The BMW Deep X–ray Cluster Survey

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Abstract. We describe the main features of the BMW survey of serendipitous X–ray clusters, based on the still unexploited ROSAT–HRI archival observations. The sky coverage, surface density and first deep optical CCD images of the candidates indicate that this sample can represent an excellent complement to the existing PSPC deep cluster surveys and will provide us with a fully independent probe of the evolution of the cluster abundance, in addition to significantly increasing the number of clusters known at \( z > 0.6 \).

1. Introduction

In the last few years, X–ray selected samples of clusters of galaxies have become a formidable tool for cosmology. Deep surveys using ROSAT PSPC archival data have been used to study the evolution of the cluster abundance and X–ray luminosity function (XLF) and constrain cosmological parameters (e.g. Borgani et al. 1999). The lack of evolution of the XLF observed for \( L \sim L^* \simeq 4 \cdot 10^{44} h^2 \) erg s \(^{-1}\) out to \( z \sim 0.8 \) favours low values for \( \Omega_M \) under reasonable assumptions about the evolution of the \( L–T \) relation. At the same time, the original hint from the EMSS (Gioia et al 1990; Henry et al. 1992) of evolution at the very bright end of the XLF seems to be confirmed (Vikhlinin et al. 1998, Nichol et al. 1999, Rosati et al. 2000 and references therein). The main statistical limitation of this conclusion rests with the small sky coverage of the ROSAT deep surveys, which clashes with the intrinsic rarity of highly luminous clusters. XMM–Newton and Chandra are already attracting justified attention as the likely source for future samples, but no significant sets of serendipitously selected clusters can be reasonably expected from these observatories for at least another 2 years. This presents the window of opportunity for our survey, which uses data from the ROSAT High–Resolution Imager (HRI) archive. With respect to the PSPC, the HRI offers superior angular resolution. Our results indicate that it is actually a surprisingly good source of samples of high-redshift clusters.

Our new X–ray selected sample of candidate clusters of galaxies is based on the recently completed BMW survey of serendipitous X–ray sources over 3000
Figure 1. **Left:** Sky coverage of the BMW survey, as a function of X–ray flux and extension of the sources. **Right:** Same, but for a typical faint–source core radius $\sim 10$ arcsec, compared to some previous X–ray cluster surveys (see Rosati et al. 2000 for relevant references). Note the good compromise between the fairly large area at intermediate fluxes ($\sim 100$ sq. deg. around $10^{-13}$ erg cm$^{-2}$ s$^{-1}$), and the depth of the BMW sample (1 sq. deg. at $2.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$).

ROSAT HRI fields. The sample includes 287 candidates, with a significantly large sky coverage in comparison with other recent deep surveys. We are conducting a multi-site imaging campaign to fully identify the cluster sample. First results at ESO and TNG are extremely encouraging: with approximately an 80% rate of photometric confirmation in the first subsample of 35 candidates.

2. The BMW Project

The Brera Multi-scale Wavelet (BMW) project has currently completed the systematic analysis of about 3100 HRI pointings using a wavelet detection algorithm (Lazzati et al. 1999). This resulted in a catalog of $\sim 19000$ serendipitous sources with measured fluxes and extensions (Campana et al. 1999, Panzera et al. 2001). A clever selection of the HRI energy channels produced a reduction of the background noise by a factor of $\sim 3$, thus greatly improving the ability to detect low–surface–brightness sources as clusters. The BMW general catalogue is built excluding fields with $|b_{II}| \leq 20^\circ$ or pointed on the LMC and SMC. Furthermore to build BMW cluster catalogue we have excluded cluster–targeted HRI fields to avoid the bias produced by the cluster–cluster angular correlation function, for which we have a clear positive detection in these fields. Cluster candidates were isolated on the basis of their extension, selecting at a high significance level (corresponding to $> 5\sigma$) and using only the well–sampled HRI area between 3 and 15 armin off-axis. We ended up with a list of 287 cluster candidates which were visually classified on the DSS2 to reject obvious contaminants (30 rejections, mostly nearby galaxies). The BMW project is still under development such that a small assessment in the absolute number is expected.
3. Survey Sky Coverage

