Harvesting the Results from the REFLEX Cluster Survey: Following-up on an ESO Key Programme

H. BÖHRINGER[1], P. SCHUECKER[1], P. LYNAM[1], TH. REIPRICH[1, 4], C.A. COLLINS[3], L. GUZZO[2], Y. IKEBE[1], E. MOLINARI[2], L. BARONE[2], C. AMBROS[1]

[1]Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
[2]Osservatorio Astronomico di Brera, Milano/Merate, Italy
[3]Astrophysics Group, Liverpool John-Moores University, Liverpool, UK
[4]Department of Astronomy, University of Virginia, Charlottesville,USA

1. Introduction

The prime achievement of 20th century cosmology is clearly the establishment of the expanding universe model and the approximate measurement of the parameters, H_0, Ω_m, and Λ_0 governing the dynamics of the expansion and of space-time geometry. This development will practically reach its goal in the next decade with precise measurements of all parameters involved and we will have a good measure of the statistics of the large-scale structure of the dark matter distribution as well. So what is left for cosmological research to do for the 21st century? These results are actually only describing the Universe of the dark matter. But how this invisible Universe is related to the Cosmos we observe with our telescopes is still to a large part an open question. Aiming towards this general goal we are using galaxy clusters as cosmological laboratories to address some of these fundamental questions.

The formation time of galaxy clusters is comparable to the Hubble time. Therefore clusters are still evolving today and their evolution is closely connected to the evolution of the large-scale structure. Clusters are also well characterised laboratories in which the matter composition can be measured and taken to be approximately representative of the Universe, and the galaxy population can be studied in a controlled environment. The most important cluster characteristics is the measurement of the total gravitational mass – which can be determined quite reliably e.g. from X-ray imaging and spectroscopy of the million degree hot intergalactic gas. One of the interesting findings of X-ray astronomy is that there is about a factor five times more mass in this hot gas (~ 17% of the total mass) than in the cluster galaxies (~ 3–4%) in massive clusters. Thus, the majority of the gas seems to be left over and was not used to form galaxies.

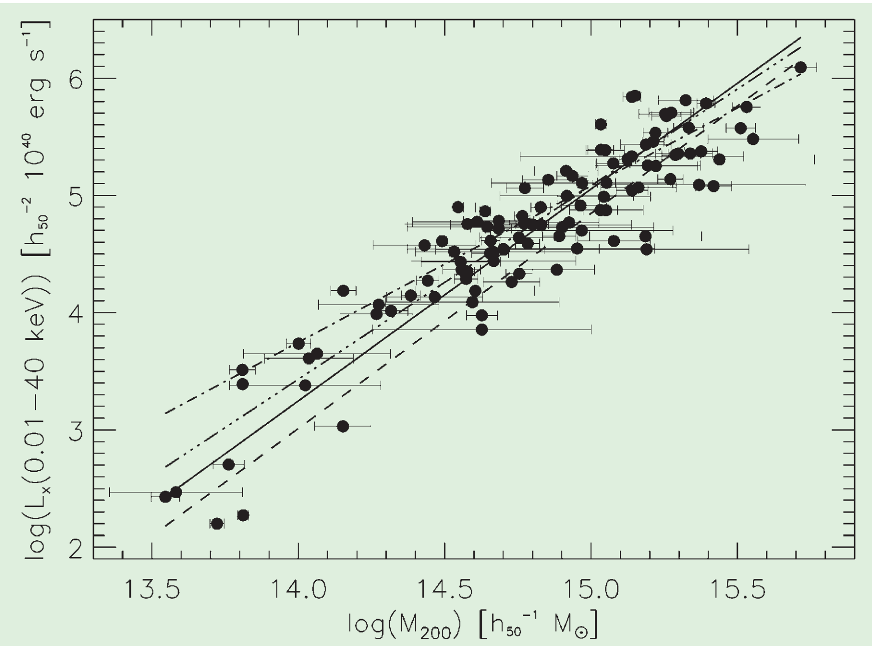


Figure 1: Relation of X-ray luminosity and gravitational mass of the brightest galaxy clusters in the ROSAT All-Sky survey (Reiprich & Böhringer 2001). The mass, M_{200}, was determined inside the virial radius taken to be the radius at which the mean density averaged over the cluster is 200 times the critical density of the Universe.

Therefore some of the major questions that we address with our studies are: How can cluster masses be estimated from easily observable cluster properties? What are the most massive dynamically relaxed objects that we can find in our Universe? How important are clusters and how much mass are they contributing to the matter in the Universe? What are precisely the mass fractions of the galaxies, the hot gas, and the dark matter in clusters, and are there significant system-to-system variations? Are these possible variations linked to variations in the galaxy formation efficiency? How fast do clusters grow at the present epoch by cluster mergers? Does the cluster growth rate depend significantly on the local matter density in the Universe? Are there properties of the galaxy population that are related to the cluster dynamical state, in particular for clusters in a state of merging?

For the study of cluster and galaxy evolution not only observations as a function of time are important, but also the study of the dependence on environment. There are two interesting aspects of the environmental dependence of evolutionary effects. On the one hand, we know from basic cosmological considerations that structure formation is more advanced and continues more vigorously in a denser environment. On the other hand, in a dense environment such as a cluster or protocluster of galaxies we expect a higher frequency of galaxy collisions and galaxy mergers which are believed to be the processes by which at least some of the elliptical galaxies are formed. A particularly important parameter characterising galaxy evolution is the star-formation rate, which can be monitored by optical line spectroscopy. A historic record of star formation is also contained in the abundances of heavy elements that can be derived from the occurrence of element lines in the X-ray spectra of the intracluster gas. These elements are solely produced by stellar processes (notably supernova explosions). Therefore it is important to ask if there are correlations of cluster properties, properties of the galaxy population in the clusters, and element abundances as a function of location in the cluster and from system to system, that could guide our understanding of the evolution of these components.

