THE ESO ALL–SOUTHERN–SKY REDSHIFT SURVEY
OF ROSAT CLUSTERS OF GALAXIES

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ABSTRACT

We discuss the rationale and the present status of a large redshift survey aiming at measuring distances for all the clusters of galaxies detected by the ROSAT X–ray All–Sky Survey in the southern hemisphere, with flux larger than $\sim 2 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. The survey is being performed using three ESO telescopes in parallel. The final sample will contain about 700 clusters. It will represent a unique database for the study of the spatial distribution of clusters, their X–ray luminosity function and their intrinsic physical properties. Serendipitous results obtained so far include two new gravitational arc systems in two clusters of galaxies. These findings, obtained on rather short exposures, confirm the advantage of searching for arcs in X–ray selected clusters.

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1. Clusters as Cosmological Probes

In the hierarchy of cosmological structures, clusters of galaxies are the largest well-defined building blocks and represent the deepest gravitational potential wells that can be found in the Universe. By well-defined, one means that they have clearly separated from the Hubble expansion and recollapsed to a nearly (or fully, in some cases) virialized object. In addition to the galaxy content, these “cosmological sinks” are filled with large masses of gas, heated at temperatures of 1–10 keV and emitting luminosities in the soft X-ray band around $10^{44}$ erg s$^{-1}$. As a consequence, X-ray emission from clusters can be detected up to very large distances (see e.g. ref. 1). This specific property makes clusters of galaxies very interesting as tracers of the large-scale structure of the Universe, both statically (to characterize present-time structure on very large scales), and dynamically (to study the evolution of clustering).

As large-scale structure tracers, clusters of galaxies present a number of advantages. The first is that they basically show a nearly frozen – though thresholded at high contrast – picture of the initial fluctuation field. Indeed, with typical mean separations $\sim 10$ h$^{-1}$ Mpc, they map scales which are essentially still in their linear regime of growth. Any clustering statistics derived from the distribution of clusters is therefore in principle easier to be compared to the model predictions. Observationally, clusters are “cheap” tracers, in the sense that for covering a given volume of space they require a much smaller number of galaxy redshifts than when using single galaxies. There is about a factor of 100 between the number of redshifts required by the two approaches, depending on the number of galaxies used for obtaining the mean cluster velocity. While cluster redshift surveys have been able to explore three-dimensional volumes already covering typical scales around $\sim 300$ h$^{-1}$ Mpc, similar volumes will be reached only by next generation single galaxy surveys, thanks to the advent of super-multiplexing spectrographs and/or dedicated telescopes (see the contributions by Gunn and by Taylor in this same volume).

The primary reference list for studies of galaxy clusters during the last few decades, has been the catalogue compiled by Abell in 1954 (together with its more recent extension to the South, the ACO catalogue). Classic results on the large-scale distribution of clusters were obtained on richness-limited subsamples of this compilation, like e.g. the estimate of the cluster–cluster correlation function $\xi_{cc}(r)$ However, the robustness of these results was often questioned in relation to the intrinsically subjective nature of the visual cluster selection, and also to possible projection effects artificially boosting the number of angularly close pairs when selecting richness-limited samples. The construction of automatic cluster catalogues from digitized galaxy data, like the Edinburgh/Durham Cluster Catalogue (EDCC) and the similar APM cluster catalogue showed a correlation function more isotropic and with a smaller amplitude than those estimated from Abell samples.

Although the use of specific algorithms considerably reduced projection effects in the automatic catalogues, the selection of the clusters from the projected two-
dimensional distribution of galaxies inevitably carries a percentage of spurious rich
cluster produced by the chance superposition of different structures along the line of
sight (∼10% for the EDCC\textsuperscript{10}). The powerful X-ray emission from galaxy clusters
provides a much better way to intrinsically define a cluster and construct virtually
projection-free catalogues. This is also helped by the fact that the X-ray emission
produced by thermal bremsstrahlung is a quadratic function of the density. If the
emitting gas follows the same radial profile as the galaxy population, it is clear that
the X-ray emission will be roughly proportional to the richness squared, providing
a more compact system in the X-ray band rather than in the optical. (In fact, the
proportionality law between luminosity and density could even be a power higher
than two if the cluster contains a cooling flow in its center).

Another related issue on which a large sample of clusters selected in X-rays would
be invaluable is that of the ‘local’ X-ray luminosity function of clusters. This is
directly related to the distribution function of the mass in the Universe, and thus
it is just another route to probe the power spectrum of density fluctuations on very
large scales (e.g. ref. 11). In addition, a reliable determination of the present–epoch
X-ray luminosity function is also crucial to the study of the evolution of the function
itself. The results obtained from the EXOSAT and EINSTEIN data point towards
the existence of rapid evolution\textsuperscript{12,13}. While observations of new homogeneous samples
doistant clusters are needed to test for this effect, a large, unbiased local sample is
also essential for proper comparison.

