Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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X-ray galaxy clusters in the large-scale structure

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Abstract. In this contribution we investigate the connection between clusters of galaxies and their large-scale environment, with an emphasis on clusters which are well characterized by their X-ray emission. We show that this connection is so tight that clusters can be used as perfect tracers of the large-scale matter distribution and thus for cosmological tests. The correlation of the X-ray traced cluster mass and the optical luminosity of the galaxy content of clusters shows that the dark matter and galaxy distribution are tightly connected, but we also observe a scatter which is so far not well understood. We further explore the correlation of the galaxy population mix with the geometry of the large-scale structure features. On larger scales we also find correlations of the properties of galaxy clusters with the density of their large-scale structure environment.

1. Introduction

Galaxy clusters as the largest well defined cosmic building blocks have dynamical time scales of Gigayears not much smaller than the age of the Universe as a whole. Therefore many of their properties are still reminiscent of the density fluctuations which were set as initial conditions in the early Universe, triggering the formation of the large-scale structure (LSS). Galaxy clusters thus form an integral part of the LSS. As shown in several talks at this conference their internal properties are connected to the surrounding LSS and the cluster outskirts are controlled by the interplay between the clusters and their cosmic environment.

In this contribution we illustrate some of these connections. We will investigate how well galaxy clusters trace the underlying large-scale matter distribution in the Universe. In the following section we provide an account of our understanding how well the main mass component, the dark matter, follows the same distribution as the optically visible component, the galaxies. We find a good correlation of the light and mass distribution but also some scatter that is most probably larger than the uncertainties in the measurement.

The next degree of detail in the galaxy distribution then concerns the mixture of galaxy types. There is a well known morphology-density relation, with an increasing fraction of early type galaxies in the denser environments – a topic that was touched by several talks at this meeting. From a slightly different point of view we search for a correlation of the mixture of galaxy types with the geometry of the structure in which the galaxies are embedded. Is there a significant difference of galaxy types if one is looking for example into a filament, a sheet of galaxies, or into the field?

In the final section we make a similar study one step up in the structural hierarchy of the Universe: we investigate if there is a significant correlation of the average properties of galaxy clusters with the density of the LSS environment. In the contribution to this meeting by Manolis Plionis it was for example shown that there is a clear correlation of the position angles of cluster ellipticities and the orientation of LSS features. In our

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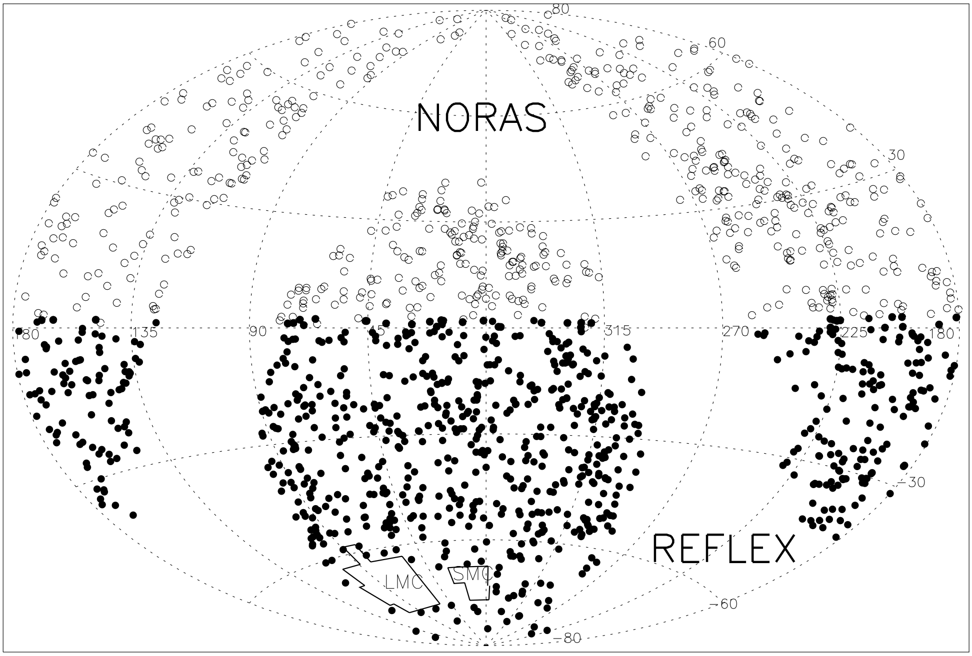

Figure 1. Sky distribution of the X-ray detected clusters in the ROSAT All-Sky Survey for a flux limit of 1.8×10^{-12} erg s^{-1} cm^{-2} in the South and 2×10^{-12} erg s^{-1} cm^{-2} in the North as far as they have been identified up to date.

study we find a correlation of the large-scale matter density with the frequency of cluster substructure and the X-ray luminosity function of galaxy clusters.