To answer these questions, we are conducting a series of systematic studies on galaxy clusters. A progress report with preliminary results is given in the subsequent sections. Such studies should not be conducted on any cluster that is found to have an appealing appearance, but we have to know for each study object what part of the cluster population and which characteristics of the large-scale structure it represents. Therefore the basis of our work is a detailed census of the galaxy cluster population in the Universe out to intermediate redshifts ($z \sim 0.4$) that we achieved with the REFLEX (ROSAT-ESO Flux-Limited X-ray) Cluster Survey. The survey was conducted as an ESO key programme based on X-ray selected galaxy clusters providing a highly complete X-ray flux limited cluster sample. With the X-ray flux limit we are essentially sampling the most massive clusters in each redshift shell (as will be explained below). The prime goal of the REFLEX survey is the assessment of the large-scale structure. This was previously described in *The Messenger* (Böhringer et al. 1998, Guzzo et al. 1999). The most important information retrieved from the large scale structure measurement is given in a statistical form by the X-ray luminosity function of the REFLEX clusters (Böhringer et al. 2002), the two-point correlation function (Collins et al. 2000), and the density fluctuation power spectrum (Schuecker et al. 2001a). This analysis provides the most important scientific result that the observations are only consistent with a mean matter density of the Universe clearly below the critical limit above which the Universe would recollapse in the future. The allowed range of the density parameter is roughly, $\Omega_m = 0.12h^{-1} - 0.26h^{-1}$ (where h is the Hubble expansion parameter in units of 100 km s^{-1} Mpc^{-1}). Thus the REFLEX programme has made an important contribution to the above-described achievement in cosmology in the last century.

For the follow-up work described below, REFLEX is now providing a highly complete cluster catalogue from which the most appropriate clusters for study can be selected.

2. Weighing the Galaxy Cluster Population

The theoretical description of structure formation as well as N-body simulations of the evolution of the dark matter Universe both describe galaxy clusters by their basic parameter, their mass. Therefore, to interpret our observations in terms of cosmological models, we need to know the link between cluster mass and X-ray luminosity. The cluster mass is not an easily observable parameter, however, but it can be deduced for example from detailed X-ray observations on the density and temperature distribution of the hot, X-ray emitting intracluster gas and the estimation of the gravitational potential needed to hold this hot gas in place. We have used such detailed X-ray observations for the 63 brightest galaxy clusters in the REFLEX catalogue and its northern complement, the NORAS Cluster Sample (Böhringer et al. 2000) to determine the masses of the clusters and to establish the correlation properties of mass and X-ray luminosity (Reiprich & Böhringer 2001). The resulting diagram is shown in Figure 1. Indeed we find a very good correlation of the two cluster properties, and the systematic study also allows us to characterise the scatter. This correlation and its scatter is an essential ingredient for the modelling of cosmological tests with the REFLEX cluster sample (see e.g. Schuecker et al. 2001a).

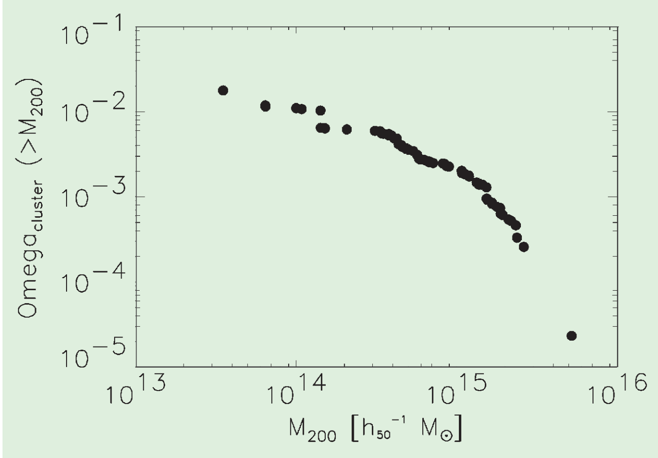


Figure 2: Cumulative mass density function of galaxy clusters normalised to the density of a critical universe ($\Omega_{cluster} = \rho_{cluster}/\rho_{critical}$; Reiprich & Böhringer 2001).

Since the clusters used in this study form a complete flux-limited sample, we can also construct the mass function of clusters. A very interesting result comes from the integral of the mass function, normalised to the mean density of a critical universe as shown in Figure 2. We observe that the matter density bound in clusters with a mass above $\sim 6.4 \cdot 10^{13}$ $M_\odot$ is about 2% of the mean density in a critical density universe. For the currently most favoured cosmological model with a density parameter $\Omega_m \sim 0.3$ we find that clusters contain presently about 6% of the total matter in the Universe (Reiprich & Böhringer 2001).

3. Going to Extremes

One of the interesting aspects of large surveys is the discovery of rare but important objects. During the REFLEX survey the so far X-ray brightest galaxy cluster RXCJ1347-1145 and the so far hottest galaxy cluster, RXCJ0658-5557 were discovered (the latter was independently found in the *EINSTEIN* Slew Survey by Tucker et al. 1995). The high temperature of the cluster RXCJ0658-5557 was first found in ASCA follow-up observations, with results of ~ 17 keV (Tucker et al. 1998) and around 14–15 keV in an analysis conducted by us (see also Andreani et al. 1999) making this cluster the record holder for the highest temperature, superseding the previous incumbent, A2163. The high temperature also suggests that this may be the most massive gravitationally relaxed object discovered to date.

