

Cosmic Structure Traced by Precision Measurements of the X-Ray Brightest Galaxy Clusters in the Sky

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Abstract. The current status of our efforts to trace cosmic structure with 10^6 galaxies (2MASS), 10^3 galaxy clusters (NORAS II cluster survey), and precision measurements for 10^2 galaxy clusters (*HIFLUGCS*) is given. The latter is illustrated in more detail with results on the gas temperature and metal abundance structure for 10^0 cluster (A1644) obtained with XMM-Newton.

Galaxy clusters have been very important tools to study cosmic structure and determine cosmological parameters. Even moderately sized samples yield competitive statistical constraints, e.g., *HIFLUGCS* (Fig. 1), [1]. However, accuracy is currently limited by systematic uncertainties. Luckily major improvements are now feasible, e.g., by taking advantage of new multiwavelength data and especially Chandra and XMM-Newton X-ray observations. We've started a project to tackle systematic uncertainties in flux, temperature, gas and gravitational mass estimates by detailed analyses of the 63 X-ray brightest galaxy clusters in the sky (*HIFLUGCS*). Many of these clusters have already been observed by Chandra and XMM-Newton. Data are accumulating in the archives. The first out of further nine approved Chandra observations proposed by us is being carried out today (2002-12-16).

The NORAS II cluster survey contains about 800 X-ray selected galaxy clusters (Böhringer, Retzlaff et al., in prep.). In order to test for systematic effects caused by different selection techniques — which must be well understood to obtain precise cosmological constraints — we started correlating the NORAS II clusters with the 2MASS extended source catalog (the latter shown in Fig. 1, [2]) and color selected point source catalog. Furthermore galaxy overdensities at cluster positions will be determined in order to estimate richness–mass relations and mass-to-light ratios.

In the following we illustrate possible improvements from the X-ray side on an especially tough example. XMM-Newton observations of A1644 show a very complicated surface brightness distribution on all scales (Reiprich et al., in prep.). A main clump and a smaller sub clump are easily identified. The emission surrounding both core regions is highly non-spherical. And the core region of the main clump itself contains a displaced core-within-a-core. How much do X-ray flux, gas, and gravitational mass estimates based on precision measurements differ from simple estimates where, e.g., the

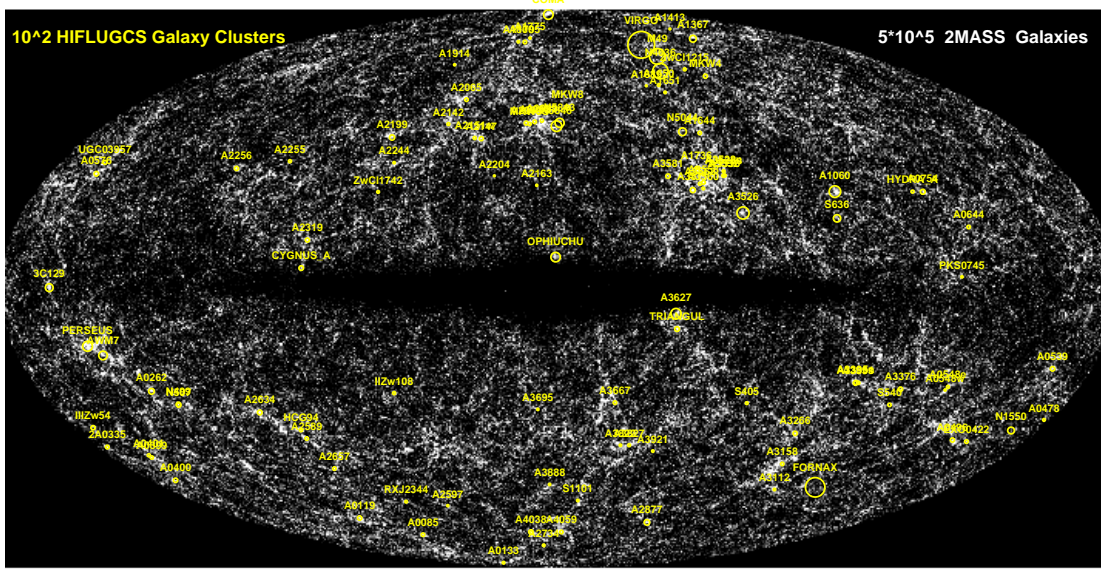


FIGURE 1. *HIFLUGCS* and other local X-ray galaxy clusters shown in Galactic coordinates on top of the distribution of half a million 2MASS galaxies. Qualitatively both populations seem to nicely trace an underlying matter distribution with clusters being located at the peaks.

whole cluster is treated as a spherical cow as might be done if only ROSAT All-Sky Survey data were available? How much do mass estimates differ when only a broad beam overall gas temperature estimate is available?