2. Galaxy clusters as tracers of the large-scale matter distribution

Structure formation theory predicts galaxy clusters to be ideal tracers of the large-scale matter distribution (e.g. Moscardini et al. 2000). As an additional advantage the clusters follow the amplitude variations in an amplified way (an effect called biasing) which facilitates the assessment of the LSS statistics in the presence of the unavoidable Poissonian noise. To make use of this very important property of the cluster population one needs to select clusters in a highly complete way above a given cluster mass threshold, which is an observational challenge. So far X-ray detections of clusters have been shown to be the best and most effective way for this selection (e.g. Henry et al. 1992). This is possibly due to the fact that the cluster mass and the X-ray luminosity are well correlated, however with enough scatter in the relation that it necessarily has to be taken into account (Reiprich & Böhringer 2002). The so far best basis for an X-ray cluster survey covering a large volume is the ROSAT X-ray All-Sky Survey (Trümper 1993). Within long term survey projects for the northern (NORAS Survey) and southern sky (REFLEX Survey) we have identified and obtained redshifts for more than 1400 X-ray galaxy clusters above a flux limit of 1.8×10^{-12} erg s^{-1} cm^{-2} in the South and 2×10^{-12} erg s^{-1} cm^{-2} in the North. Both samples are close to completion at these limits, but some further identification work is still necessary. The core parts of the REFLEX and NORAS survey

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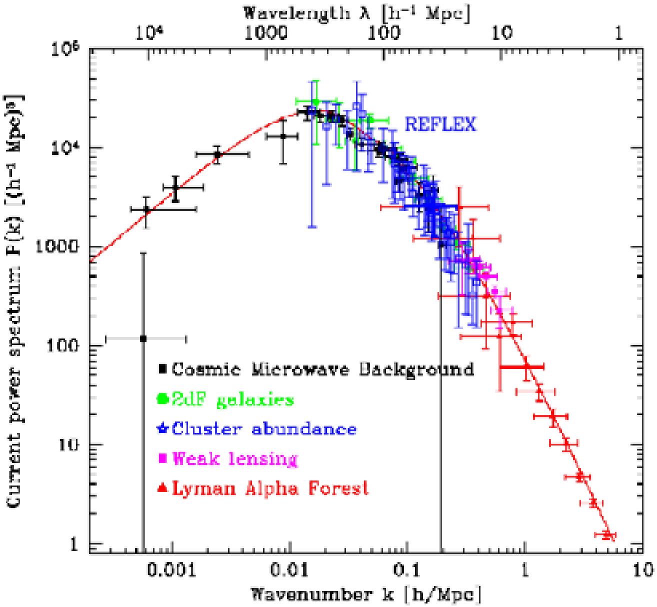

Figure 2. Power spectra for comoving coordinates of the mass density fluctuations as traced by various visible objects. Onto this plot, originally prepared by Max Tegmark, the REFLEX results from Schuecker et al. 2001a have been added.

are published (Böhringer et al. 2000, 2001, 2004). The sky distribution of the clusters from the combined catalogue at the stage of April 2004 is shown in Fig. 1.

This cluster sample, notably the core of the REFLEX Survey (REFLEX 1) has been used extensively for the assessment of the large-scale structure through the X-ray luminosity function (Böhringer et al. 2002), the two-point correlation function (Collins et al. 2001), and the power spectrum as well as Kurhunen-Loeve decomposition (Schuecker et al. 2001a, 2002a, 2002b, 2003). The results show that the X-ray luminosity function of clusters (a substitute of the mass function) and the spatial distribution of clusters (as described statistically by the density fluctuation power spectrum) is very closely bracketing the predicted statistical parameters describing the LSS in the concordance cosmology model (Turner 2001). The best constraint is obtained for the parameters $\Omega_m = 0.27 - 0.43$ and $\sigma_8 = 0.55 - 0.83$ (the amplitude parameter of the large-scale mass density fluctuations measured on a scale of $8h^{-1}$Mpc - Schuecker et al. 2002b).