Therefore we applied for a deep X-ray study of this object with XMM-Newton, an observation that was conducted recently. Figure 3 shows an image of the observation with the EPN detector on board of XMM. The cluster is obviously featuring a merger of two subcomponents, since we know already from the deep ROSAT HRI observation that both maxima visible in Figure 3 are associated with extended X-ray emission. The high throughput of XMM-Newton allows us to collect enough photons (in a useful exposure time of ~ 14 ksec in the present case) to perform a spectral analysis for several concentric rings in the cluster and to get a good temperature estimate. Figure 4 shows a very preliminary temperature profile from an analysis centred on the maximum of the Eastern main cluster while the Western cluster component was excised. The temperature profile shows that the cluster is indeed very hot around 13–15 keV over a large radial range to at least $0.6h^{-1}$ Mpc. Note that the results are preliminary and the cause of the temperature drop seen in the outermost bin still has to be explored in detail, since it could be an artefact of the very delicate background subtraction in the faint surface brightness region at large radii. From the temperature profile and the gas density distribution obtained from the X-ray image under the assumption of spherical symmetry we can estimate the cluster mass. Inside a radius of $1.5h^{-1}$ Mpc we find a mass of about

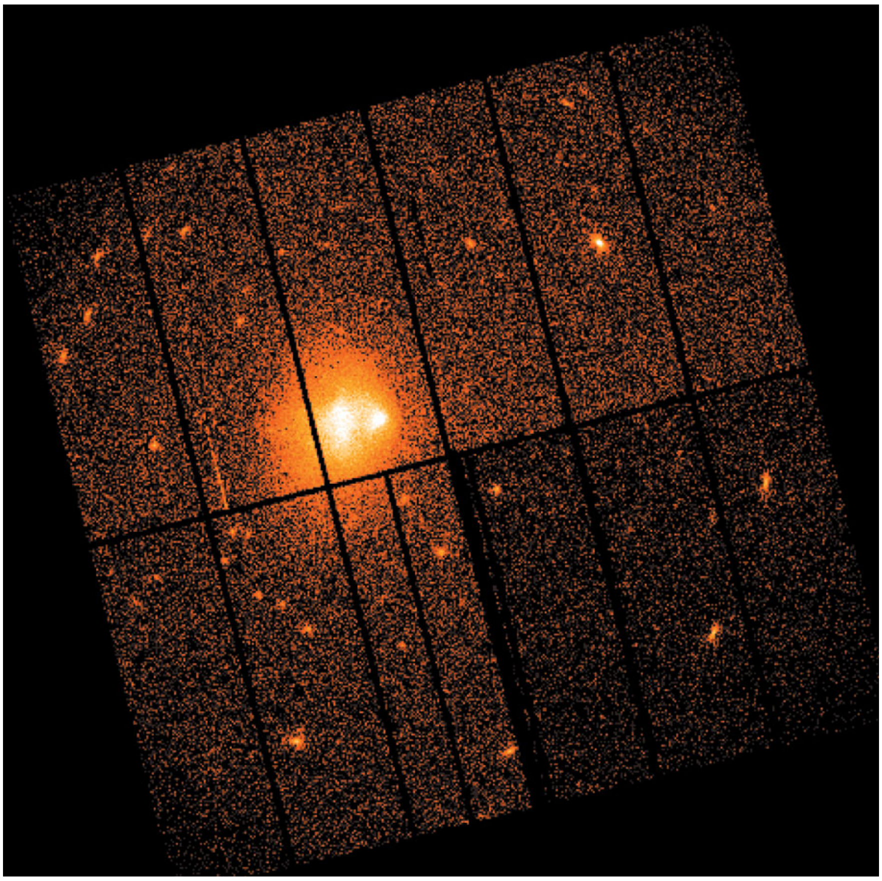


Figure 3: XMM Newton image of RXCJ0658-5557 taken with the EPN X-ray CCD detector in the energy range 0.5 to 5 keV.

$3 \cdot 10^{15}$ $M_\odot$. The virial radius of the cluster is estimated to lay at around $2.5h^{-1}$ Mpc out to which the integral mass may by higher by another factor of two, but we have no observational data that extend so far out. With these numbers this cluster is the most massive dynamically relaxed object known in our Universe. We can use our census of the cluster population to ask how large the search volume has to be to find such a rare, massive cluster. We conclude that one such object should be found in a volume of a few Gpc^3 h^{-3}. Considering that these very massive objects have formed only recently and that the chance to observe them at larger distances becomes increasingly smaller, there should only be a few of these massive objects in the whole visible Universe.

4. The Statistics of Cannibalism

We know from observations as well as from N-body simulations that galaxy clusters evolve and grow by the subsequent merging of subunits. Within the theoretical framework of gravitational growth of structure we expect that the present rate at which clusters merge is a function of the mean matter density of the Universe. Thus in a critical density universe there will at any time be overdense regions which are bound to collapse, while in a universe with low density the growth of structure will essentially be stopped when the density parameter, Ω_m, starts to diverge from unity. What is true for the Universe on average should also be true for large, local regions of higher or lower density. Therefore, we can use density variations in the very large-scale structure to test this structure formation paradigm.

The REFLEX survey is the first survey large enough and sufficiently well defined to perform such a study. The first, quite difficult step of the study is to develop an index for the likelihood that a cluster is in a state of merging. This index was derived from the X-ray morphology of the clusters as seen in the ROSAT All-Sky Survey for the brighter part of the REFLEX sample and for northern clusters (Schuecker et al. 2001b). Figure 5 shows two examples, a merging cluster and a well-relaxed system. These examples are among the best in the sample, being bright and characterised by a large number of X-ray photons. Unfortunately the exposure time for each cluster in the ROSAT Survey is only a few hundred seconds and therefore we have only typically a hundred to few hundred X-ray photons. Therefore regular clusters and mergers cannot be identified with certainty and the derived index has to be considered primarily as a statistical measure.

Figure 6 shows the statistical results of the study based on the two indices found to be most efficient, the β-method which tests for mirror symmetry and the Lee-Statistics which is sensitive to asymmetric substructure (Schuecker et al. 2001b). The parameter shown in this plot is the significance that the cluster is regular (and unlikely to be a merger) as found in two different tests. This parameter is plotted as a function of the cluster density, where the cluster density was derived from the mean distance to the five nearest neighbours. Each data point in the plot is the mean significance value of a number of clusters falling into the density interval. We clearly note that the mean significance for the clusters to be regular is decreasing with the local cluster density. Thus the likelihood to find cluster mergers is highest in the densest regions, as expected from theory.

A closer look shows that this signal is not only providing statistical information. An inspection of the location of those clusters which have a high significance to be mergers shows that these objects lay predominantly in prominent superclusters as can clearly be seen in Figure 7. The most striking structure of the dense clustering regions is the well-known Shapley Supercluster at a redshift of about 0.05 (a velocity of about 15,000 km s^{-1}).

