MACS: The evolution and properties of massive clusters of galaxies

Harald Ebeling\textsuperscript{1}, Alastair Edge\textsuperscript{2}, J. Patrick Henry\textsuperscript{1}

\textsuperscript{1}Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
\textsuperscript{2}Department of Physics, University of Durham, Durham, DH1 3LE, UK

\textbf{Abstract.} We present first results from the MAssive Cluster Survey (MACS), a new large-scale X-ray survey designed to find and characterize very massive, distant clusters of galaxies. Based on X-ray detections in the ROSAT All-Sky Survey, MACS aims to compile a sample of more than 200 X-ray luminous clusters at $z \geq 0.3$, about 50 times the number of EMSS clusters in the same redshift and luminosity range. The MACS sample is uniquely suited to investigate cluster evolution at redshifts and luminosities poorly sampled by all existing surveys.

At the time of writing the MACS sample comprises 41 clusters with measured redshifts of $0.3 \leq z \leq 0.56$ and X-ray luminosities in excess of $6 \times 10^{44}$ erg s$^{-1}$ (0.1–2.4 keV). This early sample is thus already twice as large as the high-$z$, high-luminosity subsets of the EMSS, BCS, and REFLEX cluster samples taken together. An additional 85 MACS clusters with photometric redshifts $z \geq 0.3$ are scheduled for spectroscopic observation.

From a preliminary analysis of a statistically well defined subsample of the 25 X-ray brightest MACS clusters we conclude tentatively that negative evolution is not significant at the highest X-ray luminosities ($L_X > 1 \times 10^{45}$ erg s$^{-1}$) out to redshifts of $z \sim 0.4$. Our findings thus extend the no-evolution result obtained by many serendipitous ROSAT cluster surveys at lower luminosities.

\section{Introduction}

In a bottom-up scenario of structure formation massive galaxy clusters form from rare, extreme overdensities in the primordial density fluctuation field. At what redshift clusters of a given mass collapse and virialize depends sensitively on the chosen structure formation theory. The comoving number density of clusters as a function of redshift (and, ideally, also of mass) is thus an important statistic that is well suited to constrain cosmological and physical parameters of structure formation models. The tightest constraints can be obtained from observations of very distant, very massive clusters which are the rarest in all cosmological models.

Since clusters are bright X-ray sources, wide angle X-ray surveys are an excellent way of compiling sizeable cluster samples out to cosmological redshifts ($z \sim 1$). Several such samples have been compiled (and/or published) in the past decade; an overview of the solid angles and flux limits of these surveys is presented in Figure 1. Two kinds of surveys can be distinguished: serendipitous cluster surveys (Bright SHARC, CfA 160 deg$^2$ survey, EMSS, RDCS, SHARC-S, WARPS) and contiguous area surveys (BCS, BCS-E, NEP, RASS-BS, REFLEX). The former surveys use data from pointed X-ray observations, whereas the latter
Figure 1: The selection functions of all major X-ray cluster surveys of the past decade. Also shown is the solid angle required at a given flux limit to (statistically) detect 10 (or 100) X-ray luminous cluster at any redshift (or at z > 0.3). Note how, of all previous surveys, only the EMSS, BCS, and REFLEX projects are just sensitive enough to detect a small number of distant, X-ray luminous systems.

are all based on the ROSAT All-Sky Survey (RASS). With the exception of the NEP survey, all contiguous cluster surveys cover close to, or more than, 10,000 square degrees but are limited to the X-ray brightest clusters. This fundamental difference in depth and sky coverage has important consequences. As shown in Fig. 1, the NEP survey as well as all serendipitous cluster surveys (with the possible exception of the EMSS) cover too small a solid angle to detect a significant number of X-ray luminous clusters. The RASS large-area surveys, on the other hand, are capable of finding these rarest systems, but are too shallow to detect them in large numbers at z > 0.3.

