

Searching for X-ray Galaxy Clusters in the Zone of Avoidance

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Abstract. X-ray galaxy clusters are ideal tracers of the large-scale structure of the Universe. Based on the ROSAT All-Sky Survey we are constructing a sample of the X-ray brightest galaxy clusters for cosmological studies. We have already completed the compilation of a sample of about 1000 clusters in the sky excluding a 40 degree wide band around the galactic plane. We have demonstrated with the southern sample, which is the so far most complete, that we can get reliable statistical measures of the large-scale structure of the Universe to scales in excess of $400h^{-1}$ Mpc. With the experience gained in these projects we are extending the search for X-ray galaxy clusters into the Zone-of-Avoidance. We have compiled a sample of 181 good cluster candidates with a well defined completeness of about 70% down to a flux limit of $3 \cdot 10^{-12}$ erg s^{-1} in the zone with an absorption depth of $A_v \leq 2.25$. The candidates are definitely identified and redshifts are obtained in an ongoing optical follow-up program.

1. Introduction

Clusters of galaxies as the largest well defined building blocks of our Universe are ideal probes for the study of the cosmic large-scale structure and for the test of cosmological models (e.g. Henry et al. 1992, Dalton et al. 1994, Collins et al. 1995, Eke, Cole & Frenk 1996, Borgani et al. 1999). Statistical measures of the galaxy cluster population like the cluster mass function, the two-point-correlation function, and the density fluctuation power spectrum can give very important constraints on the characteristic measures of the matter density distribution throughout the Universe and its evolution as a function of time. For such studies the compilation of a statistically complete cluster catalogue with a well controlled selection function is the important first step.

Ideally one would like to compile a cluster catalogue where the cluster are selected by their gravitational mass. The mass is not a direct observable, however, and one relies on relations of observable quantities that are closely correlated to the cluster mass. While cluster catalogues have first been compiled on the basis of optical photographic survey data (e.g. Abell 1958, Abell et al. 1989) it has been recognized that it is very difficult to obtain a cluster mass from the observed optical “richness” parameter. X-ray observations provide a much better means for the construction of cluster catalogues for the study of the large-scale

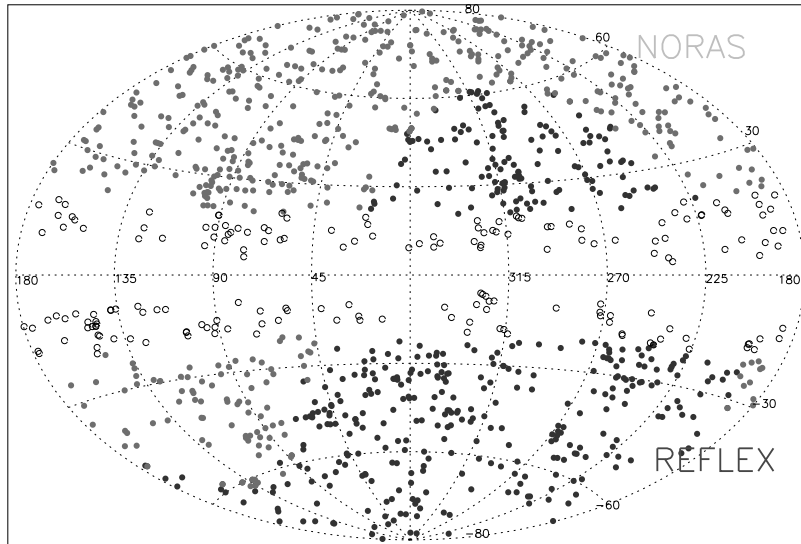


Figure 1. Sky distribution of the X-ray cluster surveys based on the RASS in galactic coordinates. The solid data points show the current samples of the NORAS Survey (northern sky) and REFLEX Survey (southern sky up to declination $d \leq 2.5^\circ$). Also shown are the cluster candidates found in the Zone-of Avoidance $|b_{II}| \leq 20^\circ$ and $A_v \leq 2.5$ (open circles).

structure. The X-ray emission observed from clusters originates from the thermal emission of hot intracluster gas bound in the gravitational potential well of the clusters (e.g. Sarazin 1986). Therefore the plasma emission is a certain indication of a true gravitationally bound structure. In addition the thermal emission for the typical intracluster plasma temperatures of several keV has the radiative emission maximum in soft X-rays where the available X-ray telescopes are most effective. This makes galaxy clusters readily detectable out to large distances with present X-ray telescopes. The main advantage of the X-ray detection is, however, the fact that the X-ray luminosity is closely correlated to the cluster mass (Reiprich & Böhringer 1999) with a dispersion of about 50% in the determination of the mass for a given X-ray luminosity.