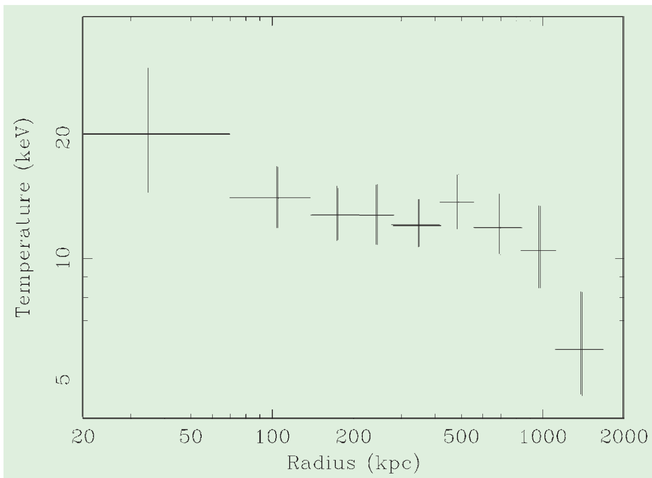


Figure 4: Temperature profile of the hot intra-cluster gas of RXCJ0658-5557 as obtained from the recent XMM Newton observation. The radial scale is given for a Hubble parameter of, H_0 = 50 km s^{-1} Mpc^{-1}

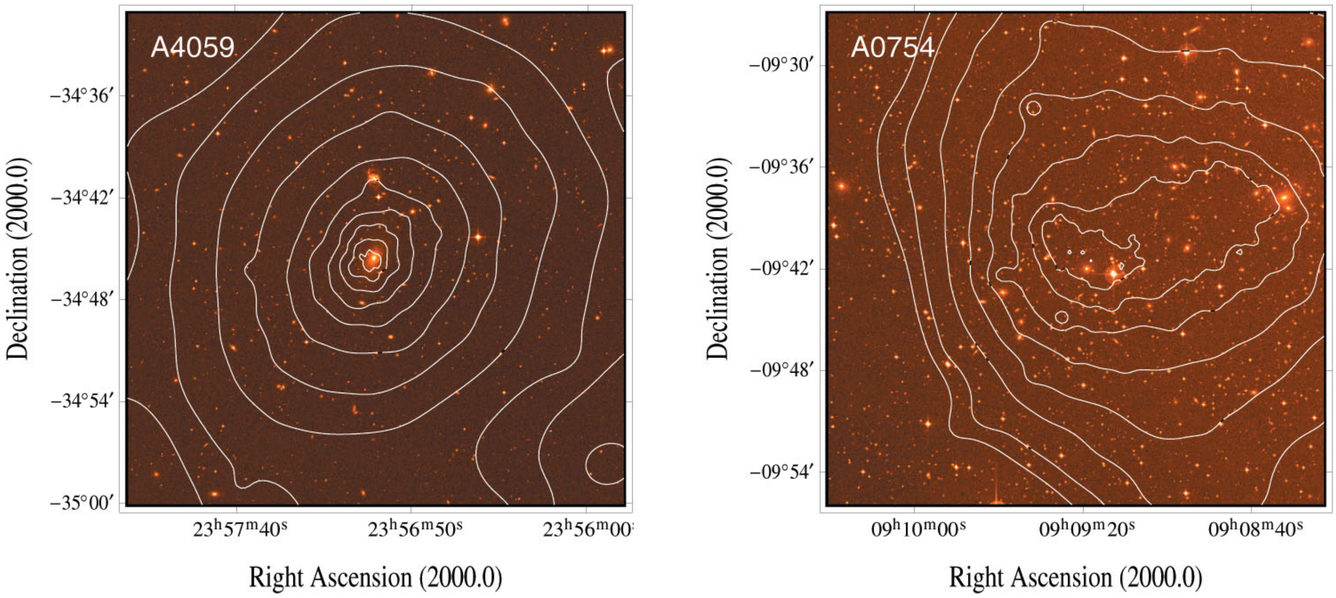


Figure 5: Example of a clearly regular cluster (left) and merging cluster (right). These clusters are among the brightest examples in the REFLEX sample.

5. Probing Large-Scale Motions

The observation of large-scale peculiar flows in the Universe is a very important addition to the study of the large-scale matter distribution. The knowledge of both allows us to investigate the origin of peculiar velocity and to test the paradigm that the flows are caused by the gravitational effects of the density inhomogeneities. The prerequisite for the study of peculiar motion patterns is the establishment of an absolute distance indicator that together with measured redshifts allows us to reconstruct the cosmic flows. Traditionally the brightest cluster galaxy (BCG) has been used as such a distance indicator since the pioneering time of Hubble. The method is based on the recognition that BCGs span a relatively small range of absolute magnitudes.

A few years ago a refined use of BCGs as distance indicators was applied to the study of streaming flows. The refinement is based on the finding that the absolute magnitude of BCGs is correlated to the structure of the galaxies, best characterised by the slope of the surface brightness profile with the slope parameter, α. This correlation can be used to reduce the uncertainty in the BCG distance estimate (Lauer & Potsman 1994). From the study of the “Abell Cluster Inertial Frame” involving 119 Abell clusters Lauer & Postman found very surprisingly a large-scale streaming velocity of 689 ± 178 km s^{-1} on scales of ~ $120h^{-1}$ Mpc pointing in a direction more than 90 degrees away from the streaming direction indicated by the cosmic microwave background dipole. Thus, both the direction and the magnitude of this effect on these large scales is unexpected in standard cosmological modelling. Several follow-up studies tested the method of Lauer & Postman and did not find an error in the method.

