and temperature for XMM–LSS groups and clusters presented in Willis et al. 2005 (solid squares). Also indicated are values of X–ray luminosity and temperature determined for the low redshift group sample of Osmond and Ponman (2004) (open squares) and for the cluster sample of Markevitch (1998) (open triangles). The solid line indicates an orthogonal regression fit to the $L_X$ versus $T_X$ relation for both the group and cluster sample incorporating a treatment of the selection effects present in each sample ($\log L_X = 2.91 \log T_X + 42.54$). Right panel: Enhancement factor, $F = L_{\text{obs}}/L_{\text{pred}}$, computed for six XMM–LSS groups and clusters located at $z \leq 0.6$ plotted versus the X–ray temperature of each system (see Willis et al. 2005 for additional details). Horizontal lines indicate expected values of $F$: the short dashed line indicates the value $F = 1.23$ expected from self–similar considerations. The dotted line indicates the value of $F$ expected at $z = 0.4$ based upon Ettori et al. (2004).](image)

Examination of the $L – T$ relation for this initial XMM-LSS sample indicates that a small amount of positive luminosity evolution is present compared to a local $L – T$ relation (see Figure 2 for more details). At a given temperature, these systems are in the median 1.46 times more luminous compared to a local $L – T$ relation, whereas, applying self-similar scaling one would expect a luminosity enhancement of order 1.23, i.e. positive luminosity evolution is present at the level of 20%. Given the modest size and the statistically incomplete nature of this initial sample, we regard these results as in need of confirmation. Ettori et al. (2004) report evolution weaker than the self–similar expectation (i.e. slightly negative luminosity evolution) from a sample of 28 clusters at $z > 0.4$ with gas temperatures $3 \text{ keV} < kT < 11 \text{ keV}$. The combined effect of self–similar scaling with the negative evolution reported by Ettori et al. (2004) would result in an enhancement factor $F = 0.86$ at $z = 0.4$ (see Figure 2). Though the overlap of the Ettori et al. (2004) sample and the systems contained in the present work is limited, further
work is clearly required to understand the $L - T(z)$ evolution of low temperature systems.

In particular, XMM-LSS is currently generating a large sample of galaxy groups and clusters displaying $kT < 4$ keV and $0.2 < z < 0.6$. More importantly however, the X-ray selection function has been computed as a function of apparent brightness (count rate or flux) and core radius of the fitted surface brightness profile (Pacaud et al. 2006). In addition, the C1 sample is temperature complete – every C1 cluster has a fitted temperature. Equipped with a large sample and an explicit selection function, the XMM-LSS is currently well placed to perform a robust investigation of the $L - T$ evolution of X-ray groups and clusters.

4 A detailed spectroscopic look at three low-T systems

Low temperature X-ray groups and clusters at $z > 0.2$ are being revealed in large numbers by XMM-LSS for the first time. A detailed magnitude limited spectroscopic study of a subset of these systems is clearly required to a) determine their dynamical state and search for evidence of recent mergers (and to assess their effect upon the ICM) and b) perform an unbiased (or “least biased”) survey of the member galaxies in an attempt to correlate the extent of recent star formation with merging activity and the properties of the X-ray emitting gas (via deviations from the $L - T$ relation).

During ESO Period 76 we obtained spectroscopy of all galaxies satisfying $R < 21.5$ in the fields of three $kT = 1 - 2$ keV groups at $z \sim 0.3$ (see Figure 3). The three systems XLSSC 013, 022 and 044 are described in detail in Pierre et al. (2006). Two of the three systems, XLSSC 013 and 044, display evidence both for velocity substructure and for additional projected structures along the line-of-sight. These X-ray groups display velocity distributions that are inconsistent with simple Gaussian distributions. In general, each system appears to display at least one other velocity component offset from the systemic velocity. The possibility that we are observing merging systems and (in the case of 022) a filament in projection, have important consequences for how we interpret such systems as reliable cosmological probes, e.g. both effects will affect the slope and scatter of the mass-temperature relation. In contrast, the group XLSSC 022 (the hottest of the three) displays a very regular velocity structure. We aim to investigate these systems further in ESO Period 79 with VLT/FORS2 spectroscopy to a deeper magnitude limit.

5 Future work

Clearly there is much that remains to be understood regarding X-ray groups and low mass clusters at intermediate redshifts. Of principle important is an understanding of the distribution of low temperature systems on the mass–temperature relation exhibited by hotter, more massive systems. A relatively detailed knowledge of the mass–temperature relation is required to compare observed correlation and abundance statistics to the predictions of dark matter clustering in a $\Lambda$CDM universe. To this end, we are continuing our detailed investigation of the dynamical state of X-ray groups at intermediate redshift with the dual aim of determining dynamical masses for these systems and understanding the extent to which their recent evolution is driven by merging. Combined with a detailed understanding of dynamical effects in individual groups and clusters, we are continuing to investigate the evolution of the $L - T$ relation for the XMM-LSS sample, incorporating a detailed treatment of the X-ray selection function (Pacaud et al. 2007 in prep.). In tandem with existing X-ray studies of individual groups and clusters at intermediate redshift, XMM-LSS is therefore providing an important census of a poorly understood and potentially very active regime of structure formation.
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Figure 3: Three low temperature X-ray groups at $z \sim 0.3$ observed with highly complete spectroscopy to $R < 21.5$. Left panels: CFHT Legacy Survey Wide Synoptic i-band data for each X-ray group. North is up and East is left. The overplotted small circles indicate galaxies confirmed at the cluster redshift (heavy circle) and unassociated field galaxies (light circles). The large circle indicates the radius $r_{500}$ for each group. Centre panels: redshift histogram of each field over $0.2 < z < 0.4$. XLSSC 044 in particular displays a number of significant redshift peaks along the line-of-sight. The association of the $z = 0.26$ galaxies with the X-ray emission is clear but additional structure may affect the derived X-ray luminosity and temperature. Right panels: the cumulative distribution of observed frame member velocities relative to the systemic velocity. Overplotted are sample Gaussian distributions describing different velocity dispersions. A comparison of the data to these simple models indicates that groups XLSSC 013 and 044 appear to be composed of distinct velocity components whereas XLSSC 022 appears to be a very regular system.