Fig. 2 shows how the bias corrected cluster density fluctuation power spectrum fits to the other measures of LSS at different scales. There is a very good overall agreement in spite of the fact that the different measurements are assessing the LSS at different epochs and the proper cosmological model has to be applied to convert the different measurements into the correct comoving reference frame. Therefore, from these results we conclude that cluster trace the large scale structure in a perfect way as predicted by purely gravitationally driven CDM structure formation models.

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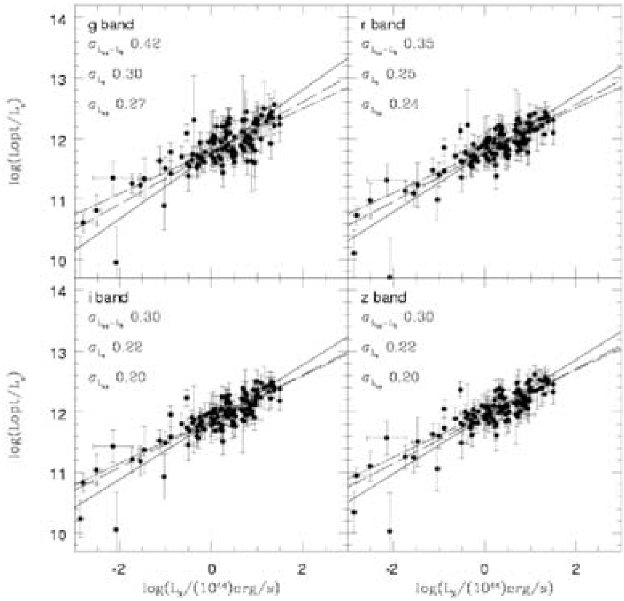

Figure 3. Correlation of the cluster X-ray luminosity with the optical luminosity measured in a $0.7h_{70}^{-1}$ Mpc aperture for the sample of ROSAT-SDSS clusters. The four panels show the results for four of the SDSS colour bands.

3. On the correlation of the galaxy and dark matter distribution

Large-scale galaxy redshift surveys, as the 2dF survey and the Sloan Digital Sky Survey (SDSS), have shown that the light is distributed in a very similar way as the dark matter and that the so-called biasing parameter for the galaxy distribution is close to one (e.g. Peacock et al. 2001). Is this also true for the galaxy and optical light content of galaxy clusters and their surroundings? This question was also raised in other talks at this conference, e.g. in the contribution by K. Rines. The size, precision, and homogeneity of the SDSS provides a new uniquely comprehensive approach to this quest. Based on the galaxy clusters detected in the NORAS and REFLEX surveys overlapping with the SDSS sky region we have performed a systematic comparison of the X-ray and optical properties of galaxy clusters added by a smaller sample of groups that have also been studied in X-rays with ASCA. A first important question to be answered by this study is: in which way can the measurement of the cluster light and the X-ray luminosity determination be combined such that the correlation of the two cluster properties shows the least scatter? That is, how can we best determine the properties in the optical to provide the highest accuracy in predicting the X-ray luminosity? The simplest and most straightforward way to determine an optical light measure is the integration of the background subtracted light of the cluster in a fixed metric aperture. A survey of different aperture parameters and different optical colors shows that the least scatter in the optical/X-ray correlation is produced by an aperture size of $0.7h_{70}^{-1}$ Mpc and the z-band (the reddest band) of the SDSS. The scatter in the i-band is similarly low (Popesso et al. 2004). Fig. 3 shows the correlation for the best correlating aperture for the 4 colors of the SDSS. The scatter in the relation in both directions is about 60% for both z-band and the i-band. We estimate that not much more than half of this scatter is due to uncertainties in the X-ray and optical luminosity measurements. Thus a significant fraction of this scatter is intrinsic.