The X-ray flux (f_X) ratio between the main and sub clump is about 3:1. This means instead of one cluster in a flux-limited sample with $f_X \approx 4 \times 10^{-11}$ erg/s/cm² one actually has two clusters with about $f_X \approx 3$ and 1×10^{-11} erg/s/cm² each. This is quite an important difference, especially for construction of luminosity and mass functions!

The intracluster gas temperature is a fundamental observable for a mass determination based on the hydrostatic assumption. One first step of refinement compared to broad beam temperature estimates is the construction of radial temperature profiles for the main and sub clump. To our surprise we found that each of the two temperature profiles appears very similar to temperature profiles of relaxed, apparently undisturbed clusters: a drop in the center to about 1/2 to 1/3 of the ambient gas temperature, an isothermal structure in the outer parts, and weak indications for a slight temperature drop in the very outermost regions accessible. This appears to be good news: this cluster may not be as complicated as it seemed, the temperature structure may not be affected by the interaction of the two sub clumps (which are located at about the same redshift). Note, however, that simple broad beam temperature estimates would still be biased low compared to the ambient gas temperature due to cool emission in the dense (high emissivity) centers. For instance, the temperature estimate in a large annulus around the main clump — taken as the ambient temperature — is a factor of 1.1–1.15 higher than a broad beam temperature estimate including both clumps. Since $M \propto T^{1.5-2.0}$ [e.g., 3] this factor translates into a factor of 1.15–1.32 in a mass estimate!

The next step we took is the subdivision of annuli into regular segments. Figure 2 shows selected regions as well as surface brightness contours overlaid onto a hardness

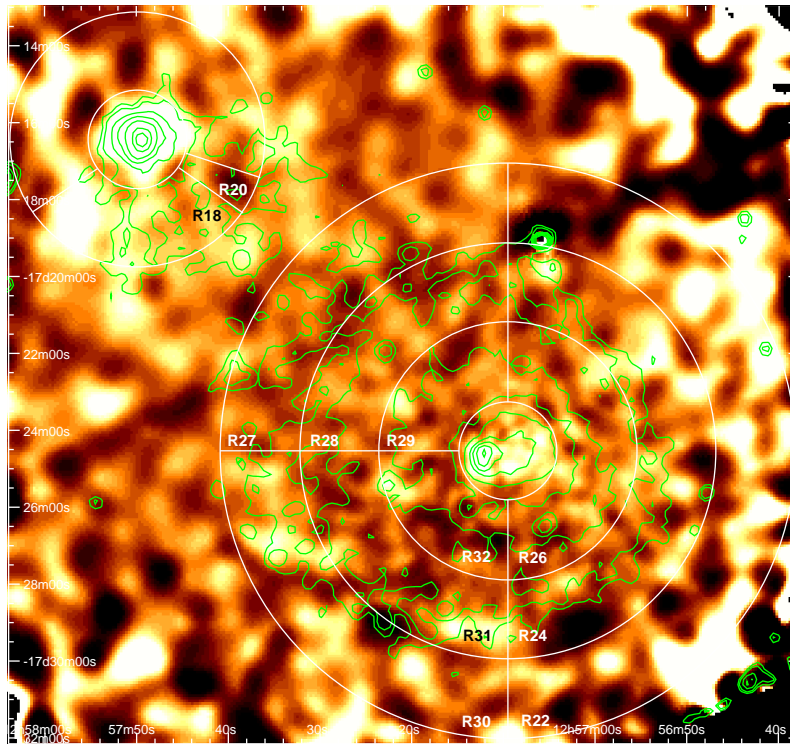


FIGURE 2. Hardness ratio map of the galaxy cluster A1644. Background, exposure, and vignetting corrected, adaptively smoothed, combined MOS1-MOS2-pn count rate image ratio for the energy bands $(0.3\text{--}2.0\text{ keV})/(2.0\text{--}10.0\text{ keV})$. Soft emission appears bright and hard emission dark. Also shown are surface brightness contours for the $(0.3\text{--}2.0\text{ keV})$ image and regions selected for spectral analysis.