2. The X-ray Cluster Survey based on the ROSAT All-Sky Survey

The ROSAT All-Sky Survey (RASS), the first and up to now only All-Sky X-ray survey conducted with an X-ray telescope (Trümper 1993), provides the ideal starting point to compile an all-sky X-ray cluster catalogue. To this end we are conducting a comprehensive follow-up identification program of the X-ray brightest galaxy clusters detected in the RASS. Since the number of photons registered in the RASS for X-ray cluster sources at the limit of our survey is typically about 20 - 30 photons this information is not sufficient to identify the nature of the X-ray sources. Thus we supplement the X-ray detection by optical

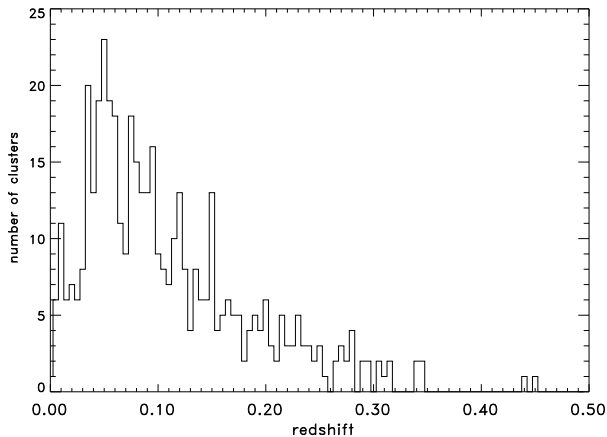


Figure 2. Redshift distribution of the REFLEX clusters.

information, which we obtain from the photographic sky surveys (in the north from POSS as digitized in the STScI scans and in the south from the UK Schmidt Survey as digitized by COSMOS, see e.g. MacGillivray et al. 1994). In addition extensive spectroscopic measurements are necessary for the final identification and redshift determination. The main part of our survey is focussed on the region outside the band of the Milky Way ($|b_{II}| \geq 20^\circ$) to avoid the regions of larger interstellar absorption and the more difficult optical cluster identification in the crowded stellar fields.

We have recently completed the first survey steps in two major programs: The NORAS survey in the northern sky (Böhringer et al. 2000a) in a collaboration of MPE with CfA, StScI and ESO and the southern REFLEX survey (Böhringer et al. 1998, 2000b, Guzzo et al. 1999) conducted as an ESO key program with a main contribution from MPE, the Universities Milano and Liverpool, CEA Saclay, NRL Washington, and the Royal Observatory Edinburgh (for results of some earlier studies related to these programs see also Ebeling et al. 1998, 2000, DeGrandi et al. 1999). The sky distribution of the clusters found in the NORAS and REFLEX surveys is shown in Fig. 1. The NORAS catalogue (Böhringer et al. 2000a) comprises so far 502 clusters. The present REFLEX sample (Böhringer et al. 2000b), containing 452 clusters above a flux limit of $3 \cdot 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$, is the so far best selected and most complete X-ray survey compiled to date showing no significant incompleteness in several tests of the selection function (see e.g. simulations in Schuecker et al. 2000). Therefore we apply the REFLEX sample to a number of cosmological studies (e.g. Collins et al. 2000, Schuecker et al. 2000) and we will base the following statistics on this sample.

