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X-Ray Substructures of BCS, NORAS, REFLEX, Radio Halos/Relics and Cooling Flow Clusters of Galaxies

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Abstract. The results of a systematic study of substructures in X-ray surface brightness distributions of BCS, NORAS, REFLEX, radio halo, relic, and cooling flow clusters of galaxies based on RASS data are presented. At least 40 percent of the clusters show substructure. Indications for a cluster morphology-density relation are found. The fraction of clusters with substructure seems to be higher for halo and relic clusters and lower for clusters with cooling flow signature.

1. Introduction

The basic aim of the present investigation is to quantify the morphology for a large set of galaxy clusters using the X-ray surface brightness distributions extracted from the data obtained in the course of the 3rd processing of the ROSAT All-Sky Survey (RASS-3). The cluster samples are selected in an homogeneous manner enabling systematic studies of their morphology and its relation to the local cluster environment. The substructure analysis uses the 452 galaxy clusters found in the ROSAT-ESO Flux-Limited (REFLEX) cluster survey (Böhringer et al. 2000a), the Brightest Cluster Sample (BCS) survey (Ebeling et al. 1998) with 201 clusters, and the Northern ROSAT All-Sky (NORAS) galaxy cluster survey (Böhringer et al. 2000b) with a statistical sample of 378 clusters. Included are 20 halo and 8 relic clusters compiled by Giovannini & Feretti (see conference proceedings edited by Böhringer, Feretti & Schuecker 1999) and 18 clusters with cooling flow signatures (Peres et al. 1998) which are also members of the REFLEX, NORAS, and BCS samples. The frequencies of clusters with substructure of each sample are determined and compared.

The β statistic is used to test for asymmetry, the Fourier elongation statistic, FEL, to test ellipticity, and the Lee statistic, LEE, to test multimodality. The statistics are sensitive to different types of substructure and are thus ideally suited for the detection of a large variety of different merger events (see N-body simulations of Pinkney et al. 1996). The tests are applied to two-dimensional X-ray images as extracted from RASS-3.

The methods are tested in the following way. Jones & Forman (1999) used the iso-intensity contour plots of the *Einstein* IPC X-ray emission of 252 targeted and serendipitously found clusters to classify their morphology into substructured and regular distributions (the subclasses are not treated here). In total 86 classified *Einstein* clusters are found in common with the REFLEX, NORAS, and BCS sample. We found that for our standard significance threshold for regular clusters, $S = 0.05$ (non-regular clusters have $S \leq 0.05$), about 50 percent of the test clusters have the same classifications by Jones & Forman (*Einstein*) and by the automated methods (RASS-3) where most of the differences between the two classification schemes result from clusters which are classified as regular by Jones & Forman and which are classified automatically as substructured. However, the fraction of coinciding classifications increases to 70 percent or more when the significance threshold of the automated classifications is set to $S = 0.01$ or lower. This might suggest that the interactive classifications of Jones & Forman are performed more conservatively compared to the automated classifications of the corresponding RASS-3 images with the significance threshold, $S = 0.05$.

2. Frequencies of BCS, NORAS, and REFLEX Clusters with Substructure

A cluster with a significant substructure is defined as having at least one of the three significances, S_β, $\mathrm{S}_{\mathrm{FEL}}$, or $S_{\mathrm{LEE}} \leq 0.05$. For comparatively large numbers of X-ray photons ($N_{\mathrm{ph}} \geq 200$) the sensitivity of RASS-3 to even minor subclusters is high so that eventually every cluster shows some kind of substructure (about 90 percent for $z \leq 0.1$). For small numbers of X-ray photons ($N_{\mathrm{ph}} < 200$) only nearby and well-separated subclusters are detectable (33–45 percent for $z \leq 0.1$). The sensitivity for subcluster detection decreases for clusters with small N_{ph} at high z (10–37 percent for $z = 0.15 - 0.20$). The most nearby REFLEX and BCS subsamples ($z \leq 0.1$) have the highest completeness and should thus give the less biased estimates of the frequencies of clusters with subclusters.

We found a morphology-density relation for galaxy clusters in the sense that clusters with asymmetric, elongated, or multi-modal X-ray surface brightness distributions are located preferentially in regions with higher cluster number density (P. Schuecker et al., in preparation).

3. Substructures in Halo, Relic, and Cooling Flow Clusters

For a proper comparison of the frequencies of clusters with substructure obtained with halo, relic, cooling flow, and reference samples one has to equalize the overall efficiencies of substructure detection. It is found that the number of photons per target, N_{ph}, is the most crucial factor determining the efficiency of substructure detection (the redshift bias will be discussed below). It is thus necessary to equalize the frequency distributions of N_{ph} for the different samples. In order to correct for the systematic effect one has to dilute the (larger) reference sample so that its normalized cumulative distribution function, $P(< N_{\mathrm{ph}})$, resembles the distribution function of the (smaller) test sample. The dilution is performed as in standard Monte Carlo experiments. We reduce the redshift bias by simply restricting the analyses to clusters with redshifts $z \leq 0.15$.

Table 1. Corrected fractions of halo, relic, and cooling flow (CF) clusters with significances $S \leq 0.05$ and redshifts $z \leq 0.15$. For comparison, for each sample the corresponding REFLEX+BCS expectations are given.

Sample	$P(S_\beta)$	$P(S_{\rm FEL})$	$P(S_{\rm LEE})$
Halo	0.80	0.80	1.00
REFLEX+BCS	0.42 ± 0.22	0.79 ± 0.18	0.78 ± 0.18
Δ	$+1.7\sigma$	$+0.1\sigma$	$+1.2\sigma$
Relic	0.50	0.67	0.67
REFLEX+BCS	0.42 ± 0.20	0.57 ± 0.20	0.59 ± 0.20
Δ	$+0.4\sigma$	$+0.5\sigma$	$+0.4\sigma$
CF	0.31	0.63	0.63
REFLEX+BCS	0.53 ± 0.13	0.67 ± 0.12	0.64 ± 0.12
Δ	-1.7σ	-0.3σ	-0.1σ

The corrected substructure frequencies are given in the table above. Included are the differences, Δ, between these fractions and the corrected frequencies for the REFLEX+BCS sample in units of the standard deviations as obtained for the reference sample. The statistical significances of the individual differences are not very large, but for all three tests and for each of the three cluster types in certain directions. Whereas the cooling flow clusters tend to show less frequent substructures, the halo and relic clusters show more often substructures compared to the reference sample, further supporting the idea that radio halos and relics are triggered by merger events, and that pre-existing cooling flows might be disrupted by recent merger events.

Therefore, promising candidates for halo and relic clusters useful for detailed radio follow-up observations are expected not only for X-ray luminous clusters but also for low-luminosity X-ray clusters with significant substructure, detectable with deep pointed X-ray observations.

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