We have therefore embarked on a similar survey now including the X-ray information on the clusters involved (Lynam et al. 2002). The survey sample is constructed from the brightest REFLEX and NORAS Abell and Abell, Corwin & Olowin clusters. In contrast to the earlier studies the BCG candidate was selected to be the brightest elliptical galaxy closest to the centroid of the X-ray emission – which is marking the centre of the gravitational potential of the clusters. In most cases the X-ray luminous clusters have a bright, dominant central galaxy and the identification of the BCG is unambiguous. Only in a handful of cases the coincidence of the X-ray maximum and the BCG position is less obvious. The first interesting finding of this study comes from a comparison of the BCGs identified for the objects in common with the Lauer & Postman survey. In 14 out of 57 common objects the optically selected BCG taken by Lauer & Postman was located far from the X-ray maximum, and in three cases the redshift of the BCG and the cluster differs. Figure 8 shows with Abell 147 one of the examples of different BCG identification. In 80% of these cases Lauer & Postman find a low α-parameter while in the present work always a significantly higher α-value was found (Lynam et al. 2002).

This leads to the second crucial finding. Figure 9 shows the distribution of α-parameters as found in the Lauer & Postman (1994) survey in comparison to the present work. There is a clear difference in the distribution of α in the samples. The major difference is that the present sample lacks the systems with low α and has a much more compact distribution function. This is very suggestive of the observation of two different galaxy populations, X-ray coinci-

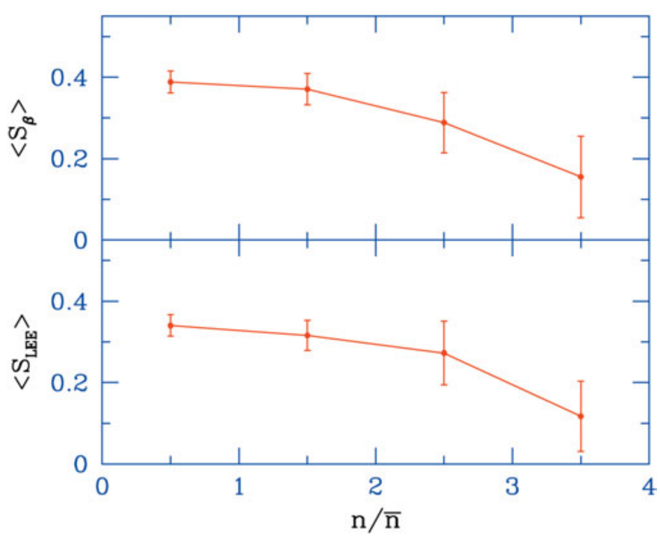


Figure 6: Mean significance of clusters to be regular as a function of local cluster density. Each data point is the mean result for a subsample of clusters. The statistics shows a clear trend that cluster merging occurs more frequently in dense large-scale structure regions.

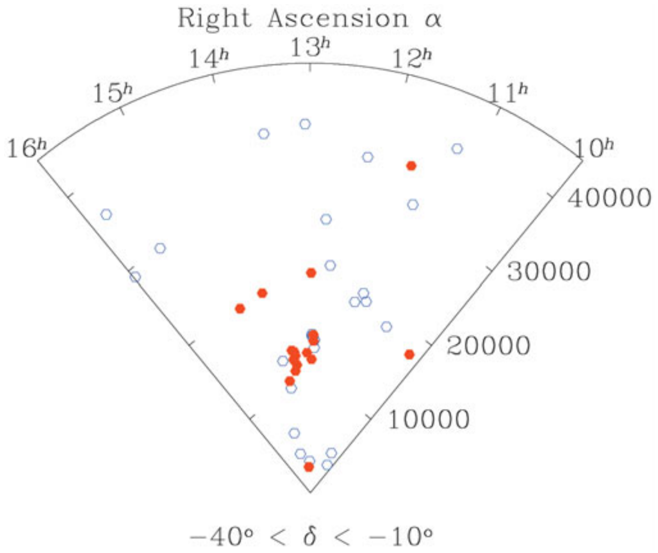


Figure 7: Spatial distribution of the clusters which show a high significance of being regular (open blue dots) and low significance (red dots). There is a clear concentration of the likely merging clusters in dense superstructures. The densest concentration in the plot is the Shapley Supercluster.

dent BCGs and other bright cluster galaxies, which are characterised by different distributions of the α-parameter. While the present sample contains only the X-ray BCG population with a seemingly Gaussian α-distribution, the Lauer & Postman sample is presumably composed of a bimodal population. This is also revealed by some other contemporary studies. A major aim of our further work in this project is therefore to establish more clearly this population difference. The Wide-Field Camera cluster survey described in the next section is particularly useful for this work.

Taking now this population difference into account and re-inspecting the α-luminosity correlation shows that for the X-ray BCGs there is no correlation effect, and therefore no improvement on the distance estimate for these galaxies is possible. The preliminary results of our survey, based on this revision of the method and on the sample of 173 clusters, do not show a significant signal of a large-scale streaming flow (Lynam et al. 2002). This is supported by almost all other independent tests not confirming the Lauer & Postman streaming signal and consistent with the expectations within the standard model..

6. Galaxy Demography

Working with galaxy clusters, it is of course most interesting to know what the clusters are made of and in particular what is the mass ratio of the two forms of visible matter, the hot gas and the galaxies, and the mass-to-light ratio. Are these ratios variable indicating that galaxy formation can be different in different clusters? To answer these questions we are conducting a detailed combined X-ray/optical study of a well selected subsample of massive REFLEX clusters at intermediate redshifts (z = 0.14–0.45) using XMM-Newton observations and the Wide-Field Imager (WFI) at the MPIA/ESO 2.2-m telescope. Having with a large effort finally tackled the reduction of dithered mosaic images and having the first XMM observational data sets at hand we can start our comparison. A first example of these combined observations is shown in Figure 10, the massive REFLEX cluster RXCJ1131.9-1955 at a redshift of z = 0.306. The image is a colour composite produced from exposures with B, V, and R filters. The image is showing a fraction of about 6% of the total mosaic frame. The zooming was chosen to still allow the recognition of galaxy images.