The dynamical state of clusters both at the present epoch and as a function of
cosmic time (also intimately related to the evolution of the X-ray luminosity function),
is a further important observation for constraining cosmological models. The
mean degree of virialization at the present epoch, that can be studied through the
correlation of X-ray luminosity and galaxy velocity dispersion, or by comparing the
X-ray and optical morphologies, is clearly dependent on the cosmological scenario.
Again, significant results on this topic depend on the size and quality of the available
X-ray cluster sample.

It becomes therefore clear how an all-sky survey in the X-ray band, like that
performed by the ROSAT satellite, represents a unique opportunity for constructing
a large, homogeneous and statistically complete catalogue of galaxy clusters to address
the above discussed issues.

2. The ROSAT All-Sky Survey

Between August 1990 and January 1991, the ROSAT satellite performed the first
ever all-sky survey using an imaging X-ray telescope\textsuperscript{14}. In the configuration used
for the survey, the ROSAT telescope has a field of view of 2 degrees, covering the
energy band between 0.1 and 2.4 keV, with a resolution of 20 arcsec on axis which
degrades to 2 arcmin at the field edges. The mean exposure time was around 600 sec,
with peaks of ∼ 40000 sec at the ecliptic poles\textsuperscript{15}. Further details on the instrument
and on the ROSAT All-Sky Survey (RASS) are presented in these proceedings by
The first processing of the whole survey with the so-called Standard Analysis Software System (SASS) produced a database of some 50,000 sources. The sensitivity limit can be placed around $10^{-12}$ erg s$^{-1}$ cm$^{-2}$, which, using results from previous surveys, gives a number of 4000–5000 clusters of galaxies expected in the whole survey. Most of these clusters are expected to be at a redshift comprised between 0.1 and 0.2, with a few very luminous objects at $z \geq 0.3$.

Optical follow-up of ROSAT clusters started early after completion of the SASS on subsets of the all-sky sample. An overview of these projects has been given by Böhringer. In particular, an extensive redshift survey has been performed in the region of the South Galactic Pole (SGP), producing an estimate of the correlation function of X-ray clusters which is in good agreement with the above mentioned results from the automatic catalogues (see also the contribution by Collins in this volume).

However, what makes the ROSAT survey unique is its all-sky distribution, which is ideal for accurate studies of large-scale structure, opening the way to clustering analyses on scales of the order of 1000 h$^{-1}$ Mpc.

3. An All-Southern Sky Redshift Survey of X-Ray Revealed Clusters

To fully exploit the above described potential of the RASS, in 1991 we proposed to ESO a key programme to survey spectroscopically all the ROSAT clusters down to a certain flux limit over the entire southern sky ($|b| \geq 20^\circ$). The project was approved, awarding 90 nights equally distributed among the 3.6 m, 2.2 m and 1.5 m telescopes.

Fig. 1. The sky distribution of the cluster candidates above a SASS count rate of 0.1 cts s$^{-1}$. Filled circles (248) mark the objects for which redshifts have been already observed in the program discussed here or in the Hydra and SGP projects. Dark grey circles (132) are clusters with redshift from the literature, while light grey circles are still to be observed.
Our observational goal is to obtain a reliable mean redshift for all clusters down to a SASS count rate limit of 0.08 cts s\(^{-1}\), corresponding to a flux limit of \(1.6-2 \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\). To this flux, the present cluster candidate list—obtained from the combined cluster identification procedures described below—contains \(\sim 700\) objects. Nearly 300 of these clusters have already a measured redshift, either from the literature or from one of the early redshift follow-ups in restricted regions (like, e.g., the SGP project). Fig. 1 shows the sky distribution of the candidates above a SASS count rate of 0.1 cts s\(^{-1}\).

3.1. Cluster Identification

A complete optical identification of all the RASS sources is presently performed only within a few selected regions, by a separate project involving the use of a large amount of telescope time. In the case of our survey, the cluster identification from the X-ray source catalogue produced by the SASS has to follow a different approach. The aim is to construct a sample which is complete for X-ray clusters, i.e. that contains virtually all the RASS sources associated with a galaxy cluster. The basic idea is to merge together the products of a few different criteria, using relatively broad boundaries to avoid discarding genuine X-ray clusters. The price to be paid is that of including in the candidate list also a number of spurious objects that will have to be discarded through a direct screening of the ESO/SRC sky survey plates. This means that we are requesting that some signature of the cluster is present on the optical sky survey images. This introduces in practice a redshift cut around \(z \simeq 0.3\). This is not problematic for the completeness of our sample, given its flux limit and the consequently expected redshift distribution which peaks at \(z\)'s between 0.1 and 0.2.

The main preidentification method adopted for the southern hemisphere, is based on the comparison of the RASS source list with an optical galaxy catalogue \((b_j \leq 20.5)\), constructed in Edinburgh with the COSMOS machine digitizing the whole southern sky ESO/SRC J survey plates. All the SASS sources are correlated with the galaxy positions in this catalogue, and also with a list of galaxy concentrations (i.e. ‘clusters’), automatically constructed from this optical database. The number of galaxies around each X-ray source is compared to the mean number expected for random fields, and overdensities above a given threshold are flagged. The SASS source list is also correlated with the Abell/ACO and Zwicky catalogues of clusters.