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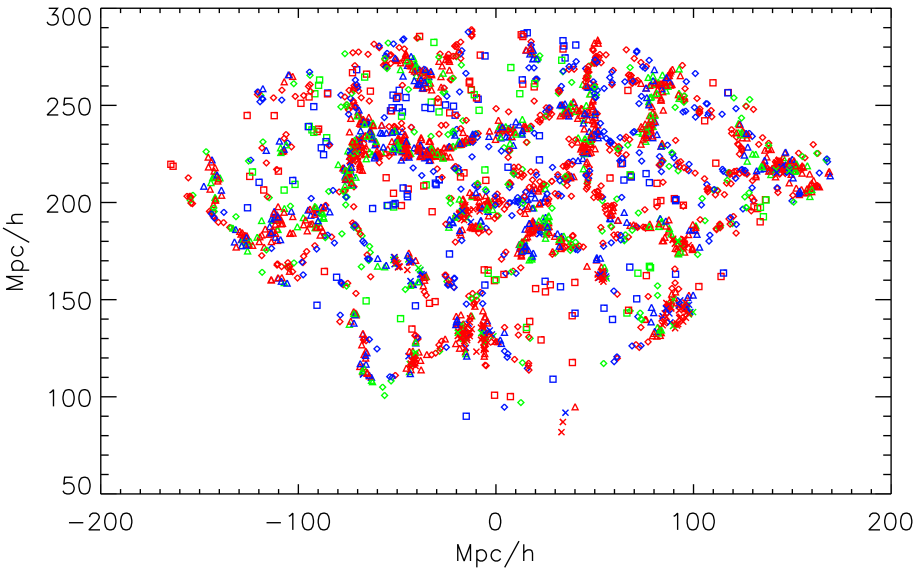

Figure 4. Distribution of galaxies with measured redshifts in a slice through the SDSS survey. The galaxies are sorted into scaling indices bins marked by symbols (crosses: $\alpha \leqslant 1.2$, triangles: $\alpha = 1.2 - 1.7$, diamonds: $\alpha = 1.7 - 2.4$, and squares: $\alpha \geqslant 2.4$) and the colors reflect the actual galaxy colors (blue: $g - r \leqslant 0.65$, green: $g - r = 0.65 - 0.8$, red: $g - r \geqslant 0.8$) from Huber et al. (2004).

First tests of a similar correlation based on primarily optically detected clusters give the surprising result that the scatter in the X-ray/optical correlation is much larger and in particular there are a lot of cases of optically luminous objects with low X-ray luminosity which fall outside the scattering range observed in the study of primarily X-ray selected clusters. This study is in progress and will hopefully shed more light on the not well understood difference between optically selected and X-ray selected cluster samples.

4. The galaxy population mix and large-scale geometry

While on the one hand we observe a tight correlation of the light and dark matter density, there is a surprisingly striking change in the galaxy population if we go from the low density field into the dense cluster environment (e.g. Dressler et al. 1997). Aspects of this morphology-density relation was one of the widely discussed topics at the meeting. Looking at the very pronounced bubbly and filamentary structure of our Universe one is led also to wonder if there is also a correlation of galaxy morphology and the type of structure the galaxies are embedded. Does it matter if the galaxies under investigation populate a cluster, a sheet, or a filament?

To determine the geometry of the local LSS we use scaling indices. These measures are equivalent to the determination of the local two-point correlation properties of a selected galaxy with the surrounding galaxies within a sphere with given radius. In addition a special radial weighting function may be included in the correlation analysis (Raeth et al. 2002). The scaling index $\alpha = 3 - \gamma$ (where γ is the power law index of the two-point correlation function) provides an indication of the dimension of the structure surrounding the selected galaxy, for example 1 for a filament, 2 for a sheet and less than 1 for a cluster (Huber et al. 2004). Fig. 4 illustrates the assignment of scaling indices to galaxies within the LSS. At present this method is tested on a slice through the SDSS survey -

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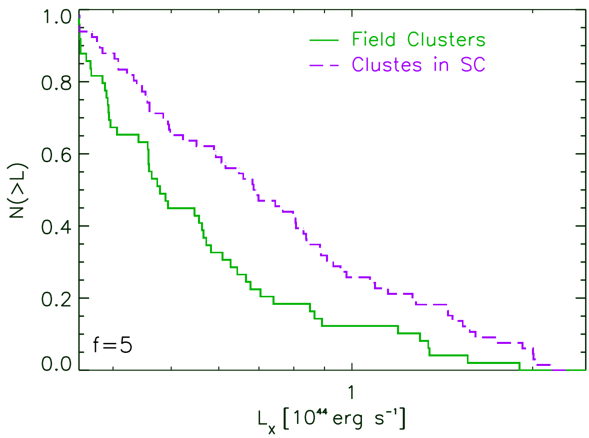