In the further analysis the galaxies are identified and separated from stars by their shape with the object recognition software S-EXTRACTOR (Bertin & Arnouts 1996). In Figure 11 we show the distribution of the objects identified as galaxies with symbols indicating their magnitudes and elongations. The cluster concentration is well visible in this image. The image scale is 26.4 × 30.5 arcmin^2 (4.4 × 5h^{-2} Mpc^2) compared to a virial radius of the cluster which is estimated to be about 1.8–2h^{-1} Mpc. The image is thus covering the whole cluster as virialised object as well as some surrounding background. The image suggests that there is filamentary structure stretching out from the cluster beyond the virial radius. The significance of these structures will be addressed with photometric redshift estimates as well as with further redshift work (see below). Also overlayed on this image are the surface brightness contours of the X-ray image obtained for this cluster with XMM-Newton. The original XMM EPN image is also shown in Figure 12. The morphology of the cluster is traced in a similar way by the hot gas as well as the galaxy component of the cluster. This implies that presumably both components are well tracing the gravitational potential and thus the dark matter distribution. We see a massive compact cluster core in the centre of the image

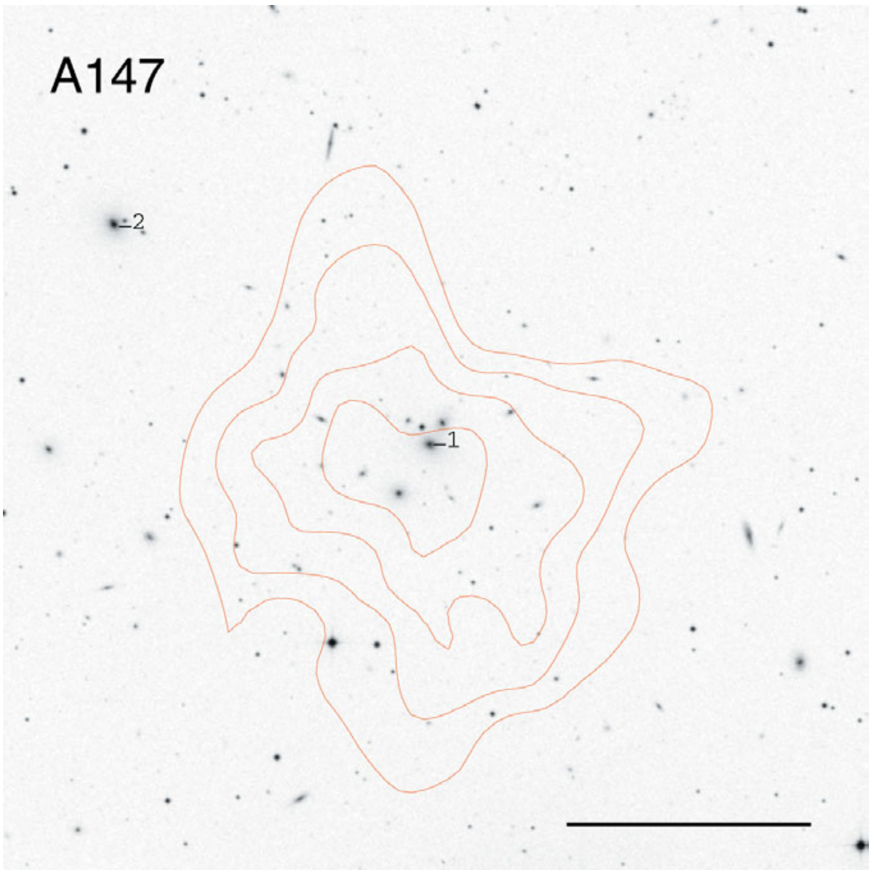
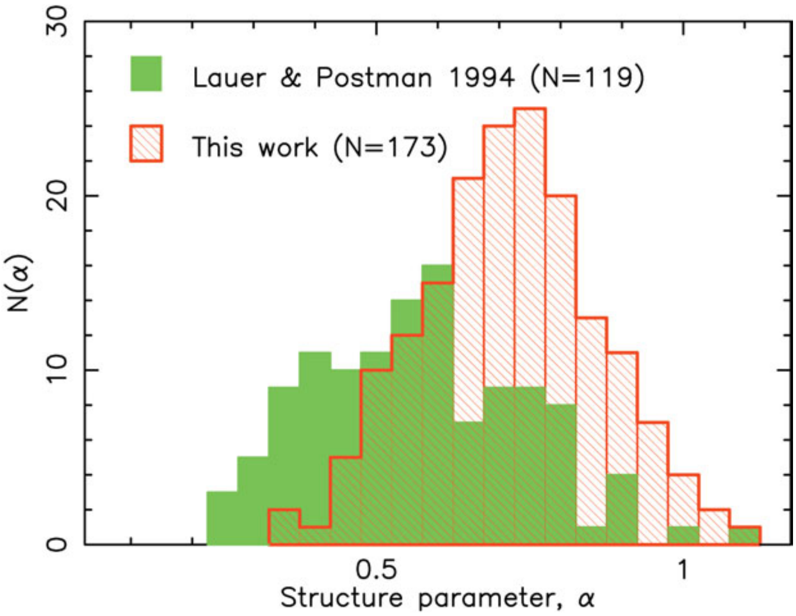


Figure 8: Example of an optically misidentified BCG in the Lauer and Postman (1994) sample. Position 1 marks the X-ray coincident BCG, while the optically selected BCG of Lauer & Postman is at location 2.