Fig. 2 shows the redshift distribution of the REFLEX clusters. The median redshift is $z = 0.09$. The most distant cluster has a redshift of $z = 0.45$ and is the most X-ray luminous cluster (RXCJ1347-1144) discovered to date. The currently most important statistic describing the large-scale structure is the density fluctuation power spectrum. Fig. 3 shows the power spectrum for the density distribution of 188 REFLEX clusters in a box with a length of $400h^{-1}$

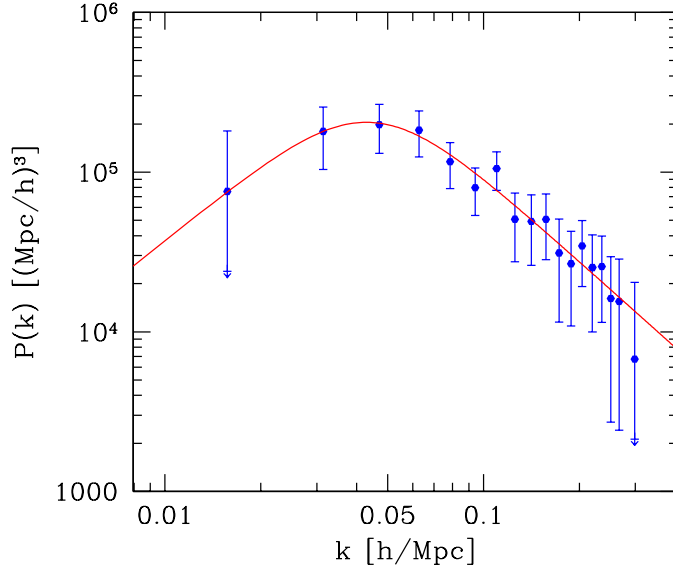


Figure 3. Power spectrum of the fluctuations in the cluster density distribution in the REFLEX Survey (Schuecker et al. 2000).

Mpc (Schuecker et al. 2000) showing significant structures up to scales of at least $400h^{-1}$ Mpc. This is the largest volume in the local Universe in which the structure has been studied in three dimensions so far. The large amplitude of the power spectrum at large scales can only be reproduced by low density cosmological models (Schuecker et al. 2000, Collins et al. 2000). In addition to the pure statistical analysis of the large-scale structure the actual cosmography of the cluster and matter density distribution is also studied which is particularly important in connection with studies of the large scale flows. This work is in progress.

3. The Search for X-Ray Clusters in the Zone-of-Avoidance

Building on the experience and the success of the REFLEX and NORAS surveys we are extending the X-ray cluster survey also into the Zone-of-Avoidance (ZoA). In this region the X-ray detection is made more difficult by the increased interstellar absorption in the galaxy. Fig. 5 provides a histogram of the distribution of the interstellar hydrogen column density in the region $|b_{II}| \leq 20^\circ$ (which we loosely refer to as the ZoA in this paper even so the definition is somewhat different to that used in most optical surveys) with values taken from the HI-survey of Dickey & Lockman (1990). We note that about 66% of the area has a column density less than $3 \cdot 10^{21} \text{ cm}^{-2}$. This corresponds to an attenuation in the hard ROSAT band (about 0.5 - 2.0 keV, which we use for the X-ray cluster detection) of a factor of about 1.9 and an optical extinction of about $A_v \sim 2.25$. Thus with a sensitivity variation of less than a factor of two we can extend our cluster survey into about 2/3 of the ZoA area. For the start we have restricted the systematic search to this region.

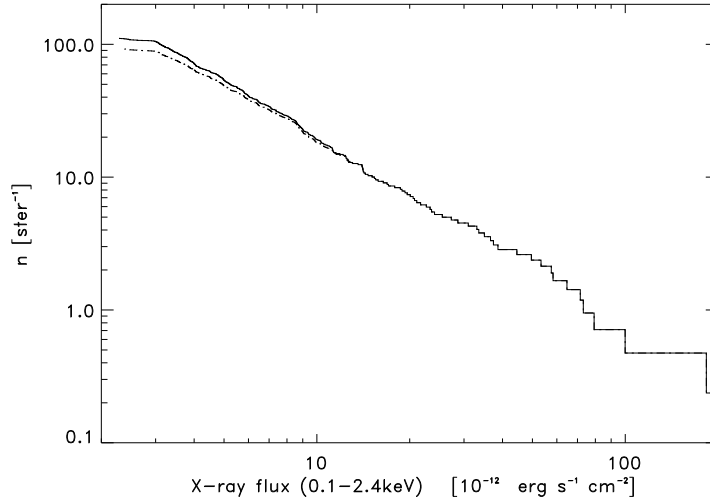


Figure 4. Number counts as a function of flux (logN-logS-curve) for the REFLEX sample. The solid line shows all clusters while the dashed line shows only the clusters displaying an extended X-ray emission.