Figure 5. Cumulative X-ray luminosity distribution of galaxy clusters from the extended REFLEX sample assigned either to superclusters or to the field (from Nowak et al. 2004).

a pseudo-two-dimensional data set. There is a clear correlation between the geometry of the LSS features and the mean galaxy color, but most of this just reflects the well-known morphology density relation. However, we also have a first indication of a geometry - galaxy color correlation if the analysis is carried out for regions of similar density. A clearly significant result is expected if we apply this method to the bulk of the SDSS data in the near future.

5. The dependence of the cluster properties on the large-scale structure environment

While, as described above, it is well known that the galaxy population changes with the large-scale structure matter density, we know less if this is also true for the population of galaxy clusters. In the first study (Nowak et al. 2004) a supercluster catalogue for the 842 galaxy clusters of the extended REFLEX survey was constructed by means of the friends-of-friends algorithm. The most convincing supercluster structures were found for a linking length corresponding to a galaxy cluster overdensity in the range of $5-10$. For this assignment of the galaxy clusters to belong either to the field or a supercluster, the luminosity distribution is investigated as shown in Fig. 5. There is a clear trend that clusters in superclusters are more luminous on average than clusters in the field. Detailed studies show that this result is significant and not an artefact of selection effects (Nowak 2004, Nowak et al. 2004). We attribute this luminosity excess either to a luminosity boost in merging clusters or to a more evolved luminosity function in the high density environment of superclusters.

In the second study the frequency of substructure was determined for a sample of clusters from the REFLEX and northern BCS sample (Ebeling et al. 1998). Three measures of substructure were used, the β-test (sensitive to deviations from mirror symmetry), the Lee statistic (most sensitive to bimodal structure), and the Fourier elongation analysis (sensitive to elongations and substructure - Schuecker et al. 2001b). As shown in Fig. 6 at least two of the three substructure measures show a clear signature that substructured clusters are more frequently observed in denser regions. That is, merging of clusters occurs with a higher frequency in denser environments.

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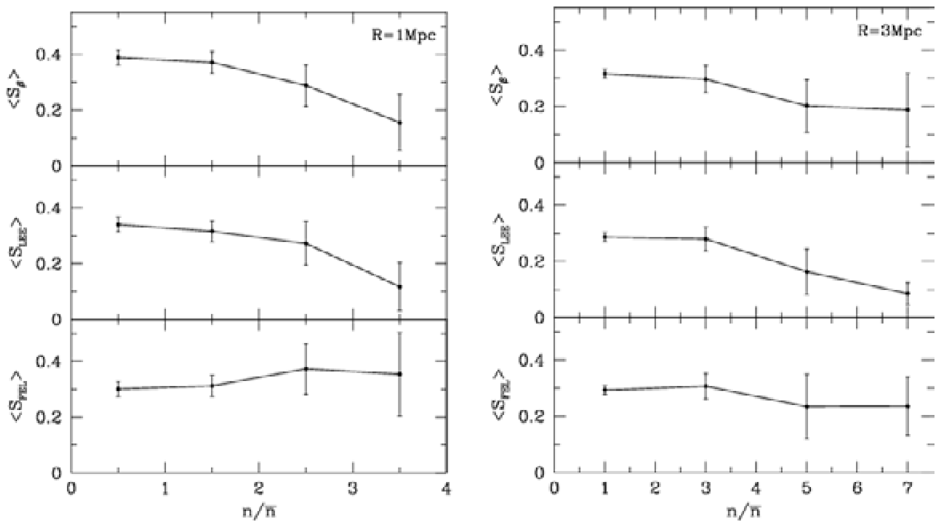

Figure 6. Average significance of clusters showing substructure for clusters from the REFLEX and BCS surveys binned according to the cluster density of the environment. Three measure of substructure are used, the β-test, Lee statistic, and the Fourier elongation test, respectively (Schuecker et al. 2001b).

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