Further potential cluster candidates are all the X-ray sources which are recognized as extended by the SASS: 70% of these are found to be real clusters. The rest are usually very bright stars or AGNs (for which small deviations between the theoretically assumed point spread function and the observed one lead to a spurious significance for the extent), or nearby galaxies. This is evidently the only selection criterion which is solely based on the properties of the X-ray emission. Note however that at \(z=0.1\) many clusters have already an angular core radius \(\sim 1\) arcmin, i.e. below the resolution of the instrument, and are therefore detected as point sources. It is interesting to note that a selection based only on the X-ray extension (though a
very clear–cut one), recovers only one–third of our present sample of ROSAT detected clusters.

There is obviously an overlap between the sources found by the different approaches. In this sense, the different ways of identifying the clusters represent an important exercise to check the relative completeness and biases of the different techniques used. We expect the present sample, defined within the limits discussed in the beginning of this section, and obtained through the screening and the merging of the different methods, to be more than 80% complete. This figure, which is rather uncertain at the moment, is possibly pessimistic and should inevitably improve with the refinements of the analysis of the RASS data. While the redshift survey is progressing steadily, we are working in parallel to different ways of detecting sources and estimating their fluxes from the RASS data. A notable example is the so–called VTP method (‘Voronoi Tessellation and Percolation’, see Ebeling, these proceedings). An important step forward in this sense will definitely be represented by the second–generation Standard Analysis of the RASS data (SASS II), which is expected before the end of 1994 and should improve significantly the detection efficiency and flux estimate for extended sources.

As a final remark, it is important to remind that not everything is golden also when selecting clusters in X–rays. In particular, a main difference with respect to optically selected samples is that once the X–ray source has been associated to a cluster of galaxies, the possibility that part (or most) of its flux comes from a single galaxy within the cluster (e.g. a BL Lac object or a Seyfert galaxy) has still to be taken into consideration. To this end (in addition to looking, when enough resolved, at the X–ray and optical morphologies), we devote special care to the presence of high–excitation emission lines in cluster galaxies as indicator of high–energy nuclear activity.

3.2. Observational Goals and Strategy

Our main observational goal is to measure reliable cluster redshifts. This implies observing spectroscopically at least 5 redshifts per cluster, possibly 10 or more. A practical benefit of this is that a velocity dispersion will also be obtained for many of the observed clusters. Another important point we already mentioned is the careful check for dubious identifications and possible AGN contaminants. These goals are met first of all by the strategy of using multi–object spectroscopy (MOS) at the 3.6 m telescope equipped with the high–throughput spectrograph EFOSC. With this instrument, around 10–20 redshifts per field are typically secured at once on moderately distant and/or compact clusters, with around 10 clusters observable per night. On more nearby, looser systems, we use single–slit spectroscopy (at the 2.2 m and 1.5 m telescopes), with, respectively, an efficiency of ~ 20 and ~ 10 slit positions observed each night.
4. Present Status, Serendipitous Results and the Future

So far (mid-1994), we have invested around 30% of the total allocated time. A total of 158 cluster candidates have been observed from our sample, 49 of which in MOS mode, for a total of more than 1000 galaxy redshifts. This rate of data acquisition is in schedule with our initial predictions, and by the beginning of 1995 we expect to be able to complete a first ‘bright’ sample of \( \sim 400 \) clusters with a flux cut of 0.15 cts s\(^{-1}\). We also expect the final sample to be finished by 1996.

During the observations, we serendipitously discovered two new gravitational arc systems, shown in Fig. 2. Although we routinely collect only very short direct exposures (typically one minute), of those clusters which are candidates for MOS, these were enough for detecting the new arcs. These results are a further indication of the potential advantage of searching for arcs in X–ray selected clusters, as also shown by other recent works (e.g. ref. 24).

![Fig. 2. Left: B image of the supplementary Abell cluster S295, with exposure of 600 s, over a 2.6 arcmin square field centered on the X–ray position. The gravitational arc, with a redshift of 0.93, is the Mexican–hat–like feature next to the elliptical galaxy northwest of the center. Right: R image of the ROSAT cluster RXJ 1347.5-1145 over a 1.4 arcmin square field. The two arclets are evident northeast and southwest of the central galaxy.]

It is relevant to mention here that in the northern sky, a comparable redshift survey is being performed by Huchra and collaborators (see ref. 16). It is planned that at some point both hemispheres will be homogenized to common selection criteria, and the two surveys combined. This will provide an all–sky sample of \( \sim 1500 \) clusters with a typical depth of \( \sim 500 \) h\(^{-1}\) Mpc, which will be invaluable for studies of large–scale structure, in particular the dipole of the cluster distribution.

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