ratio (HR) map. Preliminary temperature (metal abundance) estimates for the segments based on standard spectral model fits are shown in the left (right) hand side of Fig. 3. Now it becomes obvious that the apparently regular temperature profiles are misleading and only due to averaging over (too) large regions. The temperatures of the segments to the East of the main clump (R22, R24, and R26) are all significantly lower than almost all regions to the West (R27–R32). This may indicate that the gas in the regions between the two clumps has been heated up by adiabatic compression or even shocks.

Having found irregularities in the temperature structure a further step is to select regions based on the HR map to directly search for cool/metal rich trails (bright) or hot spots (dark). The significance of brightness fluctuations is again evaluated by direct spectral fits. Note that not all artifacts, e.g., inexact exposure correction close to CCD chip boundaries, have been removed in the HR map in Fig. 2. The spectral analysis, however, is not affected by this. The region to the South of the sub clump (R18) appears fairly bright and therefore soft, whereas a small region to the Southeast (R20) appears hard. The spectral fit results (Fig. 3) reveal that indeed the temperature estimate for R18 is significantly lower than the estimate for the rest of this annulus (R19) and especially than that for R20. Furthermore the metal abundance estimate for R18 appears enhanced. These findings together with the surface brightness structure might imply that to the South we see gas that has been removed from the cooler center of the sub clump possibly by the combined effect of some energy source related to the central galaxy of the sub

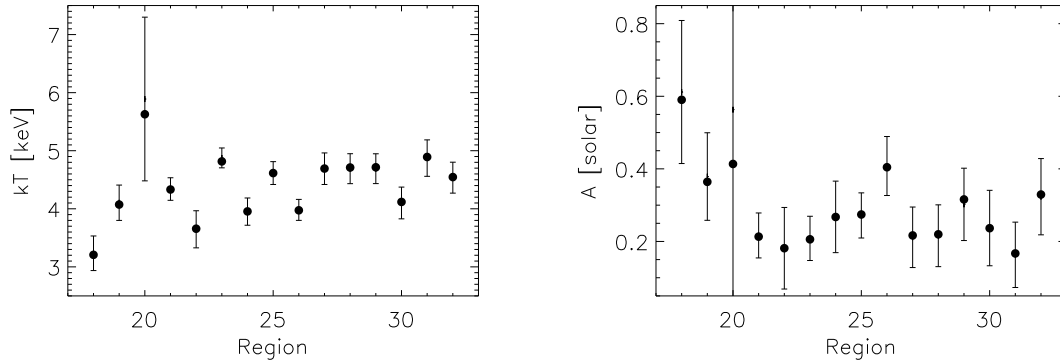


FIGURE 3. Gas temperature (left) and metal abundance (right) estimates of selected regions based on simultaneous spectral fits to background and vignetting corrected spectra from the MOS1, MOS2, and pn detectors aboard XMM-Newton. Note that R21=R27+R30, R23=R28+R31, R25=R29+32, and R19=full annulus–R18; see Fig. 2. Statistical error bars show the 90% confidence level for one interesting parameter.

clump (a radio source) and the movement through intracluster gas of the main clump. Should more detailed modeling confirm the significance of the abundance excess then other possibilities like cooling of intracluster gas onto the moving sub clump (as seen in A1795 on much smaller scales, [4]) would be more difficult to reconcile with the data.

In summary the temperature structure of A1644 shows that this system is quite complicated as indicated by the surface brightness structure. Interestingly no evidence for substructure has been found in optical and near-infrared observations [5]. The next step is to attempt an improved mass estimate and compare it to more simple estimates as generally applied to clusters at higher redshift and in larger samples. Note that this detailed study required only 12 ks of good data. Chandra and XMM-Newton observations of the complete *HIFLUGCS* are quite cheap but offer a great opportunity for clusters in the era of precision cosmology. Comparison of cluster X-ray data to the wealth of new multiwavelength data, e.g., 2MASS, will also help to reduce systematic uncertainties.

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