◀ *Figure 9: Distribution of the shape parameter, α, for the Lauer & Postman (1994) sample and the work by Lynam et al. (2002). There is a clear difference in the two distributions. Most remarkable is the extension towards low values of the α-parameter in the Lauer & Postman sample which gives this distribution a bimodal appearance and which does not appear in our survey.*

Figure 10: Central region of a MPIA/ESO 2.2-m WFI image of the distant REFLEX cluster RXCJ1131.9-1955. The size of the image is ~ 8.12 × 8.12 arcmin². For the production of the colour image we used a programme kindly provided by J. Engelhauser. ▼

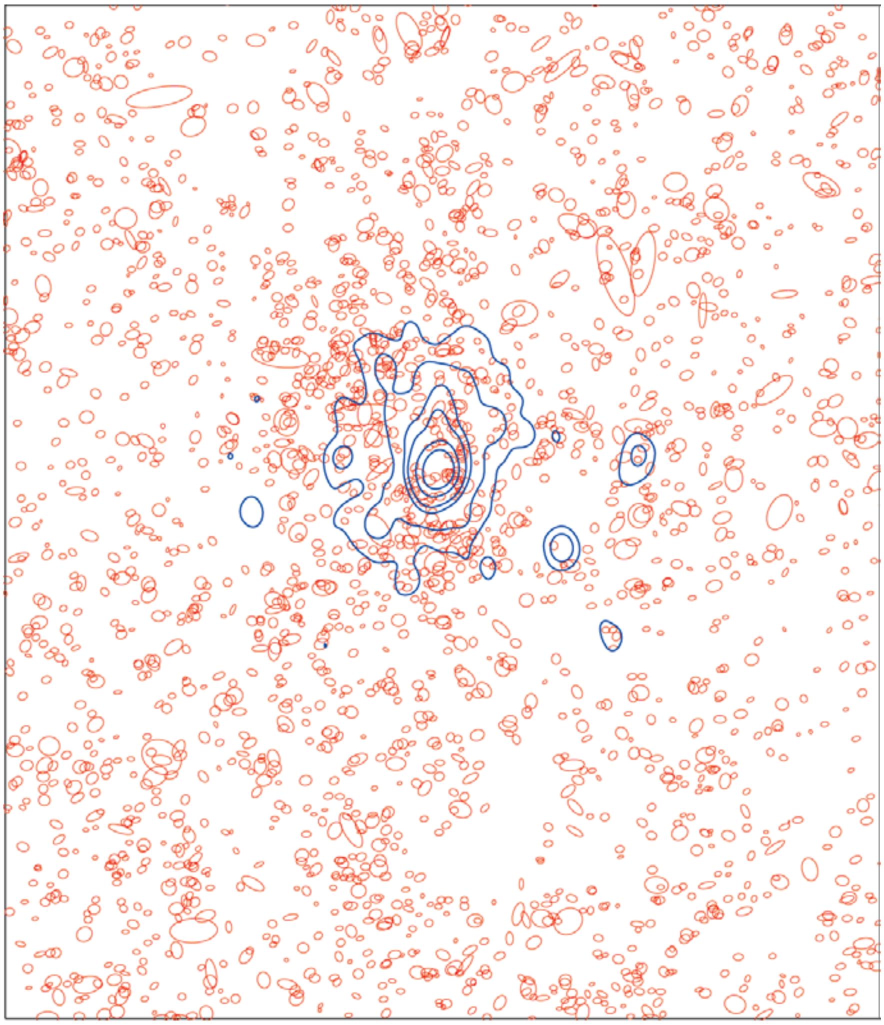


Figure 11: Galaxy distribution in the field of the cluster RXCJ1131.9-1955 as identified in the image shown in Figure 10 displayed by symbols indicating the brightness and orientation of the galaxies. The blue contours show the surface brightness distribution of the XMM EPN X-ray image. This figure illustrates that the hot X-ray emitting gas and the galaxies are displaying a very similar morphology due to the fact that both cluster components are tracing the same gravitational potential.

and a second slightly more diffuse cluster component stretching out to the North-East.

To assess the gravitational mass of this cluster we use the hot gas density profile obtained from the X-ray image and the temperature distribution in the hot gas derived from the X-ray spectra (the temperature profile is similar to that shown in Figure 4 but indicating a bulk temperature around 7 keV). From this very preliminary analysis we estimate a mass of about $2 \cdot 10^{15}$ $M_\odot$ within a radius of $1.5h^{-1}$ Mpc.

This is only one of a well-selected sample of 16 REFLEX clusters which have already been scheduled for XMM-Newton observations and which we are also studying and plan to study in the optical. The results of these studies will provide very important details on the cluster composition, dynamical state, and galaxy population of these systems and on the system-to-system variations. They will also help to solve another important problem. Selecting galaxy clusters in X-rays and in the optical yields quite different clusters samples e.g. only about two thirds of the REFLEX catalogue are clusters found by Abell and co-workers (1958, 1989), while these optical catalogues find about five times as many clusters in the REFLEX area as contained in REFLEX. While the X-ray emission clearly flags a three-dimensional mass concentration, the optical identifications are expected to be partly due to projection effects. Therefore, it is very important to understand the relation between the appearance of clusters in the two-wavelength regimes and why there is such a difference. For this we need to include morphological parameters in the optical and X-rays and to look for their correlation properties. We already know that cluster compactness plays a crucial role in these relations. The final goal here is to provide the means to predict from the well-characterised ap-