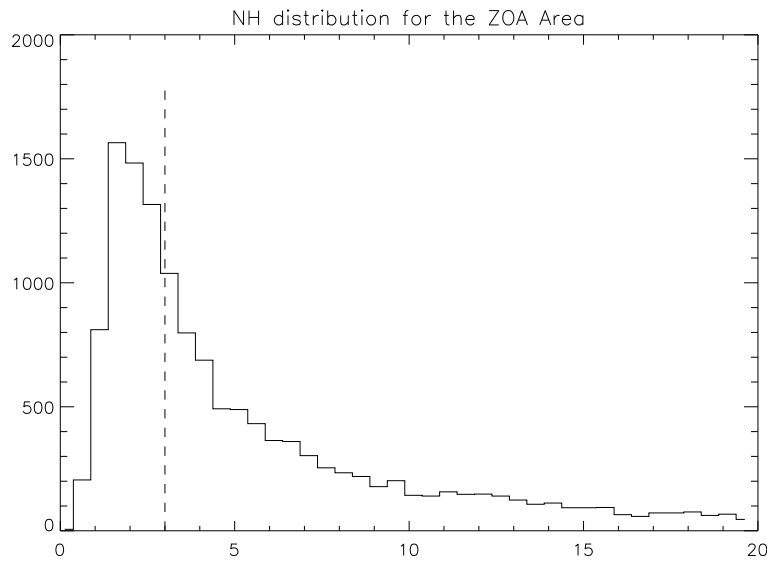


Figure 5. Histogram of the distribution of the interstellar hydrogen column density in the sky region $|b_{II}| \leq 20^\circ$. The vertical dashed line shows the current limit of our survey corresponding to an optical extinction of $A_v \sim 2.25$.

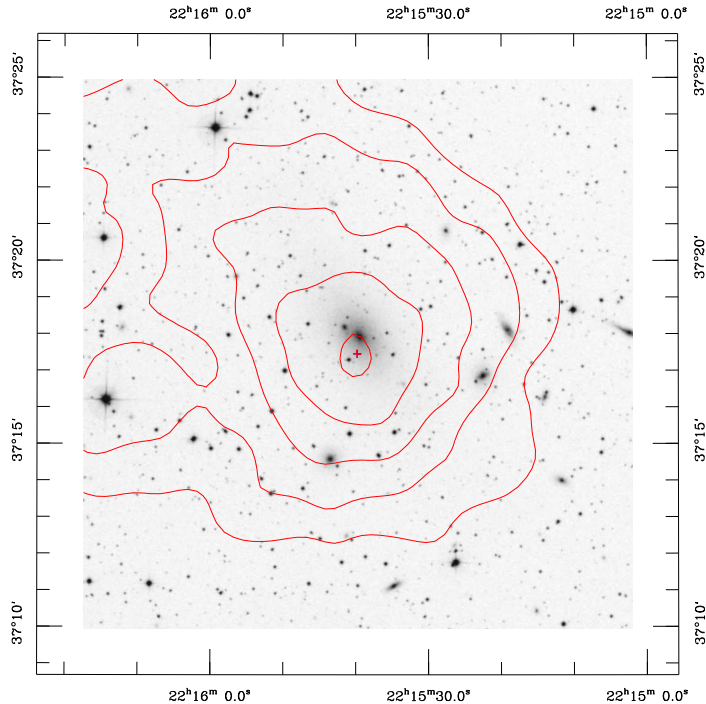


Figure 6. One of the newly discovered nearby X-ray clusters at a redshift of about $z = 0.019$. The coordinates refer to the epoch J2000. The central galaxy is NGC 7242 at $b = -15.9^\circ$.