We are thus in the unfortunate situation that the cosmologically most important systems, the massive, distant clusters, are poorly sampled by all existing X-ray cluster surveys. At low to moderate X-ray luminosities where the number statistics have greatly improved most of the above surveys find little, if any, evolution out to redshifts of z ~ 0.8. At higher luminosities, however, the EMSS and CfA cluster surveys find evidence of strong negative evolution already at z > 0.3. It is worth bearing in mind though that the latter results are based on very small samples or, in fact, non-detections.
MACS: a new cluster survey

MACS (MAssive Cluster Survey) was designed to find the population of (possibly) strongly evolving clusters, i.e., the most X-ray luminous systems at $z > 0.3$. By doing so, MACS will re-measure the rate of evolution and test the results obtained by the EMSS and CfA cluster surveys. Unless negative evolution is very rapid indeed, MACS will find a sizeable number of these systems and thus provide us with targets for in-depth studies of the physical mechanisms driving cluster evolution and structure formation.

As indicated in Fig. 1, MACS aims to achieve these goals by combining the largest solid angle of any RASS cluster survey with the lowest possible X-ray flux limit. Drawing from the list of 18,000 X-ray sources listed in the RASS Bright Source Catalog (BSC) MACS applies the following selection criteria: $|b| \geq 20^\circ$, $-40^\circ \leq \delta \leq 80^\circ$ (to ensure observability from Mauna Kea; the resulting solid angle is 22,735 deg$^2$), X-ray hardness ratio greater than a limiting ($n_H$ dependent) value derived from the BCS sample [2], and $f_{X,12} \geq 1$ where $f_{X,12}$ is the detect cell flux in the 0.1–2.4 keV band in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

Cluster candidates are tentatively identified from Digitized Sky Survey images, and are confirmed or discarded by R band imaging observations with the University of Hawai‘i’s 2.2m telescope. This process has, so far, resulted in the identification of more than 700 clusters of galaxies at all redshifts; Fig. 2 shows the redshift distribution of the 602 systems with spectroscopic redshifts. As a by-product, MACS has thus already delivered the by far largest X-ray selected cluster catalogue to emerge from the RASS to date. Our spectroscopic follow-up observations focus exclusively on the most distant of these clusters. Redshifts are estimated from the imaging data, and spectroscopic observations with the UH2.2m and Keck 10m telescopes are performed of all systems with $z_{\text{est}} > 0.2$.

A prediction for the size of the final MACS sample can be obtained from the MACS selection function and the local cluster X-ray luminosity function. In a no-evolution scenario we expect to find 57 clusters at $z > 0.3$ and $f_{X,12} \geq 2$, and 151 at $z > 0.4$ and $f_{X,12} \geq 1$. More than 20 MACS clusters are predicted to lie at $z > 0.6$. This constitutes an improvement of a factor of about 50 over existing samples in the same redshift and luminosity range.

3 Status and first results

The MACS cluster sample currently comprises 41 systems with spectroscopic redshifts in the range $0.3 \leq z \leq 0.56$ (Fig. 2). An additional 85 MACS sources with photometric redshifts $z \geq 0.3$ are scheduled for spectroscopic observation.

The completeness of this preliminary sample cannot be easily quantified. However, the bright part of the MACS/BSC source list ($f_{X,12} \geq 2$) has been mostly identified, and the completeness of the sample of (presently) 25 clusters found above this higher flux limit can be estimated. We thus use this subsample to
Figure 2: The redshift distribution of the 602 clusters identified in the MACS project to date. The 41 clusters at $z > 0.3$ that form the preliminary MACS sample are highlighted. Note that all 602 clusters have spectroscopic redshifts.

Attempting to constrain cluster evolution at the very highest X-ray luminosities ($L_X > 1 \times 10^{45}$ erg s$^{-1}$). Even if we knew nothing about the completeness of this subsample, the observed 25 clusters (where 57 are expected) already limit any negative evolution to about a factor of two. If the estimated incompleteness of this subsample is taken into account (R.A. range not yet fully covered, softer X-ray sources not yet screened, etc), we expect to eventually find 43 of the predicted 57 clusters. When the statistical and systematic errors of measurement and prediction are taken into account, the difference of about 15 clusters is statistically not significant. Our tentative conclusion is that there is no significant evolution of the X-ray cluster luminosity function out to $z \sim 0.4$ at any luminosity.

References

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