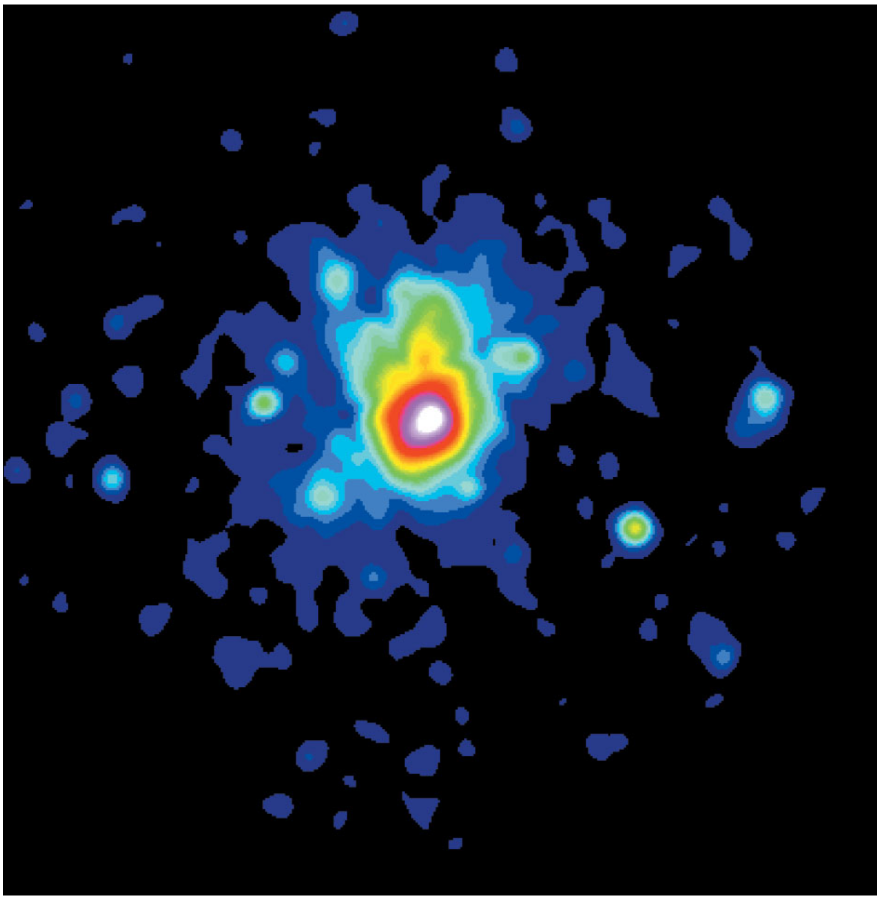


Figure 12: XMM-Newton EPN image of RXCJ1131.9-1955. The image was smoothed by a Gaussian filter with σ = 16 arcsec.

pearance of the cluster in one wavelength band its properties in the other. This would be very valuable for the many planned future surveys either in X-rays or the optical.

To extend this work to the study of star-formation rates as a function of galaxy and matter density in the cluster environment, a closer inspection of the dynamical state of clusters by comparison of optical velocity data and X-ray results, and a better understanding of the connection between the cluster structure and the large-scale structure filamentary network, we have proposed detailed spectroscopic studies with the forthcoming VIMOS instrument. Of the order of 2000 galaxy spectra could be obtained in less than one night, providing an unprecedented spectroscopic census of the galaxy population of the clusters and their surroundings almost into the dwarf regime. This in-depth study is bound to provide new insights into cluster as well as galaxy evolution.

7. Outlook

Having now well tested the reliability of the REFLEX catalogue by a series of investigations and having demonstrated its scientific value, not least by the studies described here, we are preparing the publication of the catalogue of the REFLEX I Survey as conducted within the frame of the ESO key programme "A Redshift Survey of Southern ROSAT Clusters of Galaxies" prospectively for January 2002. This survey is restricted to a flux limit well above the depth of the ROSAT All-Sky Survey which guarantees that clusters are still well characterised as X-ray sources. We have explored the value of a further extension of the REFLEX Survey and found that it is still possible to essentially preserve most of the sample quality while extending the flux limit from presently $3 \cdot 10^{-12}$ erg s^{-1} cm^{-2} to a value of $\sim 1.8 \cdot 10^{-12}$ erg s^{-1} cm^{-2}. This increases the sample from currently 452 to about 900 clusters providing a significantly higher precision for the measurement of large-scale structure and cosmological parameters. We have already embarked on this extension with the REFLEX II programme and so far conducted three further observing runs at the ESO 3.6-m telescope. A number count diagram of the clusters and cluster candidates is shown in Figure 13. It illustrates how little is left to complete the survey with a high degree of completeness. With about three further campaigns we can finish this extension project.

We could continue describing further important REFLEX-based studies. In particular the extended sample, taken together with NORAS, which will provide a denser sampling of the cluster distribution in space will allow us not only to improve the statistical measures of large-scale structure but also to look, for example for alignment effects, supercluster structure, and to attempt a three-dimensional reconstruction of the dark matter distribution. In addition the cluster catalogue will serve as a shopping list for many future studies of cluster physics.

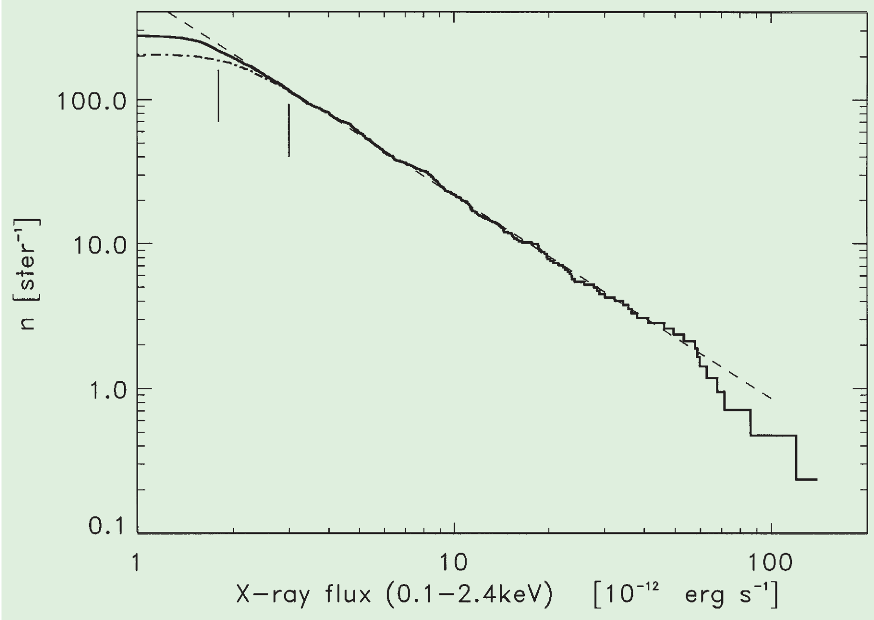


Figure 13: Number count sky density of the REFLEX II survey clusters and cluster candidates as a function of X-ray flux. The solid line gives the total list of clusters and still-to-observe cluster candidates, while the dashed line designates the confirmed clusters with redshifts. The thin line indicates a logarithmic slope of –1.4, the slope approximately expected for a complete sample. The two vertical bars indicate the flux limit of REFLEX and the prospected flux limit of REFLEX II, $1.8 \cdot 10^{-12}$ erg s^{-1} cm^{-2}. Note, that a high completeness is still to be expected for REFLEX II flux limit.

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