One efficient way to find cluster candidates is to look for extended X-ray emission. Fig. 4 shows the number counts of REFLEX clusters as a function of the X-ray flux limit and it also gives the fraction of clusters that have been found as extended X-ray sources in our special analysis of the X-ray sources with the growth curve analysis method (GCA, see Böhringer et al. 2000a). At the flux limit of $3 \cdot 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ 81% of the REFLEX clusters feature an X-ray extent.

Therefore we have started our search for X-ray clusters in the galactic band among the extended X-ray sources. To this end we have reanalysed the 46404 X-ray sources detected with a likelihood $L \geq 6$ in the standard analysis of the RASS II (the second processing of the ROSAT survey data, Voges et al. 1999). In total we found 358 X-ray sources with an extent probability larger than 99% (based on a Kolmogorov-Smirnov method run within GCA), a flux limit $F_{lim} \geq 3 \cdot 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ and an interstellar absorption $n_H \leq 3 \cdot 10^{21} \text{ cm}^{-2}$. From a closer inspection of these sources in their detailed X-ray properties, their appearance on optical survey plates, literature information, and on some follow-up observations we can rule out 138 X-ray sources as cluster candidates. Most of these sources are multiple stellar X-ray sources which are classified as extended as long as no special care is taken to deblend these multiple sources. Other non-cluster sources feature a spurious extent (tests have shown that a failure rate in the extent classification of up to 5% has to be expected).

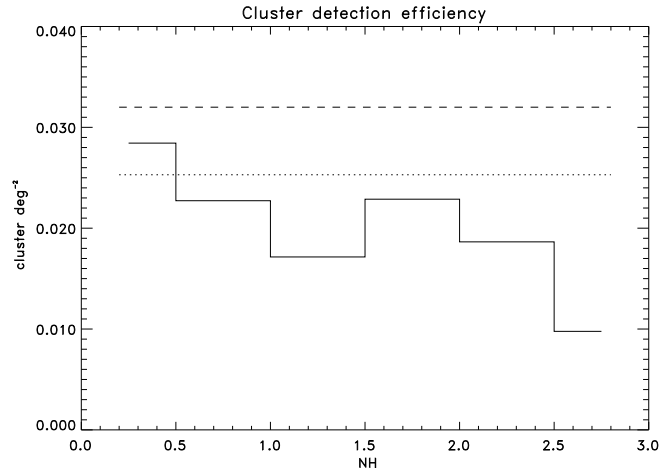


Figure 7. Surface number density of the cluster candidates found in the ZoA region (solid line). The dashed line shows the total REFLEX number density and the dotted line the density of extended REFLEX clusters for comparison.

On the other hand 181 sources show cluster candidates on the optical plates. With the additional information that the X-ray emission of these sources is extended the probability that these sources are clusters is very high. For the remaining 39 X-ray sources no definite classification could be reached and we expect that a smaller fraction of them could be more distant clusters not easily visible on the survey plates.

The distribution of the 181 very likely cluster candidates in the sky is shown in Fig. 1. Fig. 6 shows one of the newly found poor galaxy clusters which is relatively nearby at a redshift of $z \sim 0.019$. The redshift distribution we expect for the clusters found should be similar to that shown in Fig. 2.

4. Conclusions

To illustrate the efficiency of the cluster detection as a function of the interstellar absorbing column density, n_H , we show in Fig. 7 the surface density of the cluster counts in the sky as a function of n_H . Also shown is the surface density of all REFLEX survey clusters and those which are found to be extended. In the low n_H region up to about $n_H \leq 2.0 \cdot 10^{21} \text{ cm}^{-2}$ we almost recover the surface density of the extended REFLEX clusters which is almost 80% of the total sample. Beyond $n_H \sim 2.0 \cdot 10^{21} \text{ cm}^{-2}$ the detection efficiency drops significantly showing that the cluster search becomes more difficult. In summary we estimate that we can recover at least 60 - 70% of the clusters above a flux limit of $3 \cdot 10^{-12} \text{ s}^{-1} \text{ cm}^{-2}$ in 2/3 of the ZoA region which is less affected by absorption. Definite identifications and redshifts for these cluster candidates are currently obtained in an ongoing follow-up observation program in the northern and southern sky.

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