An important parameter characterising a survey of serendipitous sources as the BMW is its sky coverage, i.e. the effective solid angle covered as a function of the limiting flux. Being based on archival pointings, different parts of the sky are observed with different exposure times. Thus, for each value of the X-ray flux \( f_x \) the sky coverage is given by the total area of all observed fields with limiting flux \( f_{lim} \leq f_x \). In addition, due to the radial dependence of the point-spread function (PSF) of the ROSAT X-ray telescope, within a single field the effective flux limit is different for different off-axis angles and extensions of the sources. For this reason, the effective solid angle covered at different flux limits must be carefully estimated considering the instrumental set-up and the detection and characterisation methods adopted (e.g. Rosati 1995). We have therefore first estimated the sky coverage of the BMW survey for extended objects by assuming a \( \beta \) model with \( \beta = 2/3 \), with a set of different core radii. For each core radius we have convolved the analytic profile with the PSF of the instrument at different off-axis angles and we have calculated the corresponding maximum in the wavelet space. Each HRI image has a detection threshold which is calculated in the wavelet space (Lazzati et al. 1999) and is only function of the background. Thus for each image we could estimate directly the limiting detection flux as a function of both the off-axis angle and source extension. In Figure 1 we compare the BMW cluster sky coverage to some previous X-ray cluster surveys. This relatively quick and straightforward method has some limitations (e.g. it does not tell us how well the wavelet extension is measured), that need to be explored through simulations. To this end, we are currently running an extensive set of simulations following the approach of Vikhlinin et al. (1998), and the first outputs for a small sample of fields give results which are very close to the semi-analytic calculation, confirming that the sky coverage of Figure 1 should be a fair representation of our data.

4. First Results from Optical Follow-up

From the 287 candidates we have further selected a high priority sample of 165 objects by excluding the HRI fields with exposure time smaller then 10 ksec. In spring 2000, we started a long-term program of multi-band photometry and spectroscopy of these fields, which is currently underway using telescopes in both emispheres (mostly the TNG in La Palma and the ESO 3.6 m telescopes). We have recently (September 2000) reached a total of 35 candidates for which deep optical imaging has been secured in at least two bands. Preliminary analysis of these observations suggests a success rate (i.e. evidence for a galaxy overdensity correlated with the X-ray source) of about 80%. The still unidentified 20% fraction does not show any obvious pathology and we plan to add deep imaging in \( K' \) band, where the contrast of early-type galaxies is maximised, to definitely ascertain their nature.
Figure 2. Deep $g + r + i$ images (typical exposure times $\sim 5000$ sec) with overlaid ROSAT–HRI X–ray contours, for a few examples of identified groups/clusters in the BMW survey. Indicative redshifts for these clusters range from $z \sim 0.2$ (top left) to $\sim 0.8$ (bottom right). In each image the field of view is $3 \times 3$ arcmin.
Figure 3. CCD image of BMW 080459+241 (left, 6000 sec exposure in $r+i$ Gunn bands) with X–ray contours superimposed, and its colour–magnitude diagram (right). A number of galaxies display a similar colour along an apparent red sequence (filled dots) and their position on the sky correlates significantly with the X–ray emission (diamonds over left image). The colour is that expected for an early–type population at $z = 0.6$.

5. Discussion

A hint of the scientific potential of the BMW catalogue can be obtained from the left panel of Figure 4 where the expected number of clusters as a function of redshift is plotted. These predictions use the computed BMW sky coverage of the high priority sample (165 objects) and integrate the local X–ray luminosity function (De Grandi et al. 1999) considering or not the evolution suggested by the RDCS, as reported in Rosati (1999). Simple comparison to the total expected numbers from Figure 4 would seem to imply that the BMW survey sees evolution in the XLF similar to the RDCS results. However, one has to await for the completion of the identification campaign to be able to place serious constraints on evolution. We should remark here the potential advantage of working with HRI data. In the right panel of Figure 4 we have plotted the apparent diameters of a rich cluster ($r_c = 250$ kpc) and of a group of galaxies ($r_c = 100$ kpc) as a function of redshift, together with a measure of the resolution of the ROSAT HRI compared to the PSPC. As one can see, the PSPC is not as suitable as the HRI for distinguishing groups of galaxies from point-like sources beyond redshift 0.4. Of course, this simplistic plot depends on several variables, as the underlying cosmology, the source profile and in particular does not take into account the different noise level of the 2 instruments. Nevertheless, it shows that we should be able to explore the faint end of the XLF, the realm of groups, which could not be studied from PSPC data. In fact, the potentially large number of clusters in the BMW sample, when compared to prediction of evolution or no–evolution models, could also be produced by a steeper local XLF.

References
Figure 4.  **Left:** Expected integral distribution of BMW clusters as a function of redshift, with or without the evolution of the X-ray luminosity function suggested by the RDCS (Rosati et al. 1999).  **Right:** Apparent angular diameter of a rich cluster (core radius 250 kpc) and a group of galaxies (core radius 100 kpc) as function of redshift, compared to the PSF of the two ROSAT instruments at the same off-axis angle